

Effect of laser welding on the microstructure and properties of ultrathin Inconel 718 sheets

Research Article

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Abstract: Inconel 718 is a high-strength, high-temperature alloy with a nickel matrix containing elements such as niobium (Nb) and molybdenum (Mo). It exhibits excellent corrosion resistance and high-temperature mechanical properties. It is widely used in the manufacture of critical sealing components. However, there is currently limited research on the welding of ultra-thin Inconel 718 sheets with a thickness of 0.25 mm. To address issues such as deformation and poor fusion during welding, this study proposes a combined approach of finite element simulation and experimental analysis to investigate the effects of pulsed laser welding parameters on the temperature field, weld morphology, and mechanical properties. The optimal process parameters obtained through orthogonal experiments were a laser power of 300 W, a welding speed of 60 mm/s, and a duty cycle of 55%. The results show that, with these parameters, the tensile strength of the weld was 856 MPa, approaching 80% of that of the base material, and the weld morphology was uniform and defect-free. The experimental and finite element simulation results were in good agreement. The microstructure at the weld was compact and uniform, with a reasonable distribution of Laves and δ phases, and no obvious defects were observed. This study provides valuable reference data for designing the actual laser welding process for Inconel 718 thin sheets.

Keywords: Inconel 718 • Pulsed laser welding • Thin sheets • Welding parameter optimisation • Weld microstructure

1. Introduction

As turbocharger technology continues to develop, the operating temperature of engines has steadily increased [1]. Consequently, high-temperature environments have imposed stricter requirements on the sealing performance of automotive exhaust systems [2]. Sealing components in automotive exhaust systems, such as V-shaped metal sealing rings, are often made of high-temperature and corrosion-resistant alloys with good weldability. Examples include Inconel 718, which exhibits excellent weldability and resistance to welding-induced cracking, and Inconel 625, which is recommended for exhaust system sealing. Other options include stainless steel grades 304 and 316. These materials are widely used due to their structural and processing properties [3,4]. Poor sealing performance and leaks can affect the achievement of emission standards and lead to increased fuel consumption, thereby adversely impacting the vehicle's fuel efficiency and environmental

performance. However, previous research has shown that the wall thickness of V-shaped metal sealing rings is only 0.25 mm [5], making welding significantly more difficult. Traditional welding techniques suffer from issues such as high heat input and significant deformation during welding, rendering them unsuitable for such thin metal sheets [6]. Pulse laser welding, on the other hand, has the characteristics of concentrated energy and high precision in heat input control. High-energy pulses act on the material for an extremely short period of time, ensuring sufficient weld strength while significantly reducing the heat-affected zone (HAZ)'s instantaneous effect. This method is particularly suitable for joining precision parts as it can form a narrow, uniform weld zone, effectively suppressing thermal deformation of the parts [7–9]. Additionally, the laser beam can be focused to a fine spot size, enabling precise positioning, which is why laser welding is more suitable for welding small components than other methods [10–12]. Therefore, further research on laser welding technology is needed to improve the performance of welded joints.

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Recent studies have revealed further insights into the inherent challenges faced by Inconel 718 and other nickel-based high-temperature alloys during welding. Saurabh et al. [13] investigated the optimisation of laser welding processes for Nimonic 80A high-temperature alloys and noted that incorrect process parameters can result in hot cracking, microporosity, and a reduction in tensile strength. This suggests that a multi-objective optimisation strategy is required to ensure both the quality of the welding process and the structural safety of the final product. Voropaev et al. [14] investigated the layer-by-layer laser welding of Inconel 718 in the context of additive manufacturing, demonstrating that excessive energy input may promote the growth of the Laves phase and cause fluctuations in the melt pool. Sharif et al. [15] used digital image correlation to track changes in the strain field during laser welding of Inconel 718. This demonstrated that precise control of welding speed and heat input is crucial in reducing residual stress and deformation. Studies have shown that the microstructure and properties of Inconel 718 welds are highly complex during laser welding, necessitating optimised process control to achieve the desired microstructural and mechanical properties. Furthermore, the thickness of the weld material during laser welding influences the heat input, welding deformation, and microstructural evolution of the weld, in addition to the metallurgical properties of the alloy itself. Consequently, an increasing number of studies are focusing on regulating the thermal–mechanical behaviour in laser welding of ultra-thin nickel-based alloy plates.

In recent years, controlling the heat input of laser welding and issues of welding deformation in ultra-thin high-temperature alloy materials have attracted the attention of the industry. However, due to the large number of laser welding parameters, methods based on experimental verification require significant time and manpower to determine the optimal parameters, resulting in wasted raw materials. Therefore, combining finite element simulation with orthogonal experiments can reduce the time and cost of testing. Uranga et al. [16] proposed a generic calibration method for laser welding thermal–mechanical coupled finite element models. This method enhances the reliability and generalisability of numerical models. Han et al. [17] investigated the influence of the size of the HAZ and the shape of the melt pool on the degree of welding deformation in 0.6 mm zirconium alloy plates. Baruah and Bag [18] employed a dual-cone heat source simulation method to analyse and simulate the thermal field and deformation behaviour during the laser welding of 0.5 mm Ti₆Al₄V alloy plates. The results were highly consistent with experimental data. To control the

development of the HAZ and microstructure during laser welding, Zhang et al. [19] proposed the synchronous gas cooling method. During the welding of 1.5 mm thick Ti₆Al₄V plates, this method was found to effectively reduce deformation, residual stress, and plastic strain while also refining the β grains and α' phases. Chen et al. [20] observed that, during the welding of 0.32 mm thick Inconel 718 alloy, an increase in heat input caused the cross-section of the weld to transform from a V-shape to an H-shape. This was accompanied by grain refinement in the central region and the formation of a continuous, dense joint microstructure. In order to meet the demand for ultra-thin welding of dissimilar materials, Kumar et al. [4] used a flexible laser electrode welding process on 718 and 410 steels. Compared to traditional resistance welding methods, the results demonstrated improved joint strength, flexibility, and efficiency. Additionally, Li et al. [21] investigated the effect of environmental pressure on the weld quality. They found that, as the environmental pressure decreases, the alloy's boiling point also decreases. This promotes stable melt pool formation and significantly improves weld quality.

As can be seen from the above literature, current research on laser welding primarily focuses on plates with a thickness greater than 0.3 mm. In contrast, studies on the laser welding process parameters for thinner Inconel 718 sheets (0.25 mm thick) are scarce. Therefore, this study uses a combination of finite element simulation and experimental validation to investigate how the laser power, welding speed, and duty cycle affect temperature field evolution and weld morphology. The experimental results were then used to validate the simulation outcomes. The findings offer both theoretical support and practical guidance for optimising the laser welding process of ultra-thin Inconel 718 sheets and hold substantial significance for engineering applications and academic research.

2. Finite element analysis and model development

During laser welding, the microstructure and chemical composition of metals undergo significant changes. To facilitate the development of numerical models and their integration with actual operating conditions, the following simplifications are adopted in this study: turbulent flow in the melt pool and chemical reactions between elements are neglected; the material is assumed to exhibit isotropic thermophysical properties; the laser energy absorption

C	Si	Mn	Mo	S	Ni	Cr	Nb
≤0.08	≤0.35	≤0.35	2.8–3.3	≤0.01	50–55	17–21	4.75–5.5

Table 1. Typical chemical composition of INCONEL 718 (mass fraction, %).

coefficient of the material surface is assumed to be constant; and the vapourisation effect of the material under high-temperature conditions is ignored.

2.1 Thermophysical properties of the material

The thermophysical properties of Inconel 718 sheet change as the temperature changes. Table 1 shows the chemical composition of Inconel 718 [22], and Figure 1 illustrates the material's thermophysical properties at various temperatures [23].

2.2 Finite element model development

This study uses COMSOL software to perform finite element analysis. The dimensions of the specimen are set to 18 mm × 10 mm × 0.25 mm to ensure consistency with the actual specimen. Figure 2 shows the finite element analysis model of the laser welding process, in which the weld and the surrounding areas are divided into tetrahedral meshes. Due to the significant temperature gradients and rapid thermal cycling processes in the HAZ, the region extending ±1 mm from the weld center is discretised using a refined mesh (element size: 0.004–0.4 mm) to ensure computational accuracy. Meanwhile, the area 2 mm

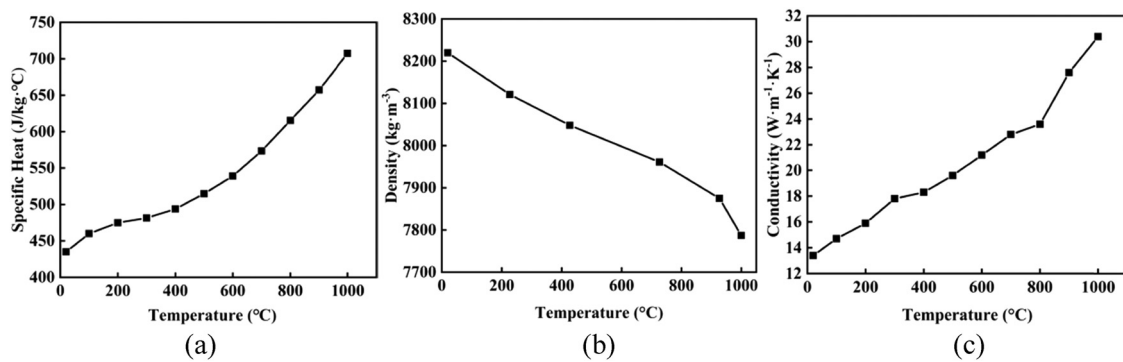


Figure 1. Thermophysical parameters of Inconel 718: (a) specific heat, (b) density, and (c) conductivity.

