https://doi.org/10.33261/jaaru.2024.31.4.002 *Association of Arab Universities Journal of Engineering Sciences (2024)31(4):13–23*

Association of Arab Universities
Journal of Engineering Sciences
مجلة اتحاد الجامعات العربية للدراسات والبحوث الهندسية

كلية الهندسة - جامعة بغداد

جمعية كليات الهندسة
اعضاء اتحاد الجامعات العربية

Evaluation of joint strength in laser transmission welding of PMMA polymer

Saja Adnan Hussein[1]*and Bassim Shaheen Bachy[2]

[1] *Department of Mechanical Engineering, University of Baghdad, Baghdad- Iraq, saja.adnan2103m@coeng.uobaghdad.edu.iq*

[2] *Department of Mechanical Engineering, University of Baghdad, Baghdad- Iraq, b.bachy0903@coeng.uobaghdad.edu.*

**Corresponding author: Saja Adnan Hussein and email: saja.adnan2103m@coeng.uobaghdad.edu.iq*

Published online: 31 December 2024

Abstract— This study reports on experimental research of laser transmission welding of Polymethylmethacrylate (PMMA) using two different welding path strategies: box and spiral. The influence of laser welding parameters, such as laser power, welding speed, and laser pass number, on the weld strength was investigated by applying Response Surface Methodology (RSM) depending on Box-Behnken Design (BBD) methodology in the experimental design. A series of carefully designed tests and evaluations have been used to create mathematical models that show how the responses and the process parameters are related. These sequential analysis-of-variance (ANOVA) approaches were also applied to evaluate the developed models' appropriateness. Tensile tests were conducted after welding to evaluate the effect of the kind of joint and the weld passes on the weld stresses strain curve of the weld joint and its strength. The results showed that high-quality welding was produced under process parameters that appeared in run number 8 the parameters for this run are (V=10 mm/min, P=20 Watt and one pass number) for the box weld path while for the spiral were shown in run number 4 (V=40 mm/min, P=30 Watt and two passes number).

Keywords— Laser Transmission Welding, PMMA, Mechanical Testing, Joint Strength.

1. Introduction

Laser welding of plastic offers advantages such as accurate heat transfer, improved localization of heat-affected zones, no visible damage, welding of pre-assembled plastic components, design freedom, easy automation, and high mechanical performance [11]. Plastics can be classified into thermoplastic and thermosetting polymers in addition to the natural, semi-synthetic, and synthetic forms. Thermoplastic polymers are plastics that have been sculpted and softened by heat. When cooled, they assume their original techniques for joining thermoplastics include welding, solvent bonding, adhesive bonding, mechanical bonding, and fastening [11, 23]. Light Amplification by Stimulated Emission of Radiation (laser) has been used extensively in many applications in recent years. In the 1970s, laser welding on thermoplastics was first shown [9]. Laser Transmission welding (LTW) is one of the most recent joining methods for fusing two thermoplastic surfaces. [22]. this method works well for connecting metal and thermoplastic [18]. Because industries using plastic welding want high-quality couplings with shorter cycle times, laser welding of plastic to plastic or plastic to metal is becoming increasingly frequent. The newest advancement in the plastics joining sector is laser transmission welding. Although numerous companies have used this method, academic research is being conducted. A laser beam is focused on two overlapping thermoplastic components with distinct optical properties to execute laser transmission welding. LTW is a preferred technology in various sectors, including medical, automation, electronics, microtechnology, and textiles. It offers clean, pollution-free welding, excellent repeatability, vibration-free connections, minimal thermal load, and particle release. It is widely used in car dashboard assembly, sensor housing, microfluidic devices, and technical textiles for continuous and fat-connecting plastic sheets and textiles [5, 14, 15, 17, and 27]. Transparent Polymethylmethacrylate (PMMA) acrylic is used in optical equipment like cameras because of its superior optical glass properties [2, 4, and 20]. Because PMMA has great dimensional stability, easy to bind, robust, stiff, optically clear, and is weather resistant, it is utilized as the foundation metal in this research. The furniture, pharmaceutical, and biological sectors are the main businesses that use thermoplastics. Additionally, because of its excellent flexibility, low cost, and low density, acrylic, specifically Polymethylmethacrylate (PMMA), finds extensive use in the biomedical and industrial domains [3, 26].

Laser Transmission welding (LTW) is a process where one polymer component is one of the materials is transparent or translucent to laser, while the other material absorbs the laser beam impacts the polymer, moves through the top section, and arrives at the connecting component. The bottom portion absorbs the laser beam, converting it into heat, which melts the substrate surface and softens the top layer. The weld pool forms and material mixing occurs. Following cooling and diffusion, joining occurs, as seen in Figure .1 [5, 10, 18, and 19]. The clamping pressure is essential for the LTW operation, which is significantly for effective contact conduction, polymer surfaces should be smoother to avoid the effects of any air gap between them. There are various joint configurations for LTW, with the most common being a lap joint arrangement. T and Butt joints are challenging to achieve due to "The transparent polymer requires a high level of optical penetration depth." [1, 23, 25].

