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The Effect of Heat Input on the Weld Geometry, Distortion and Peel Strength on Pulsed Laser Wobbling of Austenitic Stainless-Steel Foils

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ABSTRACT

The significance of stainless-steel foils, specifically SS304, cannot be overstated in the dynamic field of materials science, given their wide range of industrial applications. A pulsed Nd:YAG laser wobble welding method is considered to be the most effective method of joining these foils, due to its high precision and minimal influence of heat. Despite this, it remains a considerable challenge to determine the complex relationship between heat input and the quality of the weld produced. The purpose of this study was to investigate the effects of three specific heat inputs (0.34, 0.39 and 0.43 J/mm) on the welding of SS304 foil. A methodical approach was employed to employ these distinct heat levels and the resulting welds were rigorously evaluated. Key findings highlighted the peel strength for specimens S1, S2 and S3 as 188.29 N, 363.05 N and 634.10 N, respectively. The maximum penetration depths of these three samples were 0.16 mm, 0.22 mm and 0.18 mm, respectively. Moreover, both vertical and horizontal distortions were measured across the various sections of the weld. The S2 specimen, with a heat input of 0.39 J/mm, displayed pronounced distortions in both axes, while S3, with a heat input of 0.43 J/mm, presented the highest peel strength and volume penetration. There is a delicate balance that welding operations must maintain in order to enhance weld attributes such as strength without inadvertently exacerbating distortions. Taking into account the synthesized insights, it is clear that judicious heat input management is critical. Even though a higher heat input can enhance certain weld qualities, it is crucial to be aware of the consequences of such distortions, thereby requiring a well-calibrated approach. The findings of this research not only contribute to a deeper understanding of welding dynamics, but also lay the foundation for developing future processes that are more nuanced and productive.

1. Introduction

In many industries, stainless steel is one of the most versatile and durable materials available. As a result, A variety of applications can be addressed with this material because it combines strength,

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corrosion resistance and ease of maintenance [1-4]. There are numerous applications for stainless steel as a material, including the automotive industry, medical instruments and construction materials. On the other hand, there are some drawbacks associated with using stainless steel 304 for automotive components manufacturing such as hydrogen fuel cell bipolar plate joining by laser micro welding including its susceptibility to cracking due to rapid cooling after heating up during welding operations; difficulty achieving uniform welds due to inconsistent surface finishes on different types of metal; higher cost compared with other metals like aluminium; potential issues related to galvanic corrosion when dissimilar metals are joined together via laser micro-welding. The application of stainless steel 304 for bipolar plate laser micro welding requires precise control over parameters such as power output levels, pulse duration times and focal positions to achieve optimal results with minimal heat input into the base material being welded together. The heat input is critical for optimizing weld quality during pulsed laser wobbling of austenitic stainless-steel foils. A major consideration is laser power, in which a balance is sought between obtaining deep penetration from a high-power laser and melting just enough material at a low power to prevent distortion. There is also pulse duration to consider, which is essentially defined by how long laser energy interacts with the material. By experimenting with various pulse duration, the heat input and determine the most effective weld geometry. Wobbling frequency or the rate at which the laser oscillates, plays an important role in this technique. It is essential to use a frequency that ensures both uniform heat distribution and thorough fusion. By providing instant insight into weld quality, modern real-time monitoring tools, such as thermal imaging, enhance this process. The most important aspect of this process is that can continually refine it through systematic iterative testing in which parameters are varied and effects are observed. In order to consistently obtain high-quality welds, consistent attention to detail is essential.

As of nowadays, laser wobbling is still a relatively new technique of laser micro welding. Several potential applications of this material are now being explored, such as attaching bipolar plates in hydrogen fuel cells, among others. Yuce [5] investigate The Effect of Laser Beam Wobbling Mode on Weld Bead Geometry of Tailor Welded Blanks. As a result of the experiment, the results have shown that the maximum diameter of the wobble has a direct effect on the width of the weld bead which increases with the amplitude of the wobble. Li *et al.*, [6] conducted a study of Analysis and improvement of laser wire filling welding process stability with beam wobble and found Beam wobble parameters can improve keyhole stability and modify liquid metal fluidity, resulting in wider and shallower weld morphology. As a result, they discovered that the amplitude of the wobble had a significant impact on the geometry, microstructure, mechanical strength and electrical resistance of the welds. There is an optimum wobble amplitude of between 0.8-1 mm that has been found to be effective [7]. In addition, Shah *et al.*, [8] investigate the effect of beam wobbling on laser welding of aluminium and magnesium alloy with nickel interlayer. It was found that Laser beam wobbling enhances joint quality by widening the joint area and mitigating the formation of brittle secondary phases at the joint fusion zone.