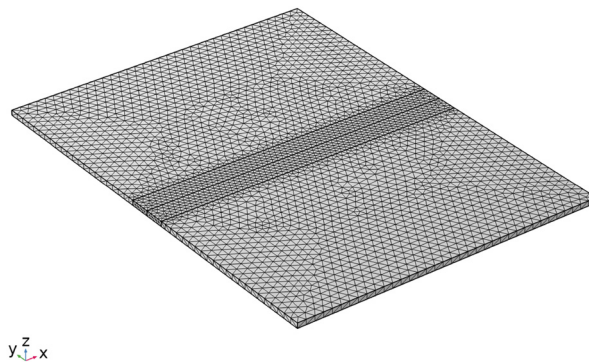


Figure 2. Grid division of the finite element model.

outside the weld centre, which is subject to relatively minor thermal effects, is divided into a coarser grid (element size: 0.2–1.6 mm) to improve the computational efficiency. A transition mesh is applied in the intermediate regions (approximately 0.5–1 mm adjacent to the refined mesh) to ensure smooth gradient transitions between mesh densities. The coordinate system is defined as follows: the x-axis aligns with the welding direction, the y-axis is perpendicular to the welding direction, and the z-axis is oriented along the thickness of the specimen.

2.3 Heat source model development

In finite element analyses of temperature fields in laser welding, different heat source models are typically chosen according to the shape of the melt pool and how the laser operates. The establishment of these models is crucial to the accuracy of the simulation. Surface heat sources are generally classified as pulsed or continuous. This study adopts the pulsed heat source model [24], the distribution function of which is shown in the following equation):

$$q_v(x, y, z) = \frac{6\mu\eta P(t)}{2\pi r^2 H + m\pi r H^2} \exp\left[-\frac{3(x^2 + y^2 + z^2)}{r^2}\right] \left(\frac{mh + r}{r}\right). \quad (1)$$

In the equation, $q_v(x, y, z)$ represents the heat flux density inside the cylinder, μ is the proportional coefficient of the heat source input, and η is the laser absorption

rate. $P(t)$ represents the pulse laser power, r the effective radius of the volumetric heat source, H the effective depth of the volumetric heat source, m the linear decay coefficient, and h the distance between the position of the heat source and the weld surface.

In COMSOL, the heat source input can be defined by creating a square wave function with a frequency of 4,000 Hz. The mathematical expression for the pulsed heat source is shown in the following equation:

$$P(t) = \begin{cases} P, & (0 \leq t < (nT + \beta T)) \\ 0, & (nT + \beta T \leq t < (n+1)T), \end{cases} \quad (2)$$

where n is any integer, P is the laser power, and β is the duty cycle coefficient.

To ensure the accuracy of the numerical simulation, the boundary conditions primarily consider temperature boundaries and fixed constraints. During the welding process, the worktable constrains the rotational motion of the metal plate in the X and Z directions, while the translational motion near points A and B is also constrained to ensure consistency between the simulation and experimental conditions, as shown in Figure 3. Temperature boundaries primarily consider heat convection and radiation. The initial temperature of the specimen is generally set to ambient temperature (20°C). The expressions for heat convection, heat transfer, and heat radiation loss are shown in the following equation:

$$q_c = h_c(T - T_0) + \varepsilon\sigma_b(T^4 - T_0^4), \quad (3)$$

where q_c represents the heat loss due to convection and radiation, T is the boundary temperature, h_c is the

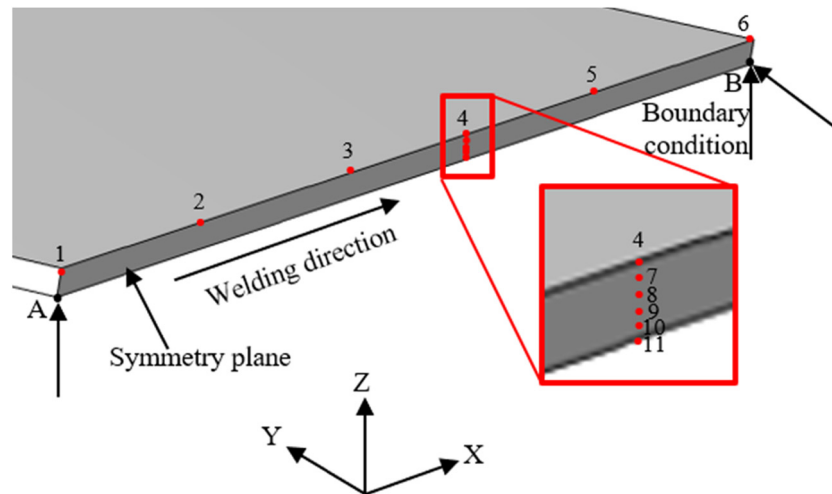


Figure 3. Finite element model and boundary condition.

convective heat transfer coefficient, ε is the emissivity, σ_b is the Boltzmann constant, and T_0 is the ambient temperature.

Laser welding is primarily influenced by the duty cycle, welding power, and welding speed. The following analysis of the temperature field will be used to determine suitable welding parameters. Since data obtained from the central cross-section are more stable and accurate, temperature probes were added to this cross-section to facilitate temperature analysis. The positions and numbers of the temperature probes are shown in Figure 3. Probes 1 through 6 are positioned along the central cross-section at intervals of 3 mm. Probes 7 through 11 are aligned vertically with probe 4, each spaced 0.05 mm apart.

3. Finite element simulation results and analysis

3.1 Macroscopic temperature field analysis

Figure 4 shows the transient temperature distribution field when the laser beam moves 9 mm along the x -axis from the workpiece. The maximum temperature of the workpiece reaches 1,910 K, and as the welding process progresses, the temperature gradient in the front region steepens, while that in the rear region shallows, indicating a transition from rapid heating to cooling in the material. Additionally, the HAZ influenced by the pulsed laser is significantly smaller than that of traditional welding methods. The temperature field results show that the temperature lines exhibit a typical elliptical distribution, with

a noticeable “tailing” effect of lower temperatures observed behind the heat source. This distribution pattern is consistent with the heat transfer characteristics of high-energy-density beam welding [25].

3.2 Thermal cycle curve analysis

The preliminary process parameters were determined based on the results of finite element simulation analysis as follows: a welding power of 300 W, a welding speed of 55 mm/s, and a duty cycle of 60%. Figure 5(a) shows the lateral thermal cycle curves of different sample points over time during the welding process. When the laser beam moves to a marked point, it can be seen that the temperature at that location rises rapidly to approximately 2,000 K and then cools down quickly [26]. This is especially evident during the intermittent heating process of pulsed lasers, where the temperature peaks of adjacent marked points exhibit an alternating high–low trend. When the heat source moves away, the temperature cools rapidly, typically dropping below 700 K within 0.5 s. As the heat source approaches the end of the specimen, the corresponding thermal cycle curve reaches its peak temperature due to the heat accumulation effect. This phenomenon is closely related to the heat conduction characteristics of the boundary conditions.

Figure 5(b) shows the thermal cycle curves of the points marked on the vertical axis over time. It is observed that the maximum temperature at probe 4 occurs after 0.2 s. When the laser moves and reaches this point at 0.2 s, it can be seen that the temperature continues to rise. When the center of the laser spot passes directly over the point at approximately 0.22 s, the temperature

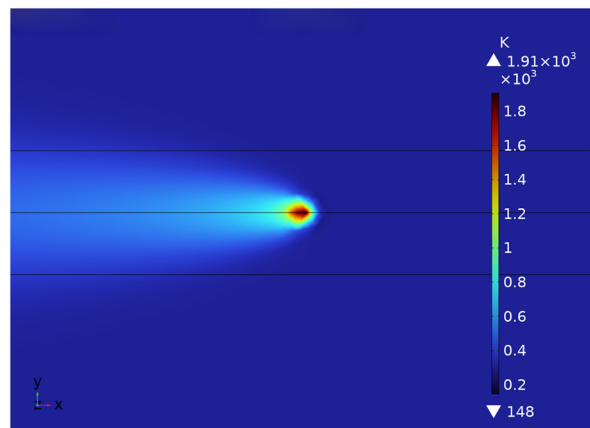


Figure 4. Laser welding macro temperature field.