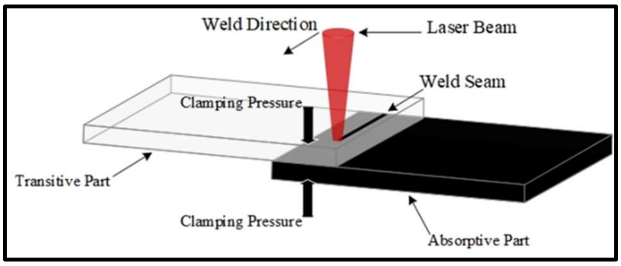


Figure 1: The laser transmission welding process's working principle

Laser transmission welding (LTW) is a flexible, non-contact polymer welding technique that offers high-quality joint and aesthetic results. Its non-contact nature and minimal heat generation make it suitable for delicate electronic and medical components. LTW has a quick cycle time, allowing for the welding of long and large thermoplastic pieces at acceptable speeds. It is flash-free and capable of hermetic welding, making it suitable for welding microfluidic devices and 3-D weld contours. Its precise weld zone is achieved through laser beam size and molten flash flow control, and it can be used to join elastomers and semi-crystalline polymers in mixtures of similar or different materials. [11].

However, LTW has limitations, such as precise weldment position, difficulty achieving fixture positions, porosity and embrittlement problems, high equipment costs, and the need for protective masks [25].

Several academics have used both theoretical and experimental efforts to study the LTW. The study by **Kucukoglu et al.** explores using PMMA to ABS to improve laser transmission welding settings in car taillight manufacturing. They propose a multi-response Taguchi-based TOPSIS technique to optimize LTW parameters and provide optimal parameters for a multi-response with fewer tests. The study found that power was the most important machining parameter for weld width and breaking strain, and pressure force significantly impacted weld strength quality [17]. **Foram et al.** examined the impact of laser processing parameters on the weld strength of Polypropylene 2mm using the Response Surface Methodology RSM approach. They found that composites with carbon black content between 0.5 and 1.0 wt. % were successful, while composites with higher CB content were difficult to weld due to degradation. The study also found that carbon black concentration influences the laser process window for improved weld quality [11]. **Kumar et al.** examined the effect of laser transmission welding (LTW) process parameters on weld strength and seam width of polylactic acid sheets. The study found that scanning speed significantly influenced weld breadth and tensile strength, while stand-off distance, laser power, and scanning speed influenced maximum weld strength. Power, scanning speed, and stand-off distance contributed to minimum weld seam width [18]. **Wu et al.** explore thermoplastics' composition and structure during laser transmission welding, highlighting the impact of laser settings, reinforcement, and additives on welding strength. The study also discusses modeling and simulation techniques, emphasizing the need for further research to enhance thermoplastic welding quality [9]. **France et al.** examined the mechanical strength of welded connections from 2 mm and 4 mm thick semi-transparent polyamide specimens combined with carbon black-filled polyamide. The study found that process variables like energy density, laser beam speed, and component thickness impacted the strength of the welded connection. The study also compared thermomechanical and optical characteristics [8]. **Acherjee** experiment on PMMA and ABS polymers used coherent diode laser systems and Taguchi L16 & Grey relational analysis for parametric optimization. The study aimed to maximize lap shear strength and minimize weld seam width using input parameters like laser power, welding speed, standoff distance, and clamp pressure. The study found that laser power was the most critical factor, with stand-off distance having the greatest influence on total weld strength variation. The grey-based Taguchi approach improved the total quality function [3]. **Pereira et al.** studied experimental investigation and tensile testing on polyamide 6 (Ertalon SA 6) and found that using a Nd: YAG pulsed laser for scarf and lap welded connections reduced weld beads and increased joint strength. The study also found that good-quality welds were indicated by an average failure shear stress of 55% of the base material's tensile strength, potentially shortening production lead times and producing intricate device shapes [22]. **Shaker et al.** study used a diode laser to conduct laser transmission welding on PMMA with varying thicknesses. They analyzed how laser speed, spot size, and force influenced weld width and strength. . Results showed that increasing speed and spot size reduced welding width [24].

The experimental and theoretical work is based on a RSM-BBD. Using three levels and three factors, the classic box type investigated the impact of parameters on welding quality and reaction. Demonstrating welding quality and precision at three different levels and three separate parameters showed the new spiral type's impact and distinction from the box type, Figure 2 shows the used welding profiles.

Preliminary experiments accepted three levels, and the best level was chosen for further testing, the results of which were computed and examined. Tensile tests were conducted to determine each joint's quality by measuring its strength. Additionally, the effect of LTW parameters on the joint strength of the weld zone will be examined, including the laser power, scanning speed, and number of laser passes. The mathematical model tool that is being used will assist in determining how the investigated process parameters affect the defined process response. It will also provide a mathematical model that can be utilized to establish a correlation between the parameters and ultimately provide the best possible process parameters.