It is essential to achieve a high degree of precision when welding thin materials like SS304 foils. Wobble welding with pulsed Nd:YAG lasers offers potential for such materials, but its true potential lies in fully understanding and optimizing the heat input. Heat input plays a crucial role in determining the weld quality and this study aims to clarify its complexities. This research focuses on addressing the inherent challenges of welding stainless steel 304, such as distortion and quality inconsistencies. Using the pulsed laser wobbling technique, which oscillates the laser beam, it is possible to improve the distribution of heat. The significance of this research extends beyond academic interest to the real-world hydrogen fuel cell industry as well. In addition to understanding the issue, this study aims to provide practical welding guidelines, especially for thin SS304 foils. To accomplish the goal of consistently producing high-quality SS304 components, this study aims to push the boundaries of laser welding techniques for thin materials.

The objective of this paper is to investigate the effect of heat input on the weld profile and the corresponding mechanical properties of welded stainless-steel foil (SS304) by pulsed Nd:YAG laser wobble technique. Pulsed Nd:YAG laser wobble welding is a type of laser welding that is particularly suitable for welding thin materials such as stainless-steel foil. However, the optimization of the welding process is essential to achieve high-quality welds with excellent mechanical properties. Heat input is one of the most critical factors that affect the quality of the weld produced using pulsed Nd:YAG laser wobble welding. The laser power, welding speed, wobble amplitude, wobble diameter, wobble frequency and spot size of the laser beam all contribute to the heat input and it is essential to carefully control these parameters to achieve the desired weld profile and mechanical properties. Understanding the relationship between heat input and the resulting weld profile and mechanical properties is crucial. The results of this study can provide valuable insights into how to control heat input to achieve high-quality welds in the bipolar plate joining hydrogen fuel cell industry. The purpose of this study is to investigate the impact of heat input on weld geometry, distortion and peel strength when SS304 foils are wobbled using pulsed lasers. It can be challenging to weld thin foils, especially stainless steel 304, due to distortions and poor weld quality. The pulsed laser wobbling technique has shown promise for achieving high-quality welds in thin foils. The oscillation of the laser beam during welding improves heat distribution and reduces thermal stress. This study aims to optimize the welding process by understanding the relationship between heat input parameters and weld quality. The findings will provide practical guidelines for industries relying on high-quality welds in thin SS304 foils. Overall, this study contributes to advancements in laser welding techniques for thin foils, enhancing the quality and reliability of welded SS304 components.

2. Methodology

2.1 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.

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

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 100 mm as showed in Figure 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.