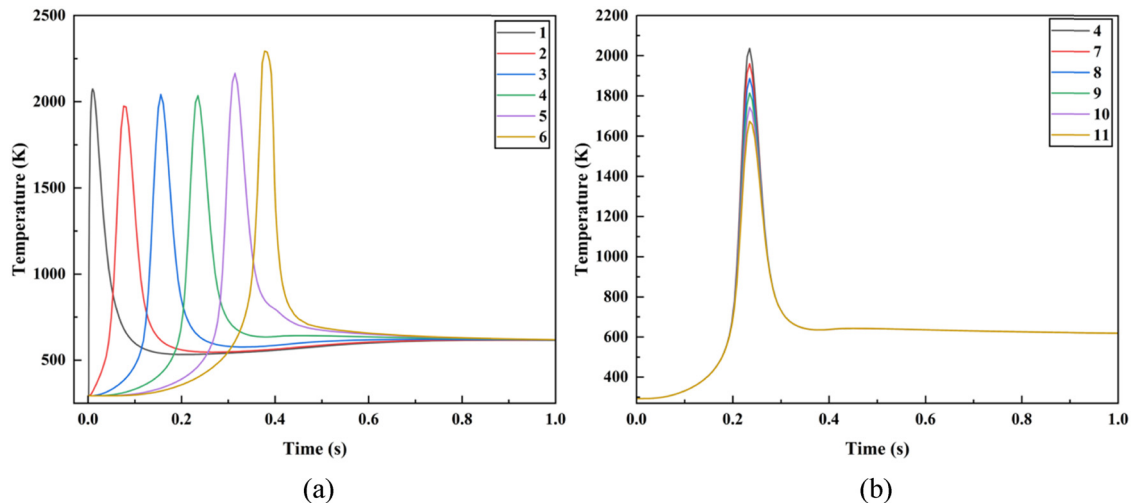


Figure 5. (a) Transverse thermal cycle curve and (b) longitudinal thermal cycle curve.

reaches its peak value. This is because thermal conduction occurs after the laser acts on the material. As the laser scans this point, the area behind it is locally heated. When the laser reaches this point again, it is easier for the temperature to reach its maximum value due to prior local heating. Once the laser has moved away from the 0.22 s mark, the temperature at this point decreases rapidly. This is primarily attributed to thermal conduction within the substrate, which is more pronounced at the surface. As the laser moves away from the sample point, the temperature at that point gradually decreases and eventually ptimizes. The top sample point reaches a maximum temperature of 2,035 K, while probe 11 reaches 1,673 K – the melting point of Inconel 718 sheet metal. This indicates that good metallurgical bonding can be achieved with these parameters.

4. Experimental methods

To validate the accuracy of the simulation analysis and ptimize the welding parameters, laser welding experiments will be conducted using a FIB-500-RK steel strip laser welding machine. The laser is a class IV laser with a spot diameter of 0.6 mm.

The test used 0.25 mm thick Inconel 718 sheets, the chemical composition of which is shown in Table 1. Prior to the experiment, the test pieces were pre-treated by grinding them with sandpaper until the metal lustre was exposed. The surface was then cleaned evenly with anhydrous ethanol and left to dry before proceeding to the next step. During welding, the specimens were clamped in a

manner consistent with the constraint conditions in finite element analysis. The protective gas used was 99.9% argon, with an inner nozzle diameter of 8 mm, a side blowing angle of 30°, and a gas flow rate of 15 L/min.

Once the welding test was completed, metallographic specimens were cut perpendicular to the direction of welding and successively ground using metallographic sandpaper. The specimens were then subjected to chemical etching using a mixture of 2 g of $\text{CuCl}_2 \cdot 8\text{H}_2\text{O}$, 8 g of FeCl_3 , 100 mL of HCl , and 100 mL of $\text{C}_2\text{H}_6\text{O}$ (for metallographic observation only), which revealed their microstructural features. This corrosion treatment does not involve any surface strengthening operations aimed at improving the weld's corrosion resistance. After corrosion, the specimen was photographed and analysed using an MR5000 inverted metallographic microscope and a Sigma 300 electron scanning microscope. The focus was on identifying defects on the weld surface and in the melt pool at the weld cross-section, as well as cracks and bubbles.

Laser welding experiments were conducted based on process parameters determined by finite element analysis. Each factor was set at three levels, as shown in Table 2. An

Level	A. Laser power (W)	B. Welding speed (mm/s)	C. Duty cycle (%)
1	270	50	50
2	300	55	55
3	330	60	60

Table 2. Test factors and level of distribution.

No.	A. laser power (W)	B. Welding speed (mm/s)	C. Duty cycle (%)	Tensile strength (MPa)
1	270	50	50	780
2	270	55	55	809
3	270	60	60	817
4	300	50	55	830
5	300	55	60	840
6	300	60	50	810
7	330	50	60	815
8	330	55	50	803
9	330	60	55	846
K_1	802	808	798	
K_2	827	817	828	
K_3	821	824	824	
R	25	16	31	
Priority factors	C > A > B			
Optimal solution	300	60	55	856

Table 3. Orthogonal test analysis.

L9(3³) orthogonal array was designed based on the Taguchi method using Minitab 19.0 statistical software, as shown in Table 3. The primary influencing factors were laser power, welding speed, and duty cycle. Each set of parameters was tested three times, and the average tensile strength was taken to ensure the accuracy of the results, as shown in Table 3. The average value was taken as the final tensile strength. Tensile strength was selected as the final evaluation criterion for the welded components, in order to assess the performance of different combinations of process parameters and determine the optimal combination.

Table 3 shows that K_i represents the average tensile strength corresponding to level i of a given factor, where $i = 1, 2$, and 3 . The range (R) represents the variability of tensile strength across the three levels of each factor; larger R values indicate greater influence on the test results. Analysis of the R values shows that factor C (duty cycle) has the largest R value, followed by factor A (laser power); factor B (welding speed) has the smallest R value. It can be seen that the duty cycle has the greatest effect on the weld strength of Inconel 718 sheets, followed by welding power; welding speed has the least effect. According to the analysis results, the optimal levels of each factor are A2, B3, and C2, respectively, and the optimal parameters are A2, B3, and C2, respectively. Therefore, the optimal combination of parameters for the laser welding process in this orthogonal experiment is a laser power of 300 W, a welding speed of 60 mm/s, and a duty cycle of 55%. Next, laser welding was performed using these optimal parameters, and the welded specimens were tested for tensile strength using a universal testing machine. The tensile strength was measured to be 856 MPa, which verifies the accuracy of the orthogonal experiment analysis.

Additionally, a tensile strength effect curve diagram was plotted based on the experimental results from the orthogonal experiments in Table 3, with the results shown in Figure 6. Figure 6(a) and (c) shows that the tensile strength of the material first increases and then decreases as the laser power and welding speed increase. However, as shown in Figure 6(b), the tensile strength of the material exhibits a continuous upward trend with an increase in the duty cycle, which further illustrates the specific influence patterns of various process parameters on the mechanical properties of the joint.

To more accurately assess the variability and stability of the tensile strength data for the samples in each experimental group, Figure 7 plots the average tensile strength for the nine groups of samples, with error bars indicating

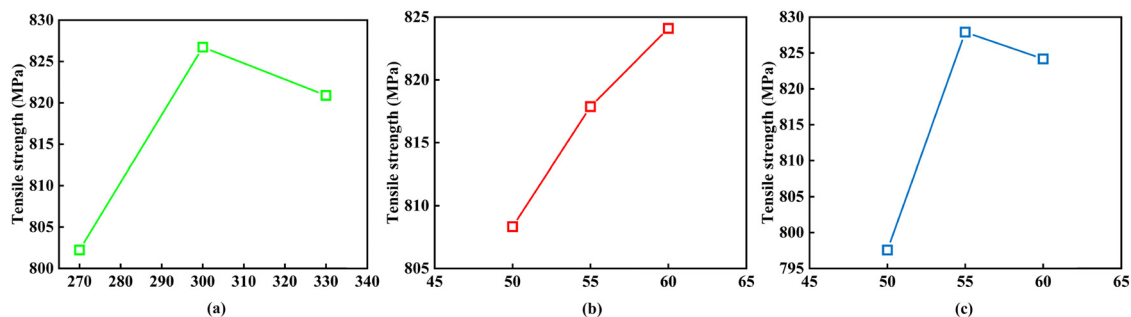


Figure 6. Effect of welding parameters on tensile strength. (a) Laser power (W). (b) Welding speed (mm/s). (c) Duty cycle.