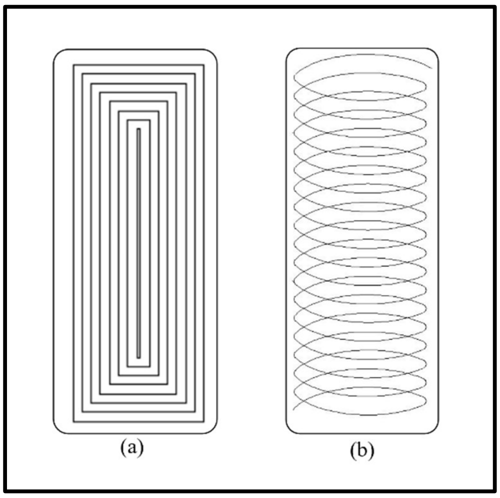


Figure 2: Welding Profile (a) Box, (b) Spiral

2. Response surface methodology / Box Behnken design (RSM-BBD)

The Response Surface approach (RSM) is a mathematical and statistical method used to model and evaluate problems aiming to maximize response while considering multiple factors [6, 21].

It involves constructing an experimental plan, using empirical statistical modeling to create an approximation relation, and process optimization to determine desired response values. When independent variables are continuous, quantifiable, and under control, the response surface can be represented as follows.

$$y = f(\xi_1, \xi_2, \ldots, \xi_k) + \varepsilon \quad (1)$$

When ε indicates the residual error which is additional variability not considered by f, and the real response function's form is unknown, ε often considers background noise, measurement error, and other variables. Assuming a normal distribution with mean zero and variance σ2 is often considered a statistical mistake.

The natural variable $(\xi_1, \xi_2, \ldots, \xi_k)$ are represented in natural units like °C and kg/m^2, which can be converted to coded variable $(x_1, x_2, \ldots, x_k)$,, which is dimensionless with zero mean and standard deviation.

In RSM practical applications, an approximation model is needed for the real response surface based on observable data. Multiple regressions create these empirical models, typically using a second-order polynomial equation [6, 7].

$$\eta = \beta o + \sum_{j=1}^{k} B_j x_j + \sum_{j=1}^{k} B_{jj} x_j^2 + \sum_{j<}\sum_{j=2}^{k} B_{ij} x_i x_j + \varepsilon \quad (2)$$

Where the regression coefficients are represented by parameters B_{ij} = 0, 1... k., K is the number of variables, X is the input parameter and Y is the process's responses (output)

This study uses the Box-Behnken Design (BBD) as a response surface methodology model specifically designed for second-order regression models. Unlike the Central Composite Design (CCD), which requires five levels for each component, BBD only requires three levels for each factor and uses face points instead of corner points [13].

The study investigates the relationship between investigated parameters and the joint strength, proposing three levels for all processing parameters. Prior experiments were conducted to determine the most sensitive LTW process parameters and their ranges and limitations.

The selected welding parameters and their limits are shown in Table 1., Following pre-experiments, it was decided that these were the most suitable limits for the research, the accuracy and precision of the experimental approach were confirmed by repeating the experiment three times and computing the average.

Table 1: The selected parameters and their limits.

Parameters	Units	Limits		
		-1	0	1
V: Laser Speed	mm/min	20	30	40
P: Laser Power	W	10	20	30
P.No.: Pass Number	/	1	2	3

3. Experimental Work

Polymethylmethacrylate (PMMA) samples that were both transitive and absorptive were created into rectangular forms measuring 80 x 40 mm for this investigation, as shown in Figure 3. A variety of experiments were performed utilizing a laser system (Figure. 4) with a fiber with a wavelength of 1064 nm, a maximum scanning speed of 10,000 mm/s, a maximum beam diameter of 30 m, a maximum laser power of 50 w, a maximum pulse

frequency of 200 kHz, and a maximum laser pulse duration of 20 nanoseconds. These polymers are in great demand for many industrial applications [12,16].
EzCad 2 CAD/CAM software was used to set up and develop parameters, additionally to produce the CAD design of the proposed welding strategy (welding profile), the interface of the software can be seen in Figure 5.

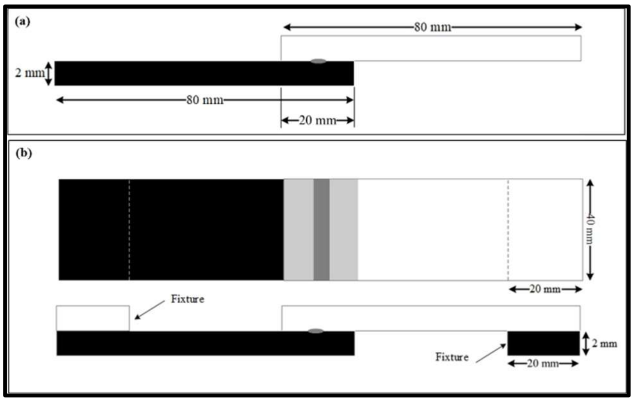


Figure 3: Welded sample (a) Dimensions and arrangement, (b)Fixture for the tensile test sample