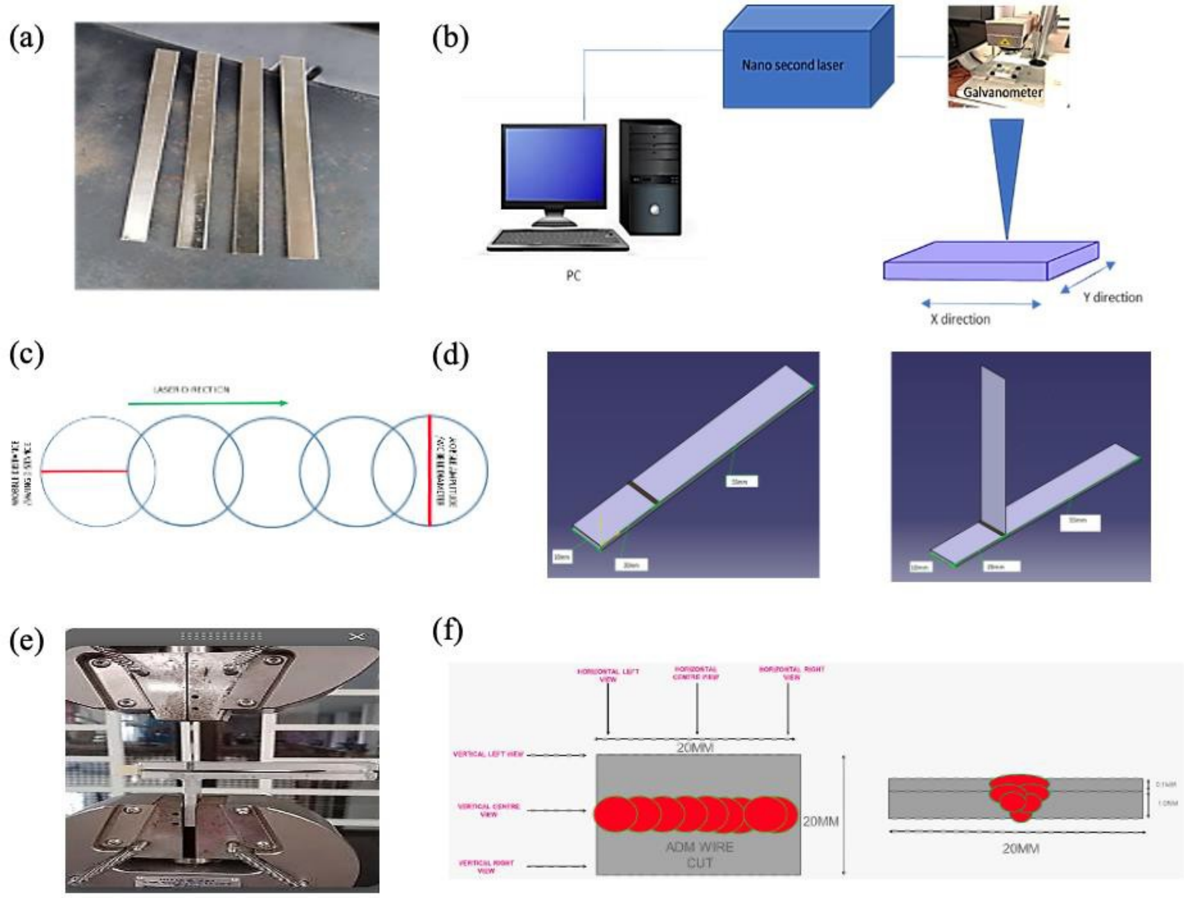


Fig. 1. (a) SS304 cut-out samples (b) Laser micro-welding process (c) sketch of Laser wobbling parametric dimensions (d) dimensions of the jig for 180-degree peel test (e) 180-degree peel test jig with samples mounted on Instron tensile testing machine (f) sample dimension and location of distortion measurement

2.2 Nanosecond Laser Wobble Welding Process

A nano-second fibre laser welding machine considering wobbling with a constant 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). While welding speed, pulse on time, wobble frequency, wobble amplitude (diameter) and wobble distance were controlled, different levels of laser power were employed [9].

According to Das *et al.*, [10], laser power significantly influences two of the key geometric features of a fusion zone, namely the width of the weld and the depth of penetration 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 70 to 90 mm/sec. Similarly, the ranges for wobble parameters were 0.1mm to 0.5mm for wobble amplitude (Diameter) and wobble distance and 70Hz to 90 Hz for wobble frequency. In this experiment, all the parameters are constant except welding speed to investigate the effect of heat input on laser wobbling welding. As a result of the heat input formula, the values for heat input for different laser power welding parameters were calculated out according to three different laser welding parameters used in the study (Table 2).

$$Heat\ Input, \left(\frac{J}{mm}\right) = \frac{Laser\ Power\ (Watt)}{Welding\ Speed\ \left(\frac{mm}{s}\right)} \tag{1}$$

Table 2
A summary of the laser micro-welding with wobbling processing parameters

Specimen	Welding Speed (mm/sec)	Heat Input (J/mm)	Welding Power (Watt)	Welding Frequency (kHz)	Wobble distance (mm)	Wobble diameter (mm)	Focal Length (mm)	Marking Loops
1	70	0.34	24	70	0.2	0.2	210	1
2	70	0.39	27	70	0.2	0.2	210	1
3	70	0.43	30	70	0.2	0.2	210	1

