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Research Article

Laser Welding of Aluminum to Copper: Properties of The Welded Joints and Optimization of Parameters

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Abstract

Laser welding is a procedure wherein materials are fused together using a beam of high-energy intensity generated through the concentration of light waves. Laser welding has gained significant prominence in the industrial manufacturing sector in recent years due to its various advantages. These advantages include high welding speed, low heat input, narrow weld seams, rapid cooling resulting in minimal heat-affected zones, suitability for automation, successful joining of different materials, and the ability to weld materials of varying thicknesses. In this study, the Taguchi Method was employed to determine the optimal parameters with minimal experimental effort. Mechanical properties, particularly tensile strength, were analyzed using the Minitab software based on the welded joints produced. Detailed examinations were conducted based on predetermined variables for the welding process.

Keywords

Laser welding, dissimilar welding

1. Introduction

Laser welding offers several superior features compared to other traditional welding methods. Due to the low heat input and the formation of a narrow heat-affected zone (HAZ) with laser beams, low residual stresses and distortions occur. Other advantageous aspects include high welding speed, deep penetration capability, flawless weld seams, and high strength values, which are some of the primary advantages provided by laser welding (1). Additionally, high efficiency, cost-effectiveness, and low defect rates are other beneficial characteristics. Dissimilar metal joints are increasingly being applied in various industrial sectors due to their technical and economic advantages. The necessity for hybrid features to meet service conditions is a driving force for the development of new different metal combinations. Copper (Cu) and Aluminum (Al) are among such combinations that need to be developed for applications in electrical connectors, busbars, cooling tubes, heat exchanger tubes, microelectronics, and solar collectors (2). Current efforts toward the electrification of vehicles have significantly increased the demand for a reliable and effective copper welding process (3).

The novelty of this study lies in the investigation of laser welding processes used to join copper and aluminum, specifically focusing on applications in electric vehicle battery configurations, including lithium-titanate-oxide (LTO) and nickel-manganese-cobalt (NMC) cell types. Since vehicles operate under challenging conditions, the quality of the weld and the penetration of materials into each other are critical details. This study further examines the role of the physical properties of the workpiece in determining the quality of the weld seam, particularly the reflectivity, absorption characteristics, and thermal conductivity of the materials (4).

The aim of this study is to identify the challenges encountered in laser welding of copper and aluminum and the methods developed to overcome these challenges. This research fills an important gap in the existing literature by addressing the difficulties arising from differences in material properties, such as reflectivity, high thermal conductivity, thermal expansion, and melting points. The study provides innovative approaches that contribute significantly to the scientific literature, offering solutions to the challenges posed by the dissimilar metal welding of copper and aluminum in laser applications (5).

1.1. Laser Welding Process

The laser welding machine has a single-mode and a maximum power capacity of 1500 watts. The maximum wavelength is 1070 nm. The maximum working area is 200x200 mm. To prevent overheating, it operates integrated with a water-cooled chiller system.

The Taguchi Method was used to find the optimum welding parameters. The welding process was carried out in a wobble pattern. Optimal welding parameters were sought using variables such as beam diameter, frequency, power, and welding speed.

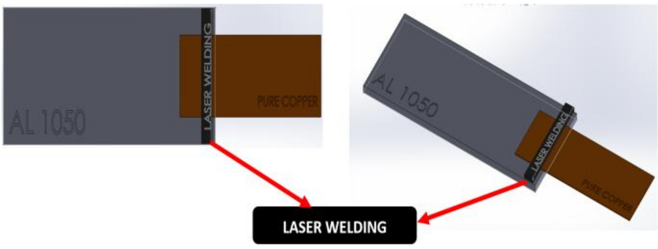

Figure 1. Schematic Representation of the Laser Welding Process [6]

METERIAL	MELTING POİNT (K)	BOILING POİNT (K)	DENSITY ($g.cm^3$)	COEFFICIENT OF LİNEAR THERMAL EXPANSİON X 10^{-6} / (K^{-1})	SPECIFIC HEAT CAPACITY ($J.kg^{-1}.K^{-1}$)	DELASTICITY MODULUS X 10^{-3} (MPa)
COPPER	1356	2573	8.92	16.4	390	108.5
ALUMINIUM	983	2335	2.7	24	880	61.68

Table 1. Properties of Copper and Aluminum Materials [6]

Three different variables were determined as a result of literature research and experiments, and these variables are Laser Power (watt), Welding Speed (mm/s), Amptitude (mm) and Frequency (Hz).