Figure 4: Used fiber laser machine

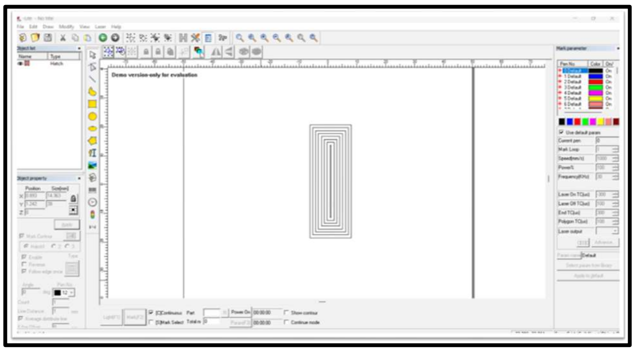


Figure 5: Interface of the used software

The plate samples were set up and supported during the welding process using a mold, as shown in Figure. 6, ten-millimeter-thick PMMA polymer was used to create this mold. It was divided in half and fastened to the machine's base using the appropriate screws and bolts. This mold has a groove that holds the sample while it is being welded, and the pressure exerted is measured using a load cell positioned underneath the sample. The screw can be tightened or loosened to adjust the applied uniform pressure, which is displayed on an LCD in a designated box.

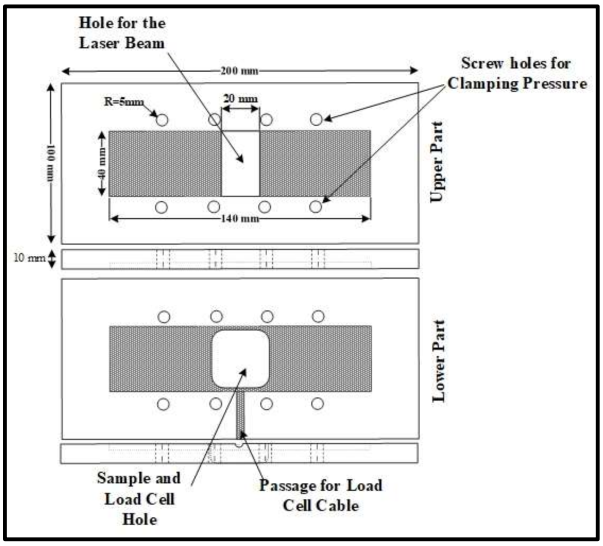


Figure 6: Schematics for mold layout

For every processing parameter, three levels were selected to investigate the relationship between the parameters under study and the LTW responses.

4. Results and Discussion

4.1 *Experimental results*

4.1.1 Stress-Strain curve results

The relationship between the stress and strain for runs in the two cases of welding profile type (Box and Spiral) is shown in Figures 7 and 8
As seen in Figure 7, the stress-strain curve for run number 1, it is indicated that the LTW with spiral profile greater

than for box profile, the joint strength for spiral = 2.88 Mpa while for box = 1.56 Mpa which is equal to the max load over unit area (equation 3) and as illustrated in table 2, same results shown for run numbers (2,3,4,5,7,8,10 and 12) stated that the joint strength for spiral greater than box profile.
Figure 8 shows the stress-strain curve for run number 6, it is indicated that the LTW for the box profile greater than for the spiral, the joint strength for the box = 3.88 Mpa while for the spiral = 3.75 Mpa, and as shown in table 2, same results for run numbers (9,11 and 13)) stated that the joint strength for box greater than spiral profile, and that's clear in Figure 9 the relationship between the joint's strength for both scenario for the thirteen run orders, obviously most of the trials show that the spiral has a greater welding strength than the box.

Table 2 shows the max load and joint strength for the two welding profile cases, it is shown that the joint's strength maximum value for the box profile appears in run number 8 the parameters for this run are (V=10 mm/min, P=20 Watt and one pass number) while run number 5 shows the minimum value (V=10 mm/min, P=30 Watt and one pass number)

The joint strength's maximum value for the Spiral profile is shown in run number 4 (V=40 mm/min, P=30 Watt and two passes number), while the minimum value shown in run number 11 (V=30 mm/min, P=10 Watt and three passes number).