2.3 Preparation of Test Samples

SS304 stainless steel plates are overlap welded according to the welding parameters in Table 3, After the welding process, one joint was used for a metallographic sample and five joints were utilized to prepare the peel test. For each set of parameters, the observed samples were cut with a dimension of 10 mm × 75 mm × 0.1 mm and 10 mm × 75 mm × 1 mm. All the samples are cut by Sodick V2 300L CNC wire cutting machine. Carpenter etchant (122 ml C_2H_5OH +122 ml HCl+6 ml HNO_3+8.5 g FCl_3+2.4 g $CuCl_2$) was applied to the sample surface for 10 to 20 s to reveal the microstructure of the weld zone. Five Peel test samples were prepared for each welding parameter according to ISO 10447 and ISO 14270:2016(E) standards [11]. The peel test jig was developed with the dimensions given in Figure 2(d). The peel tests were performed at a crosshead speed of 2 mm/min by using a 30-kN tensile testing machine (INSTRON) as presented in Figure 2(e). For the distortion measurement and volume of penetration test samples prepared were in the dimension of 20 mm × 20 mm as showed in Figure 2(f). The distortion value on the left side, centre and right side of the distortion was measured by Optical micrographs. An Olympus 3D laser microscope was used for measuring the penetration volume and geometrical aspects of the weld. The ISO4287:1997 standard is adhered to by this laser microscope. Additionally, a metallurgy microscope and optical microscope were also employed to reveal the macrostructures.

3. Results
3.1 Weld Geometry and Peel Strength

Table 3 presents the maximum penetration depth and width of the welded joints at different levels of heat input. The results showed that there is a trend of increasing maximum penetration depth with increasing heat input. Specifically, the maximum penetration depth increased from 0.16 mm at a heat input of 0.34 j/mm for S1, to 0.22 mm at a heat input of 0.39 j/mm for S2 and then decreased slightly to 0.18 mm at a heat input of 0.43 j/mm for S3. On the other hand, the maximum penetration width showed a different trend. The results showed that the maximum penetration width increased from 0.11 mm at a heat input of 0.34 j/mm for S1, to 0.07 mm at a heat input of 0.39 j/mm for S2 and then increased significantly to 0.40 mm at a heat input of 0.43 j/mm for S3. These results indicate that there is an optimum heat input that can produce the desired penetration depth and width for laser welding.

Table 3
Peel strength and weld geometry measurements for the welded specimens

Specimen	Welding Speed (mm/sec)	Welding Power (Watt)	Heat input(j /mm)	Welding Frequency (kHz)	Peel strength (N)	Peel ext. (mm)	Max penetration depth (mm)	Max penetration width (mm)
S1	70	24	0.34	70	188.29	14.32	0.16	0.11
S2	70	27	0.39	70	363.05	10.72	0.22	0.07
S3	70	30	0.43	70	634.10	10.35	0.18	0.40

As showed in Figure 2, the optimum heat input for maximum penetration depth may be different from that for maximum penetration width. Therefore, it is essential to choose the appropriate heat input level depending on the specific welding requirements. Previous studies have investigated the effects of heat input on weld depth in laser welding of dissimilar materials. For instance, Yuce *et al*., [12] found that the penetration depth and weld width increase with the increase of heat input level in laser micro welding of dissimilar galvanized steel to aluminium alloy. Similarly, Dai *et al*., [13] found that the welding heat input plays an important role in laser welding of NZ30K, affecting the depth of penetration, the width of the heat-affected zone and the distribution of precipitates. In contrast, the results presented in Table 3 show a different trend for the maximum penetration width, which decreases with increasing heat input for S1 and S2 and increases significantly for S3. This discrepancy may be due to differences in the materials, welding strategy or measurement methods used in the two studies. The wobble function can be used to manipulate the laser beam during welding, resulting in wider welds, higher heat input and lower hardness of the joint Reports of Kankala *et al*., [14].

A study by Trushnikov *et al*., [15] examined the effects of beam deflection oscillations on weld geometry and concluded that oscillations in the impinging electron beam had a small impact on the weld root shape. This resulted in the assumption that the beam self-focused at the bottom of the keyhole. In linear longitudinal oscillations, maximum weld depths were observed at focusing currents of 840–850 mA and oscillation amplitudes of 2–2.7 mm. For transverse sinusoidal oscillations, higher oscillation amplitudes are observed at focus positions below the sample surface, whereas smaller oscillation amplitudes are observed at focus positions above the sample surface. In their study, Yoon *et al.,* [16] looked at the effect of wobbling on the welding characteristics of Al/Cu Fiber Laser Welded Joints and they found that the tensile-shear load increased as the waveform's amplitude increased. In spite of this, all studies have demonstrated how important it is to control the heat input during laser welding in order to achieve the desired penetration depth and width [17]. However, the effect of other welding process parameters such as welding speed, current and shielding gas should also be taken into account to fully understand the impact on joint properties [18,19].