The material selection was inspired by pouch cells, which are critical components in energy storage systems (ESS). In pouch cells, the anode typically consists of 1050 series aluminum, offering high conductivity and corrosion resistance, while the cathode is made of pure copper, known for its excellent electrical conductivity. This configuration is widely utilized in the battery industry to enhance electrical efficiency and minimize energy loss.

In this context, the welding methods employed for joining the cells play a significant role. Particularly in battery systems, the effects of welded joints on mechanical strength, electrical conductivity, and thermal stability are thoroughly analyzed. In this study, the welding process was carried out by overlaying 0.3 mm pure copper material onto 2 mm thick 1050 series aluminum, and this method was investigated in detail. The selected materials and welding parameters were examined within the scope of research aimed at improving efficiency and reliability in battery packaging processes.

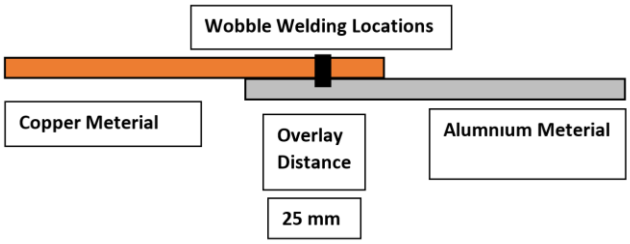

Figure 3. Laser Welding Schematic Representation

Below table shows the L18 experimental design, which includes these four factors (variables) and four different levels. A total of 18 welded joints were made using this design. After research and trials related to these robotic welding joints, the parameters determined within technological limits are shown in Table .. Values corresponding to 1, 2, 3, 4 in each column were placed to create the intended experimental conditions. Based on the tensile strength values of the welded joints made according to the created plan, parameter optimization was performed using Taguchi analysis with the Minitab program. The purpose of using the Taguchi experimental design in this study is to achieve the optimum result with fewer experiments and lower cost, minimizing time loss.

TAGUCCI METHOD EXPERIMENT						
NO	**DENEY NO**	**LASER POWER (W)**	**WELDING SPEED (mm/s)**	**AMPTİTUDE (mm)**	**FREQUENCY (Hz)**	**HEAT (Kj/mm)**
1	T1	1400	120	0,8	140	11,7
2	T2	1400	120	1	150	11,7
3	T3	1400	120	1,2	160	11,7
4	T4	1400	140	0,8	140	10,0
5	T5	1400	140	1	150	10,0
6	T6	1400	140	1,2	160	10,0
7	T7	1400	160	0,8	140	8,8
8	T8	1400	160	1	150	8,8
9	T9	1400	160	1,2	160	8,8
10	T10	1500	120	0,8	140	12,5
11	T11	1500	120	1	150	12,5
12	T12	1500	120	1,2	160	12,5
13	T13	1500	140	0,8	140	10,7
14	T14	1500	140	1	150	10,7
15	T15	1500	140	1,2	160	10,7
16	T16	1500	160	0,8	140	9,4
17	T17	1500	160	1	150	9,4
18	T18	1500	160	1,2	160	9,4

Table 2. Laser Welding Schematic Representation

1.2. Tensile Test Process

The test specimens were extracted from the welded sheets in compliance with the EN 288-4 standard. During the extraction process, visual inspections were meticulously performed to evaluate the weld seam characteristics. As required by the standard, 25 mm sections from the start and end of the welded plates were removed to eliminate potential welding defects in these regions.

The specimens were prepared according to the dimensions specified in the EN ISO 4126:2012 standard and were precisely cut using water jet technology. The cutting process was conducted with a Fagor CNC 8070 L control system, utilizing a water pressure of 4000 bar to prevent thermal distortion in the welded areas and to ensure high precision in the cutting operation.Tensile tests were conducted to evaluate the mechanical performance of the welded joints using an Instron 4411 tensile testing machine. The testing protocol specified a tensile speed of 2 mm/min. Geometric measurements of the specimens were performed with a Mitutoyo caliper featuring an accuracy of 0.01 mm, ensuring high precision in dimensional assessments.