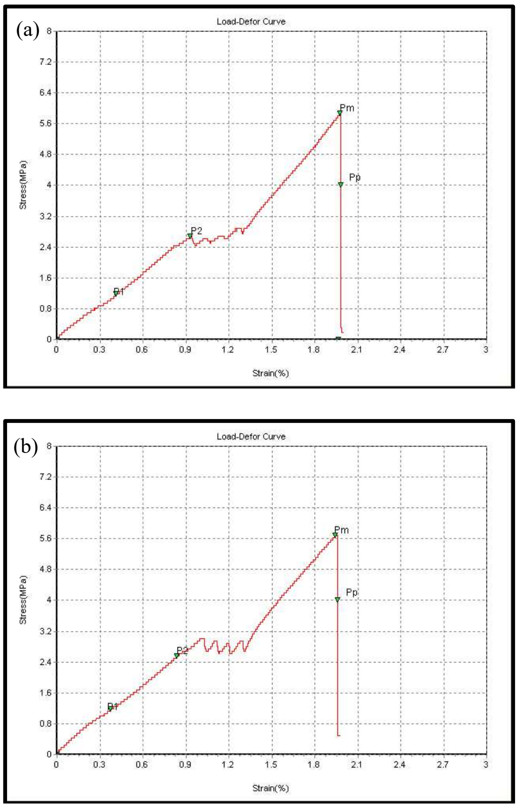


Figure 7: Stress-strain curve for #run-1, (a) Box, (b)Spiral

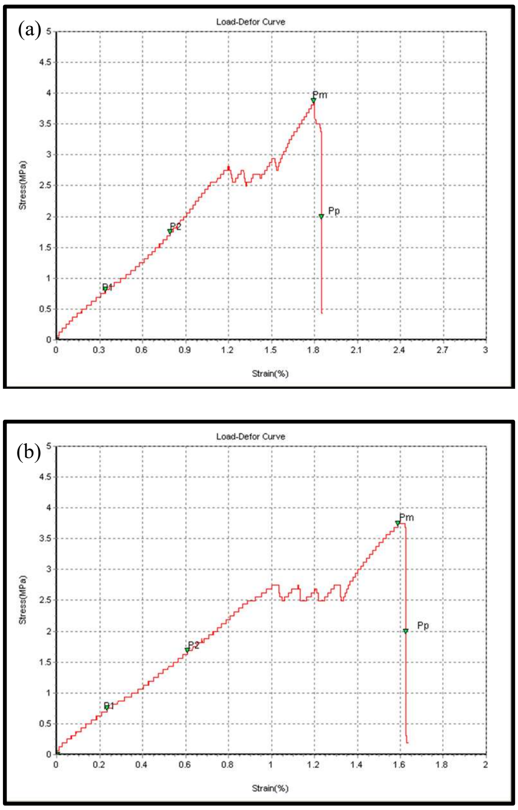


Figure 8: Stress-strain curve for #run-6, (a) Box, (b)Spiral

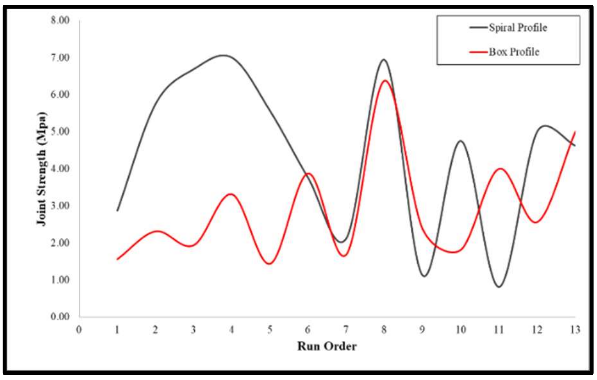


Figure 9: Joint strength curve vs. Run order

4.1.2 Weld strength

One critical factor in determining a weld's quality is the weld strength.

In many LTW studies, the welded joint strength is expressed as the shear or tensile strength of the weld (MPa), the breaking load (N) of the joint, or the weld strength per unit length of the weld (N/m) [1].

To assess weld quality, The max load of welded samples was determined by 100 kN universal testing equipment as seen in Figure 10, Higher loads imply increased joint strength and, hence, improved weld quality. To ensure consistent results, minimize misalignment and welding moment in the weld seam during lap shear testing. A welding fixture measuring 20 mm by 40 mm was used and attached to each sample for numerous iterations, as shown in Figure 2. b.

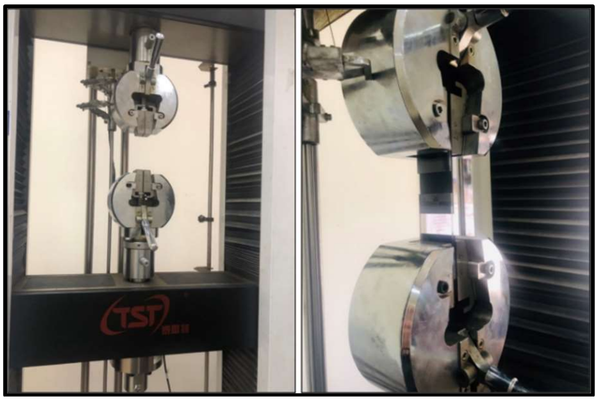


Figure 10: Universal Tensile test

Table 2 shows the experimental design with the accompanying response (Load) and the LTW process parameters established by the RSM-BBD technique for both welding profiles box and spiral; the table also presented the joint strength, computed as breaking load per unit weld area:

$$Joint\ Strength = \frac{Max\ load}{Unit\ Area} \quad (3)$$

$$Unit\ Area\ = Width\ \times Thichness \quad (4)$$

Table 2: The analyzed response and the design matrix

Run Order	Codes of BoE / BBD			Box Profile		Spiral Profile	
	V (mm/min)	P (watt)	P. No.	Load (N)	Joint Strength (Mpa)	Load (N)	Joint Strength (Mpa)
1	-1	-1	0	100	1.56	230	2.88
2	1	-1	0	195	2.31	460	5.75
3	-1	1	0	155	1.94	535	6.69
4	1	1	0	265	3.31	560	7.00
5	-1	0	-1	115	1.44	445	5.56
6	1	0	-1	310	3.88	300	3.75
7	-1	0	1	135	1.69	170	2.13
8	1	0	1	510	6.38	555	6.94
9	0	-1	-1	195	2.38	90	1.13
10	0	1	-1	160	1.81	380	4.75
11	0	-1	1	320	4.00	65	0.81
12	0	1	1	205	2.56	400	5.00
13	0	0	0	547.5	5.00	570	4.63

The failure analysis helps to increase application flexibility and accurately specify system characteristics. Two main failure modes arising during the shear testing of welded polymer components are substrate and interfacial failures. Interface failure happens when the welded joint's strength is lower than the foundation materials. A substrate failure occurs when the connection from the substrate breaks, yet the weld seam holds together [1]. Figure 11 shows the failure modes of the PMMA polymer used in this investigation.

Figure 11. a demonstrates the sample's failure at the weld interface during a tensile test; this failure mode is called (Interfacial) and happened because the bond strength is minor than the substrate strength; this failure is the most undesirable scenario. Figure 11. b demonstrates the sample's failure at the weld zone boundary during the tensile test this failure mode is named (Bulk substrate) and it has happened because the bond strength greater than the substrate strength. Figure 11. c demonstrates partial rupture at the bond contact and within the substrate, and it happened because the bond strength is approximately equal to the substrate strength.

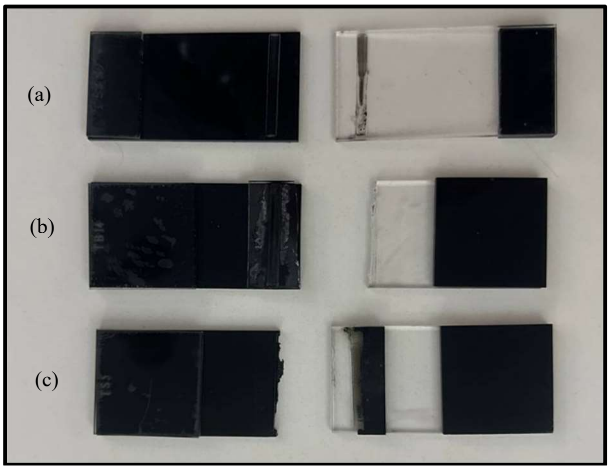


Figure 11: Samples after tensile test, (a) Interfacial failure , (b) Bulk substrate failure, (c) Substrate and interfacial failure

4.2 *Modeling results*

Minitab 19 software examines the observed responses and determines which mathematical models best suit the data. This study employed an analysis of variance (ANOVA) technique to assess the model's adequacy. It also analyzed the impact of process parameters on the selected response to develop the best-fit model. The Fisher's ratio (F-value), which can be calculated or found in the ANOVA table, was used to measure the model's effectiveness and establish the significance of any process parameter. The study's purpose was to establish if the laser power, laser scanning speed, and pass number substantially influenced the quality and accuracy of the weld. The F-test value of each parameter was compared to the standard F table value. The selected answer, the welding quality, is assessed using the selected response, such as the maximum load. Table 3 shows the results of the ANOVA for load response (F and P Values), which was performed Using a 5% significance level and 95% confidence level. To determine the importance of each given variable on the related output response(s), use the p-value in the ANOVA table. This number must be smaller than 0.05 because of this. This table illustrates the box welding profile strategy. The F-Values in this table indicate that power, pass number, and speed greatly affect the load. They were given the following F-values: 5.57, 1.22, and 0.07, respectively. The ANOVA table revealed a strong association between process factors and how they influenced process responses. According to the F-value statistics, the laser speed and pass number have the strongest association (F-Value = 94.12). This table also illustrates that the F-Values for the welding spiral strategy show that power, speed, and pass number have a greater influence on load. 221.29, 64.76, and 0.24 were the respective F-values given to them. The relationship between process factors and how they affect process responses was one of the most important conclusions drawn from the ANOVA table. The laser speed and pass number also have the strongest interaction, with an F-Value of 148.49, according to the F-Value data.