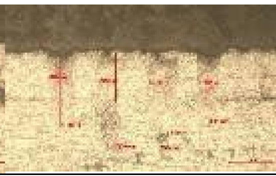
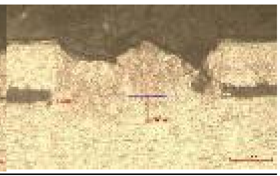
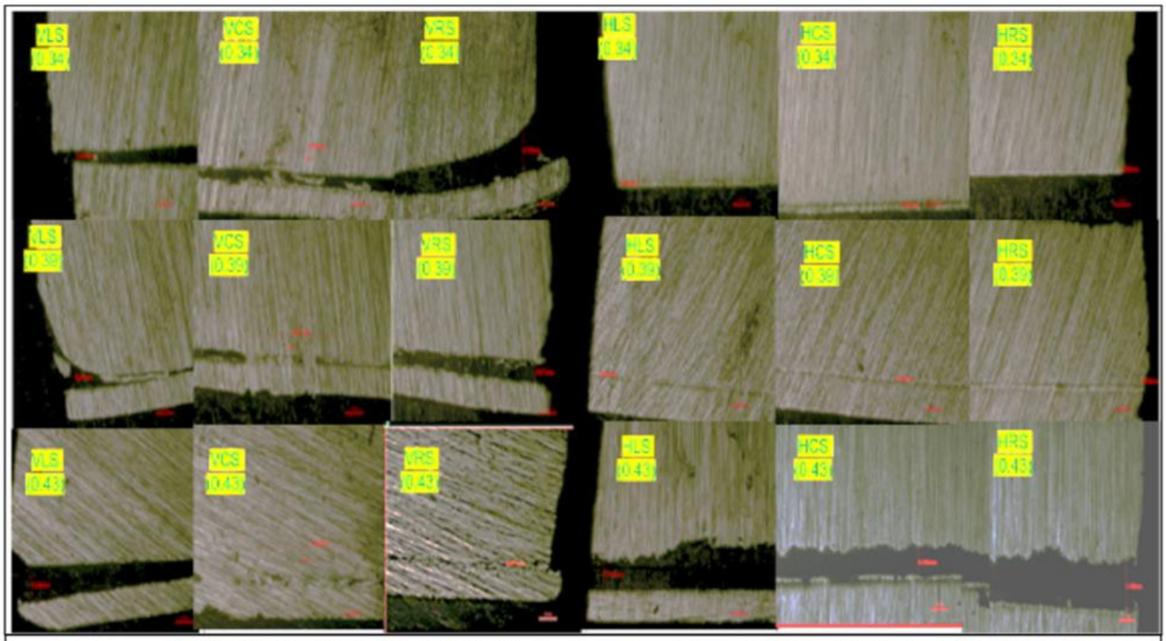
Heat input (j/mm)	0.34	0.39	0.43
Appearance			
Cross- section			

Fig. 2. 3D optical images of weld appearance and metallographic images of the etched cross- section of welded samples

3.2 Weld Geometry and Peel Strength

Figure 3 presents the samples that were distorted with the variation in heat input.



VLS= Vertical left side,VCS=Vertical centre side and VRS= Vertical right side

HLS= Horizontal left side,HCS=Horizontal centre side and HRS= Horizontal right side

Fig. 3. Optical micrographs of the vertical and horizontal measured values of distortion

Additionally, Figure 4 shows the results of the vertical view distortion experiment. Three heat input levels (0.34 J/mm,0.39 J/mm and 0.43 J/mm) were used to weld thin metal sheets and the distortion on the left side, centre and right side of the specimen was measured and presented in the table. As shown in Table 3[, the distortion increased with increasing heat input. At the lowest heat input level (0.34 J/mm), the distortion on the left and right sides of the specimen was negligible, while the centre had a distortion of 0.817 mm. As the heat input increased to 0.39 J/mm and 0.43 J/mm, the distortion on the left and right sides increased to 0.083 mm and 0.131 mm, respectively, while the centre distortion increased to 0.632 mm and 0.848 mm.