These methodologies facilitated a detailed and reliable analysis of the mechanical and geometric properties of the welded joints. The measurements provided below are expressed in millimeters (mm).

Figure 4. Tensile Testing Sample

1.3. Metallographically Sample Preparation Process

Microscopic analyses were performed to assess the penetration depth and microstructural characteristics of laser-welded joints in detail. Specimens were sectioned from the welded area using a saw operating at 3540 rpm to ensure precise cuts. The extracted samples were then stabilized by embedding them in a cold bakelite mixture prepared by combining 2 parts bakelite powder and 1 part chemical hardener. The mixture was poured over the samples, which were allowed to cure for 15 minutes to achieve a solid and uniform surface.

To prepare the specimens for microscopic evaluation, surface polishing was carried out sequentially using 320, 800, and 1200 grit sandpaper, with each polishing step performed for 1 minute to ensure optimal surface smoothness.

Following the polishing process, the specimens underwent an etching procedure to reveal the microstructural details. Etching solutions were selected based on the material: 3% nitric acid with 97% ethyl alcohol for Aluminum (Al) and 94% ammonium persulfate, 3% iron, and 3% chlorine for Copper (Cu). Specimens were immersed in the etching solution for 15 seconds, after which they were thoroughly rinsed with water to remove any residual chemicals.

In this study, the Axiolab 5 model from ZEISS was used as the electron microscope.Once the preparation steps were completed, the specimens were examined under a digital microscope to analyze the weld penetration depth and microstructural features in detail. This comprehensive analysis process was critical for evaluating the quality and reliability of the laser welding process. This study was conducted using the ZEISS EVO Family SEM. To enable deeper sample analysis, an accelerating voltage of 20 kV was selected. This voltage setting allows for the examination of internal structures with higher resolution, facilitating in-depth analysis of the sample's morphology and composition.

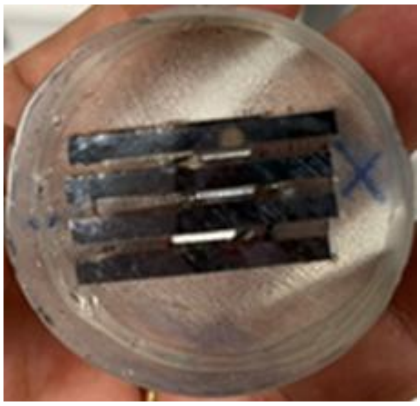

Figure 5. Metallographic Samples

2. Results and Discussion

A total of 54 tensile samples were processed. Three tensile samples were taken for each parameter, and the analyses were conducted based on the sample with the highest value. The following table has been created based on the test results along with the corresponding graphs for the relevant samples.

TAGUCCI METHOD EXPERIMENT						
NO	DENEY NO	HEAT (Kj/mm)	TENSILE FORCE (N) (1)	TENSILE FORCE (N) (2)	TENSILE FORCE (N) (3)	HIGHEST PARAMETER (N)
1	T1	11,7	680,0	1092,0	550,0	1092,0
2	T2	11,7	1012,0	1050,0	1293,0	1293,0
3	T3	11,7	1032,0	650,0	1134,0	1134,0
4	T4	10,0	1024,2	793,3	1038,9	1038,9
5	T5	10,0	1047,0	752,5	572,6	1047,0
6	T6	10,0	615,3	766,2	424,8	766,2
7	T7	8,8	872,2	1159,1	606,4	1159,1
8	T8	8,8	1075,8	1300,0	833,8	1300,0
9	T9	8,8	250,0	383,8	366,8	383,8
10	T10	12,5	400,0	643,5	807,2	807,2
11	T11	12,5	1357,0	705,8	987,9	1357,0
12	T12	12,5	1040,9	1449,7	1037,6	1449,7
13	T13	10,7	907,6	706,8	654,8	907,6
14	T14	10,7	138,8	1022,8	846,7	1022,8
15	T15	10,7	957,7	858,3	1035,6	1035,6
16	T16	9,4	878,7	638,4	1183,9	1183,9
17	T17	9,4	1169,1	917,3	767,2	1169,1
18	T18	9,4	836,2	1026,8	447,4	1026,8