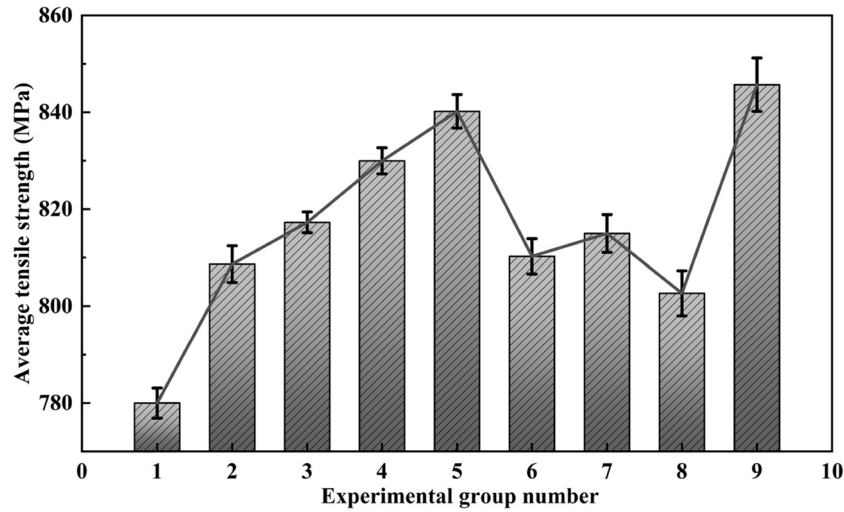


Figure 7. Average tensile strength and $\pm 2SE$ error bars of nine experimental groups.

± 2 standard errors ($\pm 2SE$), which approximate the 95% confidence interval of the sample mean. Compared to using a single standard error, $\pm 2SE$ provides greater statistical confidence and facilitates intuitive comparison of group differences and the identification of potential significant trends in tensile strength [27].

5. Results and discussion

Based on the above orthogonal experimental analysis, it can be concluded that, within a certain range, the duty cycle has the greatest influence on the weld strength of Inconel 718 of the three influencing factors. Therefore, three supplementary single-factor experiments focusing solely on the duty cycle were designed. The laser power and welding speed were set to the optimal combinations

identified in the orthogonal experiments (A2B3; 300 W and 60 mm/s). Sample numbers a, b, and c corresponded to duty cycles of 50, 55, and 60%, respectively. Details are provided in Table 4.

5.1 Comparative analysis of macroscopic morphology and weld pool characteristics

Table 4 illustrates the influence of various duty cycles on the surface morphology of the weld seam. As the duty cycle increases, significant changes can be seen on both sides of the weld seam. A small amount of porosity was observed on the top surfaces of the weld seams in specimens a and c. For specimen a, this was due to the low duty cycle resulting in short laser exposure times and

No.	Duty cycle (%)	Front side	Reverse side
a	50		
b	55		
c	60		

Table 4. Macroscopic morphology of weld seam under different duty cycles.

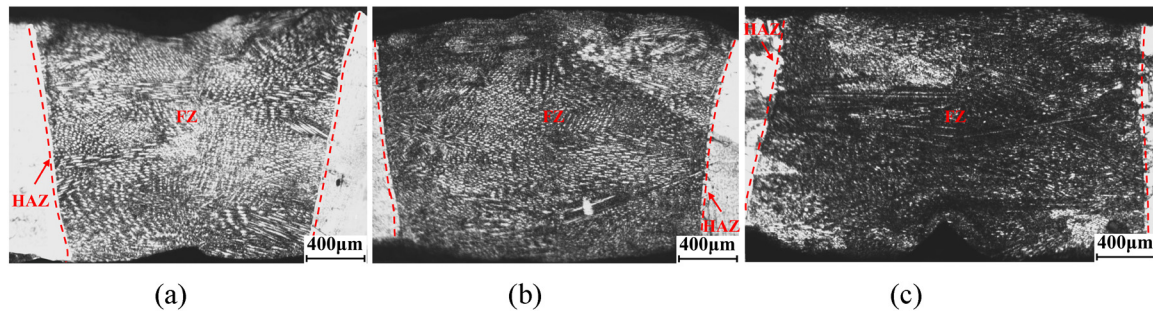


Figure 8. Metallographic section of weld. (a) Duty cycle 50%. (b) Duty cycle 55%. (c) Duty cycle 60%.

consequently reduced heat input into the weld seam, leading to an uneven heat input distribution in the weld area. In this case, some regions may overheat due to excessive heat input, while others may remain underheated and fail to fully melt. Ultimately, an uneven heat distribution can trigger the formation of pores. As the duty cycle increases, thermal accumulation occurs within the base material of specimen c, and localised laser heating may lead to excessive melting in the weld region [28]. During the material's solidification process, excessive heat accumulation and local heating may result in structural inhomogeneity and pore formation. Additionally, rapid heating and cooling of the laser welding process itself may lead to pore formation during material solidification [29,30]. In contrast, the front surface of specimen b was well formed with a smooth finish. The morphology of the weld back indicates that specimen a failed to form a good metallurgical bond due to an excessively low duty cycle. This resulted in insufficient heat being transmitted to the bottom of the material, meaning that it did not reach its melting point, thus preventing the formation of an effective metallurgical bond. The backs of specimens b and c achieved metallurgical bonding. Upon comparison, it was found that excessive heat accumulation on the back of specimen c led to defects such as pits and undercuts on the back of the weld seam. This is because gravity acts on the molten metal, causing it to escape from the weld. These defects severely impair the quality of the welded joint, resulting in reduced mechanical properties at the joint. In contrast, the back surface of specimen b exhibits good formation with no obvious welding defects.

Further microstructural observations of the cross-sections of the three welds were conducted using a metallographic microscope. The results are shown in Figure 8. All three fusion zones (FZs) exhibit symmetrical cross-sections, and the HAZs are relatively narrow, nearly coinciding with the fusion lines. As can be seen in the cross-sectional morphology diagram in Figure 8(a), no obvious defects were observed in the cross-section at a duty cycle

of 50%. However, as can be seen in Table 4, effective metallurgical bonding was not achieved at the bottom of the weld. This is due to the limited fusion area, which results in insufficient heat input that cannot be promptly transmitted to the middle and lower regions of the weld. This leads to a narrower width at the lower part of the weld and prevents the formation of a sound and continuous metallurgical bond throughout the joint. This reduces the mechanical properties of the welded joint, making it prone to fracture when subjected to vibration and impact [31]. This affects both the service life and sealing performance of the sealing ring, ultimately resulting in failure to meet design requirements and product failure or non-compliance. When the duty cycle is 55%, as shown in Figure 8(b), the weld morphology exhibits no visible cracks, pores, or other welding defects in the examined section, indicating good surface integrity with the selected parameters. This indicates that the parameter settings align with the expected results of the orthogonal experimental design. Figure 8(c) shows that, when the duty cycle is 60%, the laser remains incident on the surface of the base material for a longer time, fully melting the base material. Under the influence of gravity, the molten metal penetrates the bottom of the base material, forming a wider melt pool upon cooling and solidification. At this point, the depth-to-width ratio of the melt pool reaches 19.4; however, significant depression appears at the bottom, and the surface becomes uneven. In summary, a stable melt pool morphology is formed with uniform heat input at a duty cycle of 55%, resulting in a weld structure with good formability and no obvious defects.

5.2 Validation of finite element simulation results

As can be seen from the above, the optimal process parameters are a laser power of 300 W, a welding speed of

60 mm/s, and a duty cycle of 55%. To verify the accuracy of the finite element simulation, calculations will be performed using these parameters, and the results will be compared with the experimental cross-sectional morphology, as shown in Figure 9. Comparison of the simulated temperature field cross-sectional diagrams with the experimental macroscopic cross-sectional morphology revealed a high degree of agreement between the simulation and actual experimental results. The depth-to-width ratio of the test piece cross-section was 0.68, while the numerical simulation cross-section depth-to-width ratio was 0.73, resulting in an error of only 7%. This demonstrates that the heat source model used in this paper can effectively predict the temperature field of a 0.25 mm thick Inconel 718 high-temperature alloy plate during the pulse laser welding process.

5.3 Microstructural analysis of the welded joint

5.3.1 Microstructure analysis of welds in different duty cycles

Figure 10 shows optical microscopy (OM) images of the weld centre obtained with different duty cycle parameters. The solidification process of the Inconel 718 nickel-based high-temperature alloy weld involves directed, rapid growth from the semi-solid base metal. The temperature gradient (G) to solidification rate (R) ratio plays a critical role in determining grain morphology during weld solidification. As shown in Figure 10, Inconel 718 has an austenitic matrix with δ phase particles distributed within and between grains, as well as the blocky Laves phase. The distribution of the Laves and δ phases significantly affects

the properties of high-temperature alloys. While the stability of the Laves phase helps to maintain the mechanical properties of the material at high temperatures, enhancing the overall hardness and wear resistance, it also makes the matrix brittle and reduces the ductility and toughness, making the material more prone to cracking under stress conditions [32]. The δ phase helps to refine the grain size, improve the creep resistance, and optimise the weldability; however, it also reduces ductility, increases processing complexity, and poses phase stability issues.