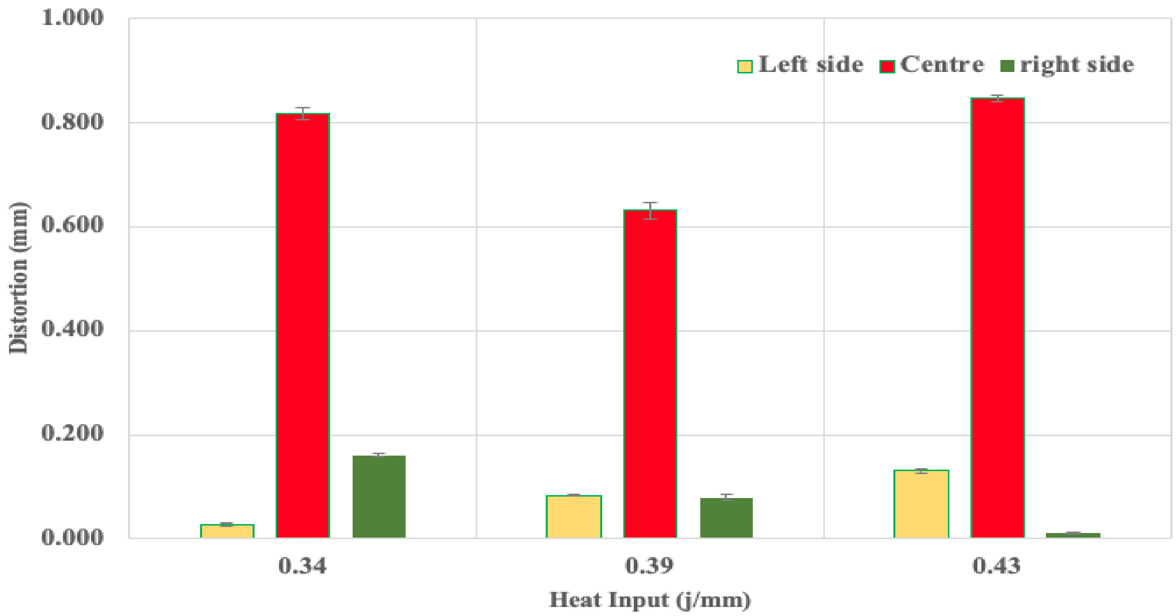


Fig. 4. Effect of heat input on the vertical measurements of distortion

Figure 5 shows the results of the horizontal distortion experiment. The same three heat input levels were used to weld thin metal sheets and the distortion on the left side, centre and right side of the distortion was measured and presented in the table.

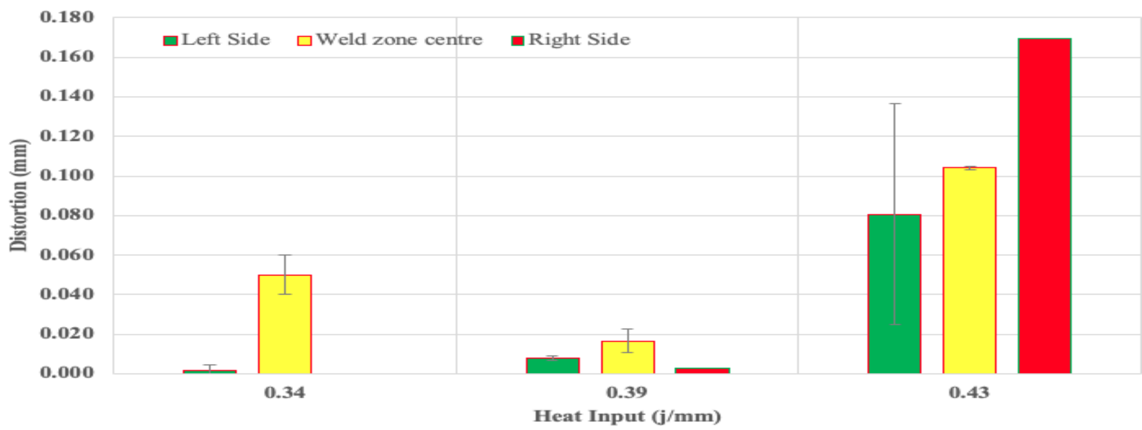


Fig. 5. Effect of heat input on the horizontal measurements of distortion

As shown in Figure 5, the distortion in the horizontal view micro welding experiment was smaller than in the vertical view micro welding experiment. At the lowest heat input level (0.34 J/mm), the centre of the specimen had a distortion of 0.05 mm, while the distortion on the left and right sides was negligible. As the heat input increased to 0.39 J/mm and 0.43 J/mm, the distortion on the left and right sides increased slightly to 0.01 mm and 0.08 mm, respectively, while the centre distortion increased to 0.02 mm and 0.10 mm.