Table 3. Tensile Test Results Table

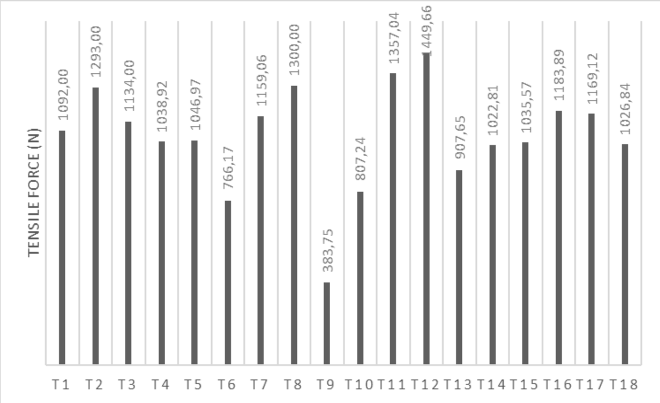

Table 4. Tensile Test Results Table-2

In the tensile test, uniform fractures were observed. It was found that the material fractured in the heat-affected zone (HAZ) of the welded joints. It was observed that the copper and aluminum formed a heterogeneous mixture in the weld pool, which led to fractures at the joint.

Based on the tensile test results, the highest tensile force was used, and analyses were performed using Minitab to determine the optimum welding parameters. The specimens exhibiting the highest tensile strength (T11 and T12), intermediate tensile strength (T2), and the lowest tensile strength (T9) were specifically analyzed. The analysis of the tensile samples reveals the significant impact of the laser welding speed parameter on the welding process. For the first group, the speed parameter was set at 150 mm/s, while for the second group, it was set at 200 mm/s. During the process of adjusting the optimal parameters, the balance between laser power and welding speed is critical. It was observed that as the laser speed increased, the penetration level in the weld area decreased, leading to variations in fracture strength values. An increase in laser welding speed results in faster processing of wobble movements on the weld surface, shortening the duration of laser beam impact. Consequently, the amount of fused metal formed at the weld surface (HAZ) decreased.

According to the tensile test results, it was determined that as the welding speed increased, the penetration decreased, resulting in a decrease in tensile strength values. In the laser welding process, a high laser power and fast welding speed are often preferred. The primary reason for this preference is to prevent overheating by ensuring the welding process on the surface occurs quickly. Additionally, minimal deformations occur in the material. Similarly, the reduction in penetration level has led to a decrease in elongation. As the tensile strength value decreased, the amount of elongation in the material also decreased. The tensile test graph of the T11 specimen, which exhibits high tensile strength, is presented below.

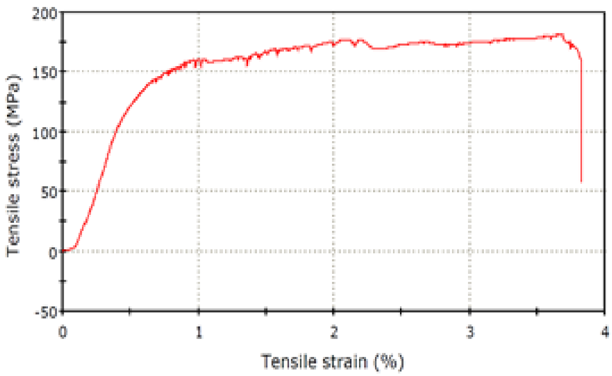

Figure 6. T11 Tensile Test Chart

The T2, T9, T11, and T12 samples identified from the tensile test results were embedded in bakelite. Initially, a 2.5x-50x-200x-500x magnification image was captured from the microscope device to examine the weld penetration area. After etching the samples using an electrolytic etching device, images were taken at 5x magnification, and the penetration distances were measured.