As can be seen in Figure 10(a), the weld zone mainly consists of fine, irregular dendritic structures. Under these conditions, the cooling rate of the melt pool is fast due to the low input heat, which inhibits the grain growth to some extent. Consequently, the weld structure is relatively uniform, and the amount of precipitated phases is reduced. This rapid cooling reduces the segregation of alloy elements and suppresses the precipitation of brittle Laves phases [33]. However, the narrow weld melt width formed results in insufficient metallurgical bond strength in the weld zone, which may limit the overall performance of the welded joint. Although a duty cycle of 50% can avoid excessive Laves phase precipitation to some extent, insufficient input heat cannot meet the requirements for weld penetration depth and strength in practical applications. In contrast, Figure 10(b) shows that the microstructure of the weld has undergone significant changes in both dendrite morphology and the distribution of inter-dendritic phases. This is due to increased welding heat input, which prolongs the melt pool residence time and moderates the cooling rate. This creates favourable conditions for uniform dendrite growth and sufficient alloy element diffusion. This effectively controls the amount of Laves phase precipitation. Furthermore, its localised inter-dendritic

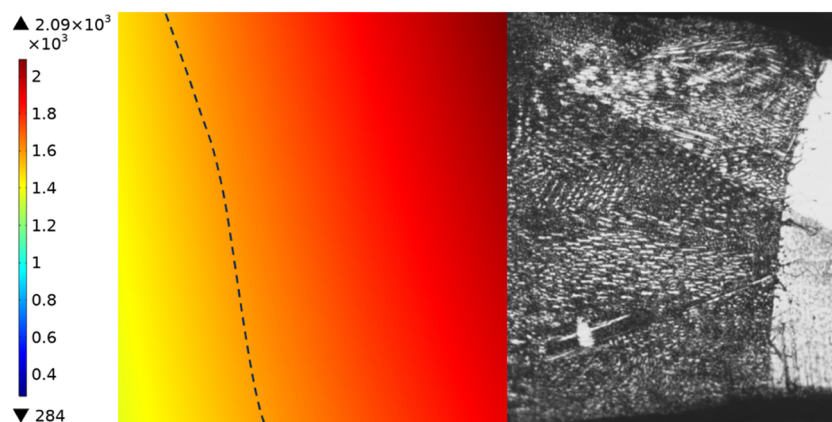


Figure 9. Comparison of metallographic sections with simulation results.

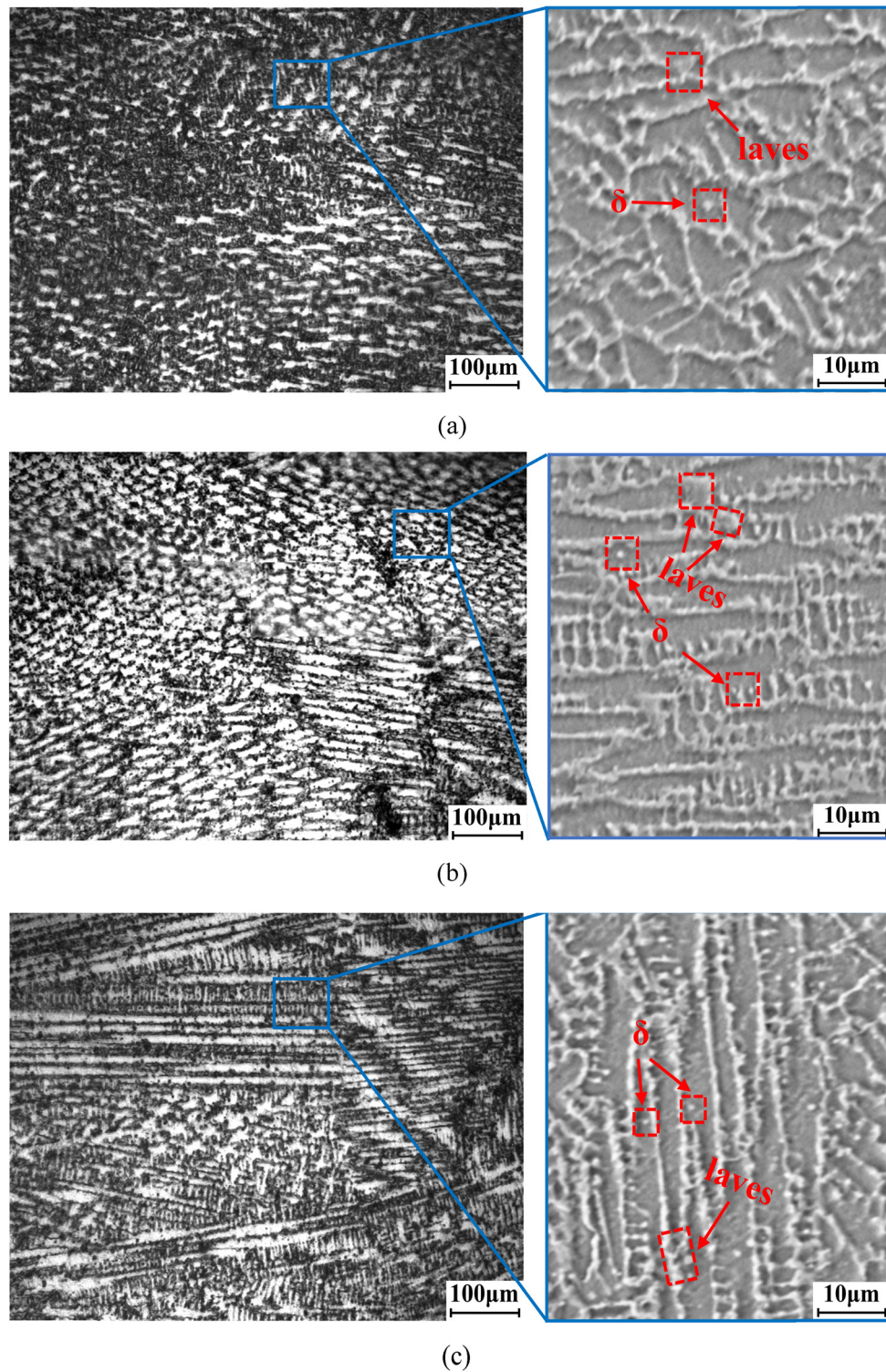


Figure 10. Optical microscopy photo of weld morphology. (a) Duty cycle 50%. (b) Duty cycle 55%. (c) Duty cycle 60%.

distribution and small particle size prevent it from significantly impairing the weld's ductility and toughness [34]. Additionally, the δ phase exhibits a favourable distribution, forming fine and discontinuous lamellar structures along the grain boundaries. This enhances the weld's creep resistance while avoiding significant effects of brittleness [35]. When the duty cycle is 55%, a good balance is achieved amongst weld penetration, dendrite growth, and control of the precipitated phases, as shown in Figure 10(c). The dendritic morphology of the weld becomes more pronounced, the grain sizes increase significantly, and the distribution of the precipitated phases becomes more concentrated. However, due to excessive heat input, the cooling rate of the melt pool decreases significantly. This exacerbates element segregation between dendrites and leads to the precipitation of Laves phases with a coarse, blocky distribution. The enrichment of these brittle compounds significantly reduces the toughness of the weld. Additionally, the δ phase exhibits a continuous distribution along grain boundaries. While this distribution pattern enhances the strength of the weld at high temperatures, excessive accumulation of the δ phase can increase the sensitivity of the weld to fracture, thereby weakening its overall mechanical properties [36]. Therefore, although a 60% duty cycle can achieve sufficient fusion, the quality of the weld is clearly inferior to that obtained with the 55% duty cycle parameters due to the uneven distribution of the precipitated phases and coarsening of the grains.

Further characterisation of the microstructure at the weld boundary was performed using scanning electron microscopy (SEM). Figure 11 shows SEM images of the microstructure near the weld joint boundary. Figure 11(a) shows that the microstructure near the weld joint boundary is primarily composed of cellular grains with distinct boundaries. Figure 11(b) shows that the microstructure near the fusion line consists mainly of equiaxed dendrites and a small number of cellular grains interspersed with cellular dendrites that have developed

from the cellular grains. The equiaxed dendrites and cellular dendritic crystals are distributed relatively uniformly, with gradually blurred boundaries. Figure 11(c) shows that the weld microstructure is primarily composed of preferentially oriented columnar crystals, with a small amount of cellular crystals. The columnar and cellular crystals are distributed in a relatively disordered manner, with unclear boundaries. A comparison of the weld boundaries with different parameters reveals that, as the duty cycle increases, the weld boundaries become increasingly coarse. This is due to the increased thermal input time during the laser welding of Inconel 718 under high-duty-cycle conditions. This enhances the dissolution and re-precipitation of phases such as γ' and γ'' , which lead to grain boundary softening and grain growth. This results in a more uniform microstructural transition between the weld and the base material with less distinct boundaries, causing grain boundary coarsening [37]. Such changes in phase precipitation and microstructural homogenisation make it difficult to distinguish the weld boundaries under a microscope, affecting the material's mechanical properties and resistance to stress corrosion. Based on the above analysis, samples with a laser power of 300 W, a welding speed of 60 mm/s, and a duty cycle of 55% were selected for further analysis and research.