Overall, these results suggest that heat input has a significant effect on distortion in micro welding and the extent of distortion is greater in the vertical view than in the horizontal view. Kumar *et al.,* [20] conclude that the lower the heat input, the lower distortion. Guo *et al.,* [21] investigated the effects of heat input on welding buckling distortion by experimental measurement method and they found that Heat input has a significant effect on welding buckling distortion. Therefore, controlling the heat input is crucial to minimizing distortion and ensuring a high-quality weld [22-24] The results also indicated that the vertical and horizontal distortion values observed in the experiment were within the acceptable limits for joining bipolar plates of hydrogen fuel cells.

3.3 Weld Penetration Volume

Table 4 and Figure 6 show the results of a study investigating the effect of heat input on volume penetration in a welding process. The data includes three specimens, each with different heat inputs and resulting volume penetrations, as well as the average and sum of the penetration values. Analysis of the data reveals that there is a positive correlation between heat input and volume penetration. As the heat input increases, the volume penetration also increases. Specimen 3, which had the highest heat input of 0.43 j/mm, also had the highest volume penetration of 1,140,636.3 µm³. Specimen 2, which had the lowest heat input of 0.39 j/mm, had the lowest volume penetration of 297,410.4 µm³. Specimen 1 had a heat input of 0.34 j/mm and a volume penetration of 926,863.7 µm³. The data also includes the average and sum of the penetration values, which provide additional insights. The average volume penetration across all specimens was 239,336.104 µm³, with specimen 3 having the highest average penetration of 380,684.7 µm³ and specimen 1 having the lowest average penetration of 218,885.8 µm³.

Table 4
Effect of heat input on the volume of the weld penetration

Specimen	Heat Input (J/mm)	Vertical Volume Penetration [µm³]	Average Penetration [µm³]	Sum Penetration[µm³]
1	0.34	926863.7	218885.8	875543.2
2	0.39	297410.4	119439.8	955518.3
3	0.43	1140636.3	380684.7	1142054.1

The sum of the penetration values across all specimens was 2,945,115.707 µm³, with specimen 3 having the highest sum of penetration values at 1,142,054.1 µm³ and specimen 1 having the lowest sum at 875,543.2 µm³. During welding, the heat input causes the base metal to melt and form a weld pool, which is a liquid metal pool that cools and solidifies to form the weld. The weld pool dynamics refer to the behaviour and characteristics of the weld pool during the welding process.

The weld pool dynamics can be influenced by various factors, including the heat input, welding speed and joint geometry. In particular, the heat input plays a significant role in determining the size and shape of the weld pool, as well as the amount of penetration into the base metal. When the heat input is too high, it can result in a more unstable weld pool. An unstable weld pool can lead to a lack of fusion or penetration, which can result in a shallower weld. This could explain why specimen 2, which had a higher heat input, had a lower volume penetration than specimen 1, despite the expectation that higher heat input should result in deeper penetration. These findings suggest that increasing the heat input in a welding process can lead to deeper and wider welds, resulting in higher volume penetrations. However, it is important to note that other factors, such as welding speed, material properties and joint geometry, can also impact the resulting weld quality and should be considered in the optimization of the welding process