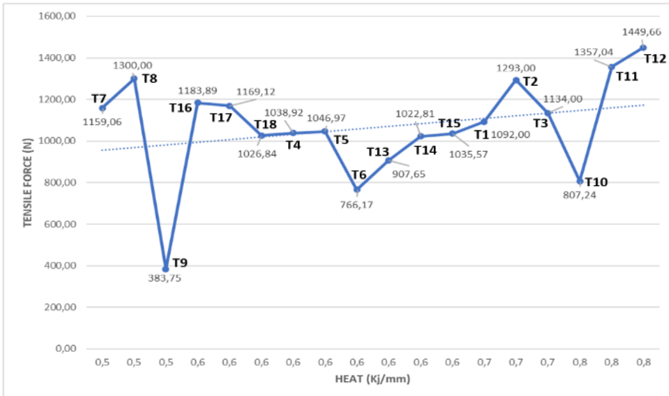

Table 6. Tensile Force and Heat Chart

Based on the obtained data, it was observed that as the penetration amount increased, the strength value of the welded structure also increased. The higher fracture stress in the T11 and T12 samples compared to the other samples supports this observation. In the T9 sample, the fracture stress value was lower than that of the T2 sample, despite having approximately the same penetration distance, due to the presence of an air gap between the two materials.

The analysis of the graph reveals a positive correlation between the heat input and tensile strength. As the heat input increases, it results in a higher amount of material melting and consequently, an increase in penetration depth. The elevation in penetration depth allows for a deeper reach into the material, often leading to the formation of a more robust weld joint. This alignment suggests a parallel relationship between the heat input and tensile strength.

In this context, the escalated heat input enables the propagation of melting and solidification processes into deeper layers of the material, promoting a more homogeneous and sturdy weld structure. Consequently, the molecular bonds between the materials become stronger, thereby enhancing the tensile strength. Thus, the trend depicted in the graph underscores a direct association between the heat input and tensile strength, highlighting the pivotal role of heat input in determining the quality of the weld joint in laser welding processes.

A detailed scanning electron microscopy (SEM) analysis was conducted on the fracture zone, providing valuable insights into the structure of the welded joint. The analysis revealed that the welded joint fractured, separating from its fusion point. This detachment often stems from weak bonds or microstructural disparities at the interface regions, typically arising from the interaction of dissimilar materials. The examination highlighted defects such as gas voids and welding spatters within the weld pool. These imperfections can adversely affect the stability of the welding process and subsequently impact the mechanical properties of the final product. However, it was observed that with the determination of optimal welding parameters and proper control of the welding process, these drawbacks can be minimized. In this context, further experimental studies and parameter optimization are necessary to enhance the quality of the welding process and reduce undesirable defects.

Huang et al. stated the necessity for decreasing the solidification rate to increase tensile strength, which allows for a more homogeneous distribution of solute in the weld pool, complete release of latent heat of solidification, and better matching of crystal lattices. These effects generally indicate the necessity of using an external heat source to increase tensile strength (7).

Stefan and colleagues investigated main parameters such as laser power and welding speed, evaluating their impact on tensile strength. They observed that at low welding speeds, spatters and melt ejections were observed, while higher welding speeds created higher-quality weld seams without visible pores in cross-sections (8).

Tomomichi et al emphasized in their research that decreasing welding speed resulted in increased penetration depth. In this case, while the weld width increased, a deep penetration depth was observed while maintaining a high aspect ratio. This finding suggests that reducing welding speed is one of the factors that increases the material's tensile strength (9).

Ojo and Taban reviews that the tensile strength of laser-welded aluminum alloys is shaped by a combination of microstructure and heat effect. The use of suitable filler metal, optimal welding parameters, and appropriate heat treatment applications can enhance the tensile strength (10).