5.3.2 Microstructural and compositional analyses of different weld zones under the same duty cycle

Figure 12 shows the microstructure of Inconel 718 pulse laser welds in the FZ of the weld (cross-section), as observed under a scanning electron microscope under the optimal process parameters of 300 W laser power, 60 mm/s welding speed, and 55% duty cycle. Figure 12(a) shows the microstructure of the fusion boundary, and Figure 12(b) shows the microstructure at the centre of the weld. The Laves particles in the columnar grain regions can be seen to be almost interconnected and

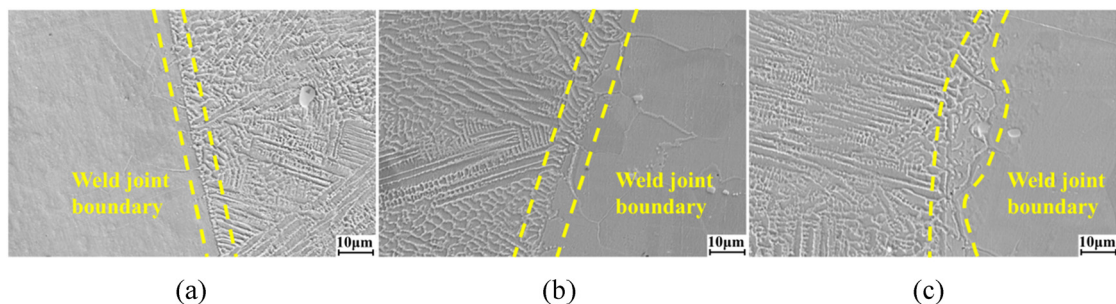


Figure 11. SEM images of welds with different parameters. (a) Duty cycle 50%. (b) Duty cycle 55%. (c) Duty cycle 60%.

slightly rougher than those in the equiaxed grain regions. Analysis of the SEM images indicates that the Laves phase content is higher in the columnar dendrite regions near the fusion boundary than at the centre of the weld, while the Laves phase content in the fine equiaxed grain regions at the centre of the weld is relatively low. As can be seen in Figure 12(a), the columnar crystals exhibit distinct directionality, indicating that the direction of heat flow significantly influences crystal growth during welding. This oriented crystallisation contributes to improved mechanical properties in the weld zone.

SEM images also reveal that smaller equiaxed dendrites appear at the centre of the weld seam, while slightly coarser columnar dendrites are present near the fusion boundary. This is due to the steeper thermal gradient in the melt pool near the fusion boundary compared to the interior of the weld seam. At the fusion boundary, this steep thermal gradient favours the growth of columnar crystals in a direction opposite to the direction of heat extraction. However, the relatively shallow thermal gradient in the weld center, combined with the rapid cooling rate inherent to laser welding, facilitates the formation of randomly oriented equiaxed dendrites. These morphological changes in the Laves phase, as well as the differences in dendrite morphology between the weld centre and the fusion boundary region, are related to these factors. Columnar dendrites near the fusion boundary grow in such a way they result in fewer, larger, continuous dendrite regions, forming coarse, interconnected Laves particles. In contrast, the growth of fine equiaxed dendrites within the weld results in numerous, small, and well-separated dendrite regions, leading to finer and more dispersed Laves particles.

Figure 13 shows SEM–energy dispersive spectroscopy (EDS) mapping images of the weld taken at various

locations. Figure 13(a) shows that the morphology at the top of the weld exhibits a fine, wavy pattern, which is characteristic of the dynamic flow behaviour of the melt pool during pulsed laser welding. The uniformity of the ripples indicates that the laser power and duty cycle are well controlled, ensuring adequate heat input to fully cover the top of the weld and maintain the stability of melting and solidification [38]. EDS analysis reveals that the main elements (Ni, Cr, Mo, etc.) at the top of the weld are uniformly distributed with no significant segregation. This uniform elemental distribution contributes to favourable mechanical properties and corrosion resistance in the upper weld zone.

Figure 13(b) shows an SEM image of the centre of the weld. As this is the region where heat concentrates in the weld pool, the microstructure of this area is a good indicator of the weld's overall performance. The image shows that the crystals in this region are densely packed with uniform grain sizes, which indicates stable heat transfer capability and a uniform distribution of heat in the central region of the weld. There is no evidence of overmelting, cracks, or stress concentration phenomena, and the solidification process of the melt pool appears uniform and orderly. This suggests that the process parameters were appropriately set. EDS analysis reveals that key elements such as Cr and Ni are uniformly distributed, consistent with the SEM characterisation findings. However, the oxygen (O) content has decreased compared to Figure 13(a), indicating that the shielding gas effectively reduced oxidation during welding. Although EDS cannot perform high-precision quantitative analysis of oxygen, it can make semi-quantitative comparisons under the same analysis conditions. When combined with the distribution trends of elements in the image, it may serve as a supplementary indicator for assessing changes in the oxygen content within welds. Further verification can be achieved by

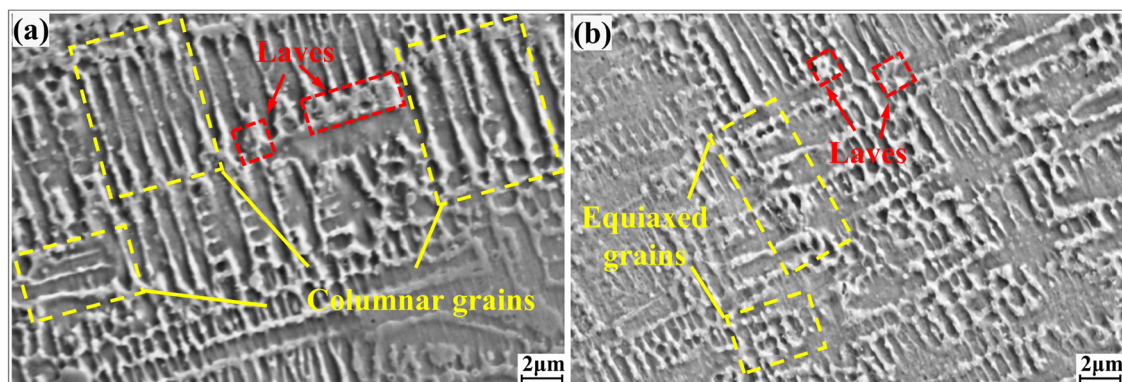


Figure 12. SEM microstructures of the weld FZ: (a) Coarse and interconnected Laves particles near the fusion boundary and (b) fine and dispersed Laves particles in the weld center.