Table 3: ANOVA analysis for the load response

Source	Box Profile		Spiral Profile	
	F-Value	P-Value	F-Value	P-Value
Model	20.45	0.015	76.58	0.002
Linear	2.29	0.257	95.43	0.002
V	0.07	0.804	64.76	0.004
P	5.57	0.099	221.29	0.001
P.No	1.22	0.349	0.24	0.659
Square	21.56	0.016	76.96	0.002
V*V	0.32	0.611	0.42	0.561
P*P	41.64	0.008	63.23	0.004
P.N*P.No	0.78	0.443	180.27	0.001
2-Way Interaction	37.49	0.007	57.34	0.004
V*P	6.27	0.087	22.22	0.018
V*P.No	94.12	0.002	148.49	0.001
P*P.No	12.09	0.04	1.32	0.334

The ANOVA findings for the F-Value and the percentage contribution shown in Table 4 show that laser power has the highest influence on load (81.40%), thereafter pass number (17.16%) and laser speed (1.43%) for box profile. In contrast, laser power has a great impact (77.30%), followed by speed (22.62%) and pass number (0.08%) for the spiral profile, so the laser power has the greatest impact in the two cases.

Table 4: The Percentage Contribution of the response to the parameters

Term	Percentage Contribution Tables for (Load) response (%)	
	Box Profile	Spiral Profile
V (mm/min)	1.07	22.62
P (W)	81.11	77.30
P. No.	17.82	0.08

Figure .12 shows how the welding parameters affect the load response. It is evident from the box profile Figure 12.a that loads grow as power increases, but at high power (20–30 Watt), loads begin to drop. The load is not greatly affected by the laser speed or pass number, but Table 4 shows that the linear term V has a positive effect of around 0.07, and the constant V*V, at 0.32, also has a positive effect. Thus, we may infer that laser speed has a good overall effect. The impact of the linear term P.N. is around 1.22, suggesting a positive impact and the constant P.N*P.N. is 0.78, indicating a positive impact.

In the case of spirals, as shown in Figure 12.b., when the speed, power, and number of passes increase, the load begins to decrease at high power (20-30 Watts) and pass number (2-3). The influence of laser speed and power, as seen in the same image, has a direct (positive) effect on the load. However, the impact of the pass number is uncertain, with a favorable benefit between 1 and 2 and a detrimental effect above 2.

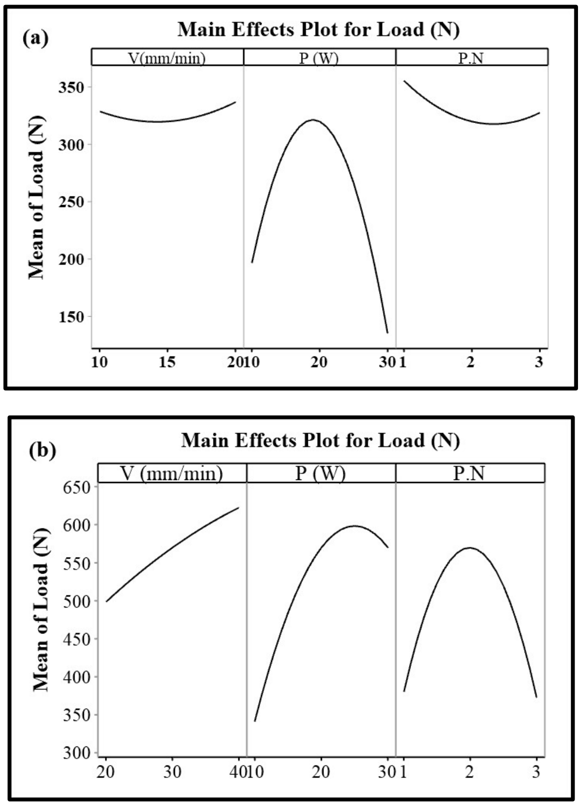


Figure 12: Main effect plots of welding settings on load for (a) Box, (b) Spiral

The mathematical models of load box and spiral welding profiles are shown in equations 5 and 6, respectively and they may be used for prediction and optimization within the same design:

$$Load(N) = 1556 - 102.8\,V + 32.2\,P - 748\,P.N + 0.513\,V*V - 1.541\,P*P + 21.6\,P.N*P.N + 0.925\,V*P + 34.87\,V*P.N + 6.25\,P*P.N \quad (5)$$

$$Load(N) = -614 - 4.44\,V + 70.06\,P + 346.2\,P.N - 0.094\,V*V - 1.144\,P*P - 193.1\,P.N*P.N - 0.512\,V*P + 13.25\,V*P.N + 1.25\,P.*P.N \quad (6)$$

4.3 *The model's validity and confirmation*

To confirm the RSM-BBD model's predictions, the expected outcomes must be contrasted with the testing data to take into account any errors that may have been made or the accuracy of the model's predictions. For the box and spiral welding profiles, Figures .13 compare the results of the experimental testing with the BBD-RSM models. The experimentally acquired values for this parameter and the expected values of load are consistent.