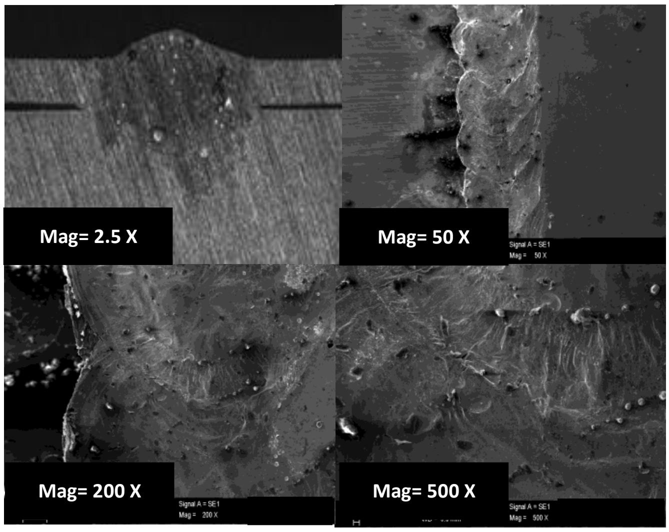

Figure 7. T11 Sample 2.5x-50x-200x-500x Magnified Weld Penetration Zone

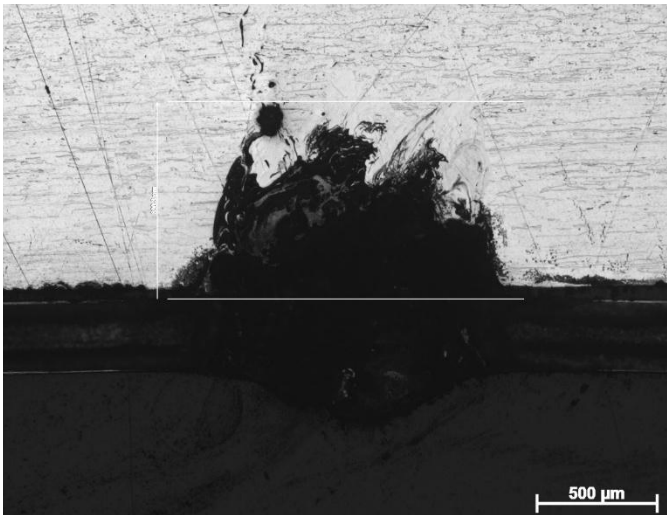

Figure 8. T11 Sample 5x Magnified Weld Penetration Zone

The weld microstructure has a significant impact on tensile strength. The presence of aluminum and copper precipitates in the weld pool and their pinning effect on dislocations can enhance the weld strength (10).

Di Zuo et al predicted in their research that tensile strength would decrease with increasing welding speed. They attributed this to the formation of heterogeneous bond structures and gas voids resulting from the joining of different metals. They argued that welding speed is a significant factor influencing microstructure, fracture behavior, and tensile strength in the process of joining dissimilar metals. Furthermore, regions in the ITAB (Interfacial Transition Active Brazing) zone with copper content ranging from 20% to 50% were found to form a brittle structure, making them more prone to fracture.

It was also noted that increasing the amplitude value increases penetration, thereby positively affecting tensile strength [11].

Trinh et al noted that with the increase in laser power, more metallic material melts and the penetration level increases. This increase leads to the formation of wide and peaked weld seams. They also mentioned that the penetration level increases with the rise in amplitude value. Particularly when high laser power is applied, a noticeable effect on the morphology of the weld seams is observed. Additionally, the effects of laser power on weld morphology were emphasized. As laser power increases, weld spatter and metal melt also increase. However, in welds performed with low laser power, there is a higher likelihood of gas voids forming on the surface. This highlights the importance of correctly adjusting and controlling laser power during the welding process [12].

Hollatz et al have determined that an increase in welding speed results in decreased penetration depth and consequently, a reduction in tensile strength. It was found that an increase in laser power can increase penetration depth while also potentially altering the amplitude value. Moreover, an increase in frequency has been shown to increase penetration, with higher frequencies enabling deeper penetration.

The difference in thermal expansion between materials can lead to the formation of stresses in the solidified material, which may result in cracking. It has been noted that a higher copper content may lead to higher tensile strength, supported by the presence of intermetallic phases. However, a high copper content can also increase the hardness ratio and lead to a more brittle joint, thereby negatively affecting tensile strength [13].

The study conducted by Masoud and his team identified laser power and welding speed as the most critical parameters influencing tensile strength. An increase in laser power generally enhances the maximum tensile strength, whereas an increase in welding speed has the opposite effect, reducing the maximum tensile strength. It was observed that the increase in welding speed reduces the molten base metal area, which adversely impacts the tensile strength [14].