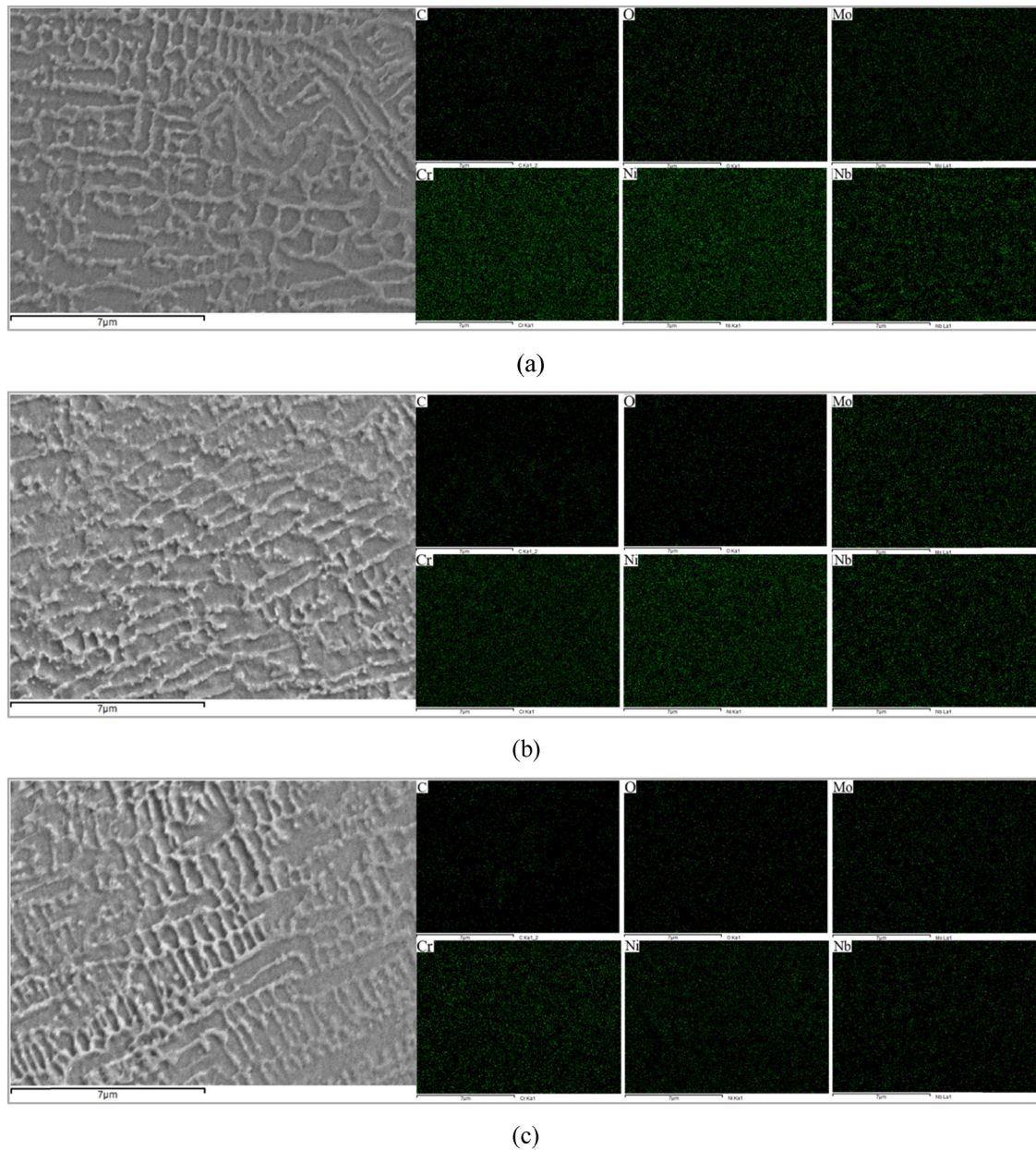


Figure 13. SEM-EDS mapping of different positions of the weld seam. (a) EDS mapping of the weld top region. (b) EDS mapping of the weld middle region. (c) EDS mapping of the weld bottom region.

combining methods such as X-ray photoelectron spectroscopy in subsequent studies. There is slight enrichment of niobium (Nb), which may be an initial indication of Laves phase formation.

As can be seen in Figure 13(c), the weld root has a regular morphology, with closely and densely arranged grains, and no obvious fusion defects are evident. This suggests that the laser power is being effectively

transmitted to the base of the weld, ensuring complete penetration. Additionally, there were no signs of common defects such as incomplete fusion, porosity, or other welding defects at the bottom of the weld, which further indicates uniform heat distribution and good penetration. EDS analysis corroborates this, showing a uniform distribution of Ni, Cr, Mo, and other elements at the bottom of the weld, with no severe segregation or separation

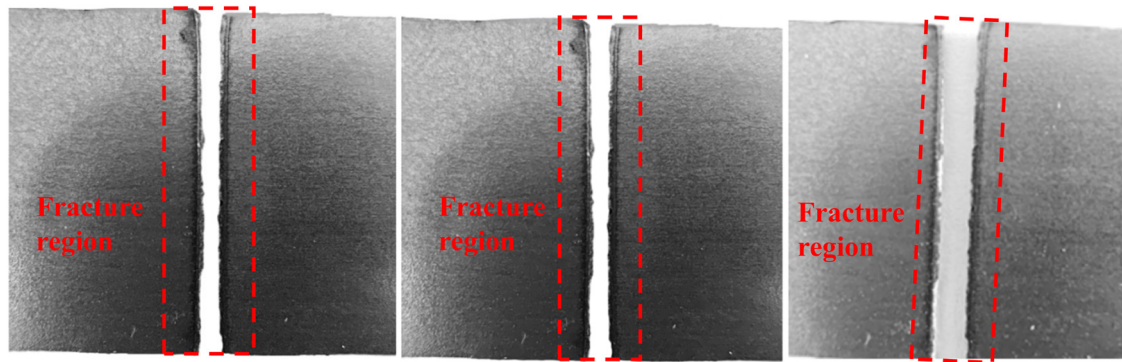


Figure 14. Macroscopic location of fracture of a partially tensile specimen.

phenomena. The relatively low C and O contents indicate that the shielding gas effectively protected the weld from oxidation or contamination during the welding process, thereby ensuring the overall integrity of the weld.

Analysis of the top, middle, and bottom of the weld seam shows that, with the pulse laser welding process parameters set to 300 W power, 60 mm/s welding speed, and 55% duty cycle, weld seams can be formed with a regular microstructure and dense structure with no obvious defects in Inconel 718 material. Moreover, the elemental distribution within the weld zone is uniform, with no significant segregation or phase separation observed. Overall, the weld's performance is excellent and meets the quality requirements for high-temperature alloy welding.

5.3.3 Fracture morphology and mechanical property analysis of the welded joint

Following tensile testing, sheets from all groups with different process parameters fractured at the weld seam.

Figure 14 presents macroscopic views of the fracture surfaces from selected tensile specimens. This fracture behaviour may be caused by the rapid heating and cooling associated with pulse laser welding, which results in varying degrees of element segregation and Laves phase precipitation at the weld seam.

Following the tensile testing of the specimens, SEM analysis was conducted on the fracture surfaces, as shown in Figure 15. The analysis revealed the presence of micro-cracks at the fracture surfaces of all the specimens, which may have been caused by the stress concentration during the tensile process. The fracture surfaces exhibited numerous ductile dimples with a small number of micro-pores interspersed amongst them, indicating that the fracture mode was ductile. As shown in Table 2, the tensile strength achieved using the optimised process parameters was 856 MPa, which exceeded 80% of the base material's tensile strength. The final laser welding process parameters were determined as follows: power: 300 W; welding speed: 60 mm/s; duty cycle: 55%.

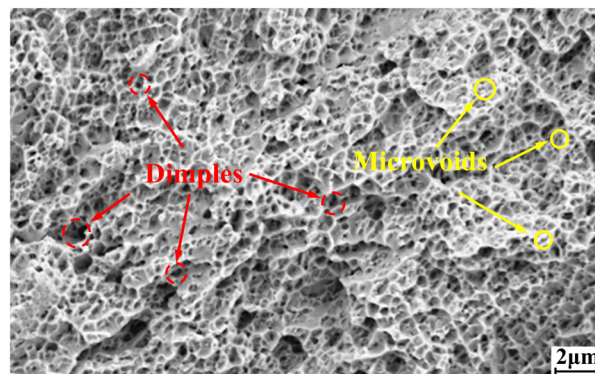


Figure 15. SEM morphology of tensile specimen fracture.

6. Conclusions

This study systematically investigated the thermal behaviour, microstructural evolution, and joint performance of ultra-thin Inconel 718 sheets during pulsed laser welding, combining finite element simulation and experimental analysis. The main conclusions are as follows:

- (1) Through finite element simulation and orthogonal experiments, the optimal process parameters for laser welding Inconel 718 thin plates were determined to be a laser power of 300 W, a welding speed of 60 mm/s, and a duty cycle of 55%. Using these parameters, the tensile strength of the welded joint was found to be 856 MPa, which exceeded 80% of the strength of the base material. The weld morphology was good, and there were no obvious defects, which indicate excellent metallurgical bonding.
- (2) Duty cycle is the most significant factor influencing weld strength. At a duty cycle of 55%, the morphology of the weld surface is optimal, with a reasonable distribution of the Laves and δ phases. This effectively enhances the weld's creep resistance and high-temperature strength while avoiding excessive embrittlement. However, excessively high duty cycles can lead to defects such as pitting and undercutting on the back of the weld, which can impair the joint's mechanical properties.
- (3) The finite element simulation results are highly consistent with the experimental welding morphology. The depth-to-width ratio error of the weld cross-section is within 7%, indicating that the heat source model can effectively predict the temperature field distribution of 0.25 mm thick Inconel 718 thin plates during pulsed laser welding, providing a reliable theoretical basis for process optimisation.
- (4) Optimising the welding process parameters significantly improves the tensile strength of the welded joints. The fracture mode is ductile, indicating that the ductility and strength of the welded joints are high and meet the quality requirements for high-temperature alloy welding.

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Author contributions

Chao Wu and Weimin Li conceived and designed the study. Chao Wu performed the experiments and analyzed

the data. Zhaoqing Tang assisted with data analysis. Jixiang Liang and Jiahui Li supervised the research and reviewed the manuscript. All authors read and approved the final manuscript.

Conflict of interest statement

All data included in this paper are available upon request through contact with the corresponding authors. The authors declare no conflict of interest.

Data availability statement

The datasets generated during and/or analyzed in this study are available from the corresponding author on reasonable request.