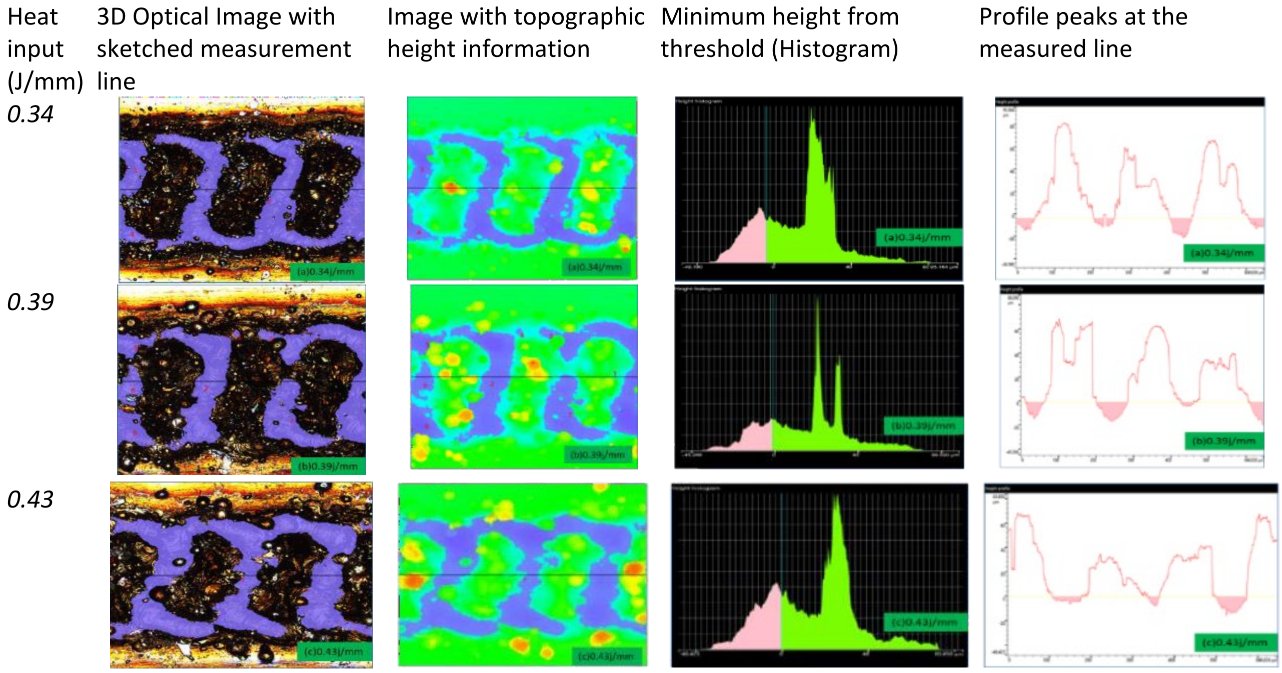


Fig. 6. The 3d optical micrograph, topographic height variation, minimum height threshold and profile peak as per measurement line in the 3D optical image for the respective heat inputs.

4. Conclusions

The study aimed to investigate the impact of heat input on the penetration depth and width, peel strength, distortion and volume of penetration by using laser wobbling-based micro-welding. The following conclusions can be drawn from this work:

i. The findings of the study showed that higher heat input and penetration depth resulted in the highest peel strength of about 634 N. However, excessive penetration depth should be carefully controlled to prevent excessive distortion of the welded joints.
ii. The distortion on the vertical side was 5 times higher when compared with the horizontal side.
iii. The analysis shows that there was a positive correlation between heat input and volume of penetration. In the specific case of specimen 2 having a lower volume penetration despite a higher heat input, it is possible that the higher heat input resulted in a more unstable weld pool, which led to shallower penetration.
iv. In summary, the weld pool dynamics are a complex interplay of factors that can impact the resulting weld quality, including the heat input, welding speed and joint geometry.

Based on the results of the study, it can be concluded that the laser micro welding process using a wobble strategy can significantly affect the quality of welded joints in bipolar plates for hydrogen fuel cell (PEM) applications.

The cumulative conclusion derived from the findings is that weld quality is not determined by a single factor, but rather by a complex interplay of variables, such as heat input and welding speed. It is clear that the dynamics governing the weld pool are more nuanced than previously perceived, necessitating further research to clarify these relationships. Although this research has made significant progress in understanding laser wobble-based micro welding dynamics, it is not without limitations. The purpose of this study is to examine SS304 stainless steel foil, although different materials may exhibit different behaviours under the same welding conditions. It is therefore recommended that future studies extend these investigations across a broader range of materials in order to foster a greater understanding of this phenomenon.

In addition, it was observed that vertical distortion was significantly higher than horizontal distortion, a phenomenon that merits further exploration. Understanding the mechanisms behind such pronounced vertical distortions could provide valuable insights into improving welding techniques.

Despite its limitations, this study provides a significant contribution by providing insight into the multifaceted dynamics of laser micro welding based on a wobble strategy This study provides insight into welding processes and paves the way for future investigations. Continual research in this area may lead to the optimization of welding techniques, thereby improving the quality and efficiency of welding processes across a wide range of industrial applications. In a world increasingly reliant on advanced fabrication methods, such findings could prove pivotal in driving innovation and excellence

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