In their study, H. Zhao and colleagues focused on aluminum alloys increasingly utilized in the automotive industry and highlighted the associated challenges and issues. The advantages and disadvantages of laser welding compared to other welding techniques were thoroughly examined. The research reviewed the current understanding of critical physical processes during laser welding of these alloys, including energy absorption in the weld pool, fluid flow, heat transfer, and the evaporation of alloying elements from the weld pool surface.

It was observed that heat-affected zones (HAZ) in laser welding are narrower compared to other fusion welding processes with lower power density, such as gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). Laser welding of automotive aluminum alloys was tested on tensile specimens, revealing two distinct fracture modes in different regions along the longitudinal direction. Ductile fractures with large surfaces near the fusion zones and in the weld center were observed. Cracks and hot tearing were detected in certain regions following laser welding.Cracking occurring in the weld fusion zone during solidification is identified as solidification cracking, while cracking in the partially melted zone caused by the liquation of low melting point components is termed liquation cracking. In continuous laser welding, 5xxx alloys can be autogenously welded without solidification cracking, whereas 2xxx and 6xxx alloys require the use of filler metals, such as 4043 or 4047, to modify the composition and prevent solidification defects.

Thermal stresses in welds are influenced by the welding process, heat input, joint configuration, rigidity, and the thermal properties of the welded materials. The focal point is critical for weld penetration; as the focal distance increases, penetration depth decreases [15].

Cong and colleagues investigated the effects of oscillation frequency and amplitude on the butt weld formation of 3 mm 6061/2A12 aluminum alloys using the fiber laser welding technique. It was observed that as the oscillation frequency and amplitude increased, the front weld width expanded, while the back weld width gradually decreased. Weld separation, represented by mixing homogeneity, was improved in laser oscillation welding and was primarily dependent on the oscillation frequency, increasing with higher frequencies.

When the oscillation frequency or amplitude was elevated, the mixing intensity of the molten pool increased. The molten pool was accelerated and mixed more uniformly, enabling alloys to be evenly distributed within the weld and detectable near the 6061 base material. The formation mechanism of laser oscillation welding was attributed to the melting of the base material to form a molten pool under laser beam irradiation. Consequently, the beam's oscillation trajectory was critical for the weld morphology.

Laser energy was predominantly concentrated on the upper weld, resulting in an increased front weld width while the back weld width diminished. The results demonstrated that, compared to conventional laser welding, laser oscillation welding significantly improved both the front and back weld morphologies [16].

3. Minitab Analysis And Results

An analysis was performed using the Minitab program based on the fracture stress values from the welded joints. The analysis was conducted according to the previously determined variables for the welding process.

Using the L18 matrix, the parameters were determined, and then the laser welding process was carried out. The analysis of the fracture stress values was performed based on the tensile test results. The effect of a parameter indicates its impact on the determined output. According to the analysis results, the most influential parameter among those used was the welding speed, followed by laser power, amplitude (weld width), and frequency in Table 7.

LEVEL	LASER POWER (W)	VELOCITY (MM/S)	AMPTITUDE (MM)	FREQUANCE (HZ)
1	23,09	24,66	23,38	23,38
2	23,67	23,30	23,38	23,38
3	-	22,19	23,38	23,38
RANK	2	1	3	4

Table 7. Minitab Analysis Outputs

Using the values determined on the L18 matrix, Taguchi's "larger is better" analysis method was employed. The combination of factor values that maximizes the fracture strength of the laser welding was determined with the "Main Effects Plot for Means" graph presented in Table 8.

As seen from the Table 8, increasing the laser power from 1400 watts to 1500 watts has shown a positive effect. Considering the increasing trend in welding speed, a decrease from 120 mm/s to 140 mm/s was observed, while an increase from 140 mm/s to 150 mm/s has shown a positive effect. Increasing the amplitude value from 0.8 mm to 1.0 mm has resulted in a positive effect, but a negative effect was observed between 1.0 mm and 1.2 mm. When the frequency value increased from 140 Hz to 150 Hz, it showed a positive effect, but when it increased from 150 Hz to 160 Hz, it showed a negative effect. Based on the results of this study, optimal parameters have been determined in Table 9.