References

- [1] Sirignano, W.A., Liu, F., Performance increases for gas-turbine engines through combustion inside the turbine, *J. Propuls. Power*, 1999, 15(1): 111–118
- [2] Zurfluh, T., Bond, S., A new high temperature exhaust sealing system, *SAE Trans.*, 2007, 116: 613–619
- [3] Special Metals Corporation, INCONEL® Alloy 718 – Technical Bulletin [Internet], Special Metals, Huntington (WV) [cited 2025 Jul 22]. <https://www.specialmetals.com/assets/documents/alloys/inconel/inconel-alloy-718.pdf>
- [4] Kumar, N., Dhara, S., Masters, I., Das, A., Substituting resistance spot welding with flexible laser spot welding to join ultra-thin foil of Inconel 718 to thick 410 steel, *Materials*, 2022, 15(9): 3405. doi: 10.3390/ma15093405
- [5] Li, W., Zhang, K., Yang, H., Diao, J., Design and optimization of V-shaped metallic sealing ring for automotive exhaust pipe, *Lubr. Eng.*, 2023, 48(7): 159–166, 220
- [6] Ohata, M., Toda, Y., Toyoda, M., Takeno, S., Control of welding distortion in fillet welds of aluminium alloy thin plates, *Weld. Int.*, 1999, 13(12): 967–976
- [7] Hou, J., Li, R., Xu, C., Li, T., Shi, Z., A comparative study on microstructure and properties of pulsed laser welding and continuous laser welding of Al-25Si-4Cu-Mg high silicon aluminum alloy, *J. Manuf. Process.*, 2021, 68: 657–667
- [8] Chai, D., Wu, D., Ma, G., Zhou, S., Jin, Z., Wu, D. The effects of pulse parameters on weld geometry and

- microstructure of a pulsed laser welding Ni-base alloy thin sheet with filler wire. *Metals*. 2016; 6(10): 237.
- [9] Sheikhbahae, H., Mirahmadi, S.J., Pakmanesh, M.R., Asghari, S., Investigating sensitivity to process parameters in pulsed laser micro-welding of stainless steel foils, *Opt. Laser Technol.*, 2022, 148: 107737
- [10] Krolczyk, G., Sedmak, A., Kumar, U., Chattopadhyaya, S., Das, A.K., Pramanik, A., Study of heat-affected zone and mechanical properties of Nd-YAG laser welding process of thin titanium alloy sheet, *Nat. Resour. Eng.*, 2016, 1(2): 51–58
- [11] Li, D., Han, Z., Zhao, P., Dong, Z., Zhao, S., Zhu, R., et al., Laser welding by focusing multi-laser beams, *Opt. Express*, 2024, 32(13): 23147–23160
- [12] Verhaeghe, G., Hilton, P., The effect of spot size and laser beam quality on welding performance when using high-power continuous wave solid-state lasers, In *Proceedings of ICALEO 2005: 24th International Congress on Laser Materials Processing and Laser Microfabrication*, AIP Publishing, Melville, NY, 2005
- [13] Saurabh, S.K., Chand, P., Yadav, U.S., Optimizing laser beam welding performance parameters on nimonic 80A superalloy: a study on experimentation, *TGRA, and PCA, Soldag. Inspeção*, 2024, 29: e2904. doi: 10.1590/0104-9224/SI29.04
- [14] Voropaev, A., Stranko, M., Sorokin, A., Logachev, I., Kuznetsov, M., Laser welding of Inconel 718 nickel-based alloy layer-by-layer products, *Mater. Today Proc.*, 2020, 30: 471–477. doi: 10.1016/j.matpr.2019.12.032
- [15] Sharif, S.M., Ramji, M., Akiyama, T., Saurabh, S.K., Ganesh, S., Petley, V.U., et al., A study on laser welding of Inconel 718 and evolution of strain field using digital image correlation to estimate the localized properties, *Opt. Laser Technol.*, 2024, 164: 109472. doi: 10.1016/j.optlastec.2024.109472
- [16] Uranga, G.U., Oiartzun, M.A., Cabello, M.J., Molpeceres, C., Morales, M., General methodology for laser welding finite element model calibration. *Processes*, 2024, 12(12): 2687.
- [17] Han, Q., Kim, D., Kim, D., Lee, H., Kim, N., Laser pulsed welding in thin sheets of Zircaloy-4, *J. Mater. Process. Technol.*, 2012, 212(5): 1116–1122
- [18] Baruah, M., Bag, S., Influence of pulsation in thermo-mechanical analysis on laser micro-welding of Ti₆Al₄V alloy, *Opt. Laser Technol.*, 2017, 90: 40–51
- [19] Zhang, Y., Ying, Y., Liu, X., Wei, H., Deformation control during the laser welding of a Ti₆Al₄V thin plate using a synchronous gas cooling method, *Mater. Des.*, 2016, 90: 931–941
- [20] Chen, J., Chang, Y., Wei, Y., Building ultra-thin Inconel 718 sheet joints using low-frequency PLBW scheme: Weld bead quality, keyhole dynamics, and solidification characteristics, *J. Mater. Res. Technol.*, 2023, 27: 4145–4156
- [21] Li, L., Peng, G., Wang, J., Gong, J., Li, H., Experimental study on weld formation of Inconel 718 with fiber laser welding under reduced ambient pressure, *Vacuum*, 2018, 151: 140–147
- [22] Zhu, W., Zhao, F., Yin, S., Liu, Y., Yang, R., Effect of tensile deformation on residual stress of GH4169 alloy, *Materials*, 2021, 14(7): 1773
- [23] Wu, C.L., Yin, H., Huang, Z.H., Optimization of pulsed laser welding parameters for GH4169 nickel-based superalloy, *Tool. Technol.*, 2020, 54(10): 38–42 (in Chinese)
- [24] Zhang, D., Wu, R., Zhang, H., Liu, Z., Numerical simulation of temperature field evolution in the process of laser metal deposition, *Chin. J. Lasers*, 2015, 42(5): 112–123
- [25] Ghosh, P.S., Sen, A., Chattopadhyaya, S., Sharma, S., Singh, J., Dwivedi, S.P., et al., Prediction of transient temperature distributions for laser welding of dissimilar metals, *Appl. Sci.*, 2021, 11(13): 5829
- [26] Yang, Z., Li, W., Zhang, Y., Song M., Gao Q., Optimization and analysis of surface milling parameters of additive manufacturing maraging steel, *Iron Steel*, 2024, 59(6): 135–144. doi: 10.13228/j.boyuan.issn0449-749x.20240091
- [27] Cumming, G., Fidler, F., Vaux, D.L., Error bars in experimental biology, *J. Cell Biol.*, 2004, 166(2): 247–251
- [28] Tzeng, Y., Parametric analysis of the pulsed Nd:YAG laser seam-welding process, *J. Mater. Process. Technol.*, 2000, 102(1–3): 40–47
- [29] Liu, T., Mu, Z., Hu, R., Pang, S., Sinusoidal oscillating laser welding of 7075 aluminum alloy: hydrodynamics, porosity formation and optimization, *Int. J. Heat. Mass. Transf.*, 2019, 140: 346–358
- [30] Yan, S, Zhu, Z, Ma, C, Qin, Q.H., Chen, H., Fu, Y.N., Porosity formation and its effect on the properties of hybrid laser welded Al alloy joints, *Int. J. Adv. Manuf. Technol.*, 2019, 104: 2645–2656
- [31] Tadamalle, A.P., Reddy, Y.P., Ramjee, E., Influence of laser welding process parameters on weld pool geometry and duty cycle, *Adv. Prod. Eng. Manag.*, 2013, 8(1): 52
- [32] Stein, F., Leineweber, A., Laves phases: a review of their functional and structural applications and an improved fundamental understanding of stability and properties, *J. Mater. Sci.*, 2021, 56(9): 5321–5427

- [33] Wang, L, Cui, R, Li, B, Jia, X., Yao, L.H., Su, Y.Q., et al., Influence of laser parameters on segregation of Nb during selective laser melting of Inconel 718, *China Foundry*, 2021, 18: 379–388
- [34] Artaza, T., Bhujangrao, T., Suárez, A., Veiga, F., Lamikiz, A., Influence of heat input on the formation of Laves phases and hot cracking in plasma arc welding (PAW) additive manufacturing of Inconel 718, *Metals*, 2020, 10(6): 771
- [35] Haisheng, Z., Lijia, F., Huan, L., Kaiqin, D., Effect of hot isostatic pressing on microstructure and high temperature properties of GH4169 alloy formed by selective laser melting, *J. Aeronaut. Mater.*, 2024, 44(1): 44–50. (in Chinese)
- [36] Kontis, P., Chauvet, E., Peng, Z., He, J., da Silva, A.K., Raabe, D., et al., Atomic-scale grain boundary engineering to overcome hot-cracking in additively-manufactured superalloys, *Acta Mater.*, 2019, 177: 209–221
- [37] Sharma, S.K., Biswas, K., Nath, A.K., Manna, I., Majumdar, J.D., Microstructural change during laser welding of Inconel 718, *Optik*, 2020;218:165029
- [38] Liang, R., Luo, Y., Study on weld pool behaviors and ripple formation in dissimilar welding under pulsed laser, *Opt. Laser Technol.*, 2017, 93: 1–8