Fatigue specimens were prepared according to these determined parameters and subjected to fatigue testing. The L18 model was examined based on the fracture stress analyses conducted with the determined parameters, and it was concluded that the model is consistent with a rate of 99.9%. These analyses are depicted in Table 10.

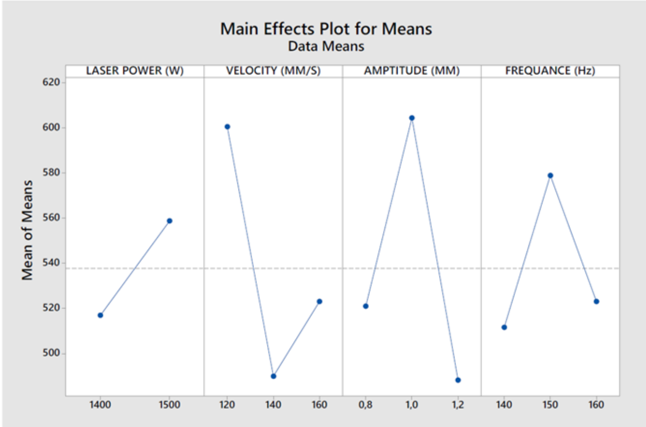

Table 8. Main Effects Plot for Means

KAYNAKLAMA PARAMETRELERİ		OPTİMUM PARAMETRE
A	LASER POWER (W)	1500
B	WELDING SPEED (mm/s)	120
C	AMPTİTUDE (mm)	1,0
D	FREQUENCY (Hz)	150

Table 9. The Optimum Parameter Determined As A Result Of The Analysis

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0,0547723	99,90%	99,83%	0,0972	99,67%

Table 10. Percent Accuracy Of Experiment

This study investigated the effects of laser welding on important factors such as tensile strength, microstructure, heat input, and IMC (Intermetallic Compound) thickness. Our findings revealed that an increase in welding speed led to decreased penetration depth and consequently, reduced tensile strength. Similarly, while an increase in laser power increased penetration depth, an increase in frequency resulted in increased penetration, with higher frequencies enabling deeper penetration.

The difference in thermal expansion between materials was found to induce stresses in the solidified material, potentially leading to crack formation. It was observed that a higher copper content could lead to higher tensile strength, but also to a more brittle joint, negatively impacting tensile strength. These findings underscore the importance of laser welding in the material joining process.

4. Conclusions

This study systematically examined the impact of laser welding parameters on the joining of Aluminum (Al) and Copper (Cu) materials, with a focus on key performance indicators such as tensile strength, microstructural integrity, heat input, and intermetallic compound (IMC) layer thickness. The results clearly indicate that laser welding parameters play a pivotal role in determining the quality and mechanical properties of welded joints.

The experimental findings established that increasing welding speed reduced penetration depth, thereby negatively influencing tensile strength. Conversely, higher laser power enhanced penetration depth, contributing positively to joint performance. Variations in frequency were observed to significantly affect penetration depth, with higher frequencies achieving greater penetration but introducing increased thermal stress.

The interaction within the weld pool revealed a heterogeneous mixture of Al and Cu, which influenced the formation of the heat-affected zone (HAZ) and the fracture behavior of the joints. It was determined that differential thermal expansion between the materials induced residual stresses during solidification, potentially leading to crack formation. Additionally, a higher copper content improved tensile strength but increased brittleness, adversely impacting overall mechanical performance.

To identify the optimal welding conditions, the Taguchi method was applied, and parameters were optimized. Fatigue tests conducted with the identified parameters demonstrated the reliability of the optimization process, yielding a model accuracy of 99.9%. These outcomes highlight the effectiveness of the employed methodology and underscore the critical importance of precise parameter control in laser welding processes.

In summary, laser welding has been validated as a highly effective technique for joining dissimilar materials with distinct physical and chemical properties. However, the necessity for meticulous parameter optimization to ensure weld quality and performance cannot be overstated. The insights derived from this study provide a robust foundation for the application of laser welding in high-stakes industries such as battery manufacturing, while also contributing to the advancement of state-of-the-art material joining technologies.

Authors' Contributions

Conceptualization, methodology, investigation, data curation, and writing original draft preparation: Fatih Şahin. Supervision and project administration: Prof. Dr. Emel Taban.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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