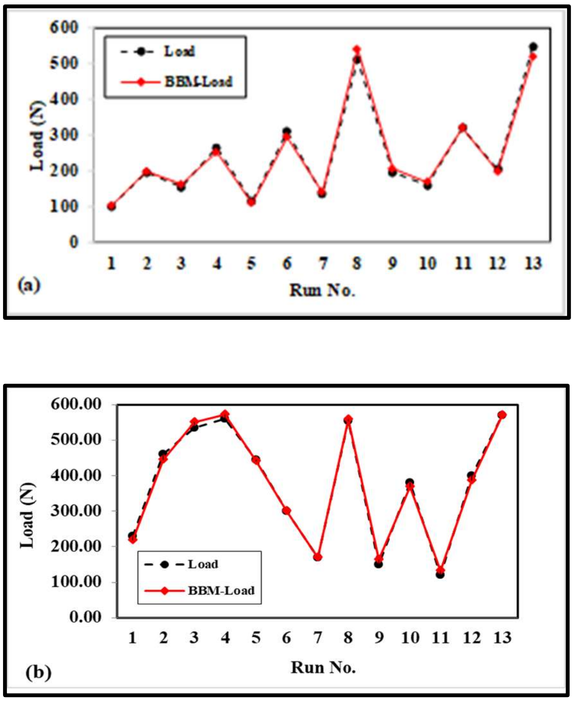


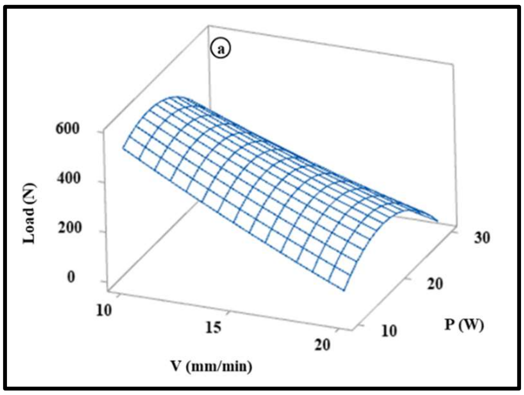
Figure 13: Comparisons between load experiments and BBD-RSM models for (a) Box, (b) Spiral

4.4 *Response to process parameter impacts*

The researchers investigated the influence of laser welding parameters, such as laser power, welding speed, and laser pass number, on the weld strength. They used Response Surface Methodology (RSM) depending on Box-Behnken Design (BBD) methodology in the experimental design to create mathematical models that show how the responses and the process parameters are related. Tensile tests were conducted after welding to evaluate the effect of the kind of joint and the weld passes on the weld stresses strain curve of the weld joint and its strength. The study found that a high laser power mixed with a slow laser speed at a single pass number might be employed to generate the high demand quantities of load. However, the maximum load may be attained by using a high setting for both laser power and speed at a multi-laser pass number.

In this study the experiments have conducted on laser transmission welding of Polymethylmethacrylate (PMMA) using two different welding path strategies: box and spiral.

Figure .14 shows the interaction effect of laser speed, laser power, and pass number on load. The load increases as laser power increases at a single pass number, as seen in Figure. 14.a. While increasing laser speed has a negative impact on load, this connection is dependent on laser power settings. At high laser power, the load is substantially more impacted by the laser speed than it is at low laser power. As the number of passes increases, the relationship between laser speed and load changes from reducing to growing; nonetheless, laser power has the same effect on the load regardless of the pass number settings., as seen in Figure. 14.b. The association between process parameters and responses is stated in Table 3, and this graphic verifies that conclusion. This led to the conclusion that a high laser power mixed with a slow laser speed at a single pass number might generate high demand quantities of load. However, the maximum load may be attained by using a high laser power and speed setting at a multi-laser pass number.



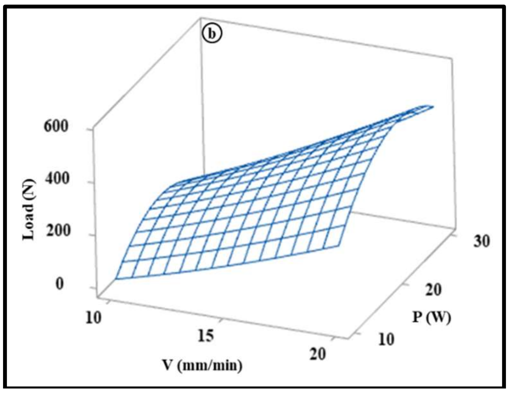
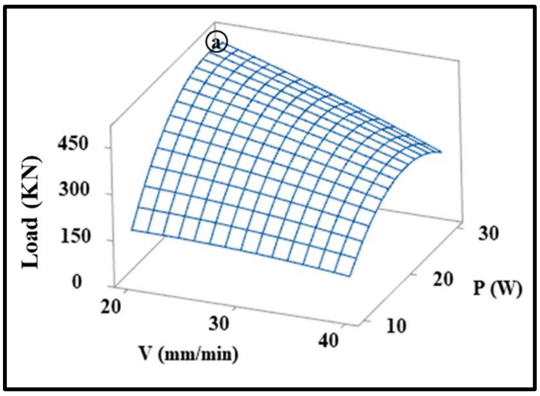


Figure 14: The effect of laser power, speed, and pass number on load for Box profile at 1 P.No. and 3 P.No.

While Figure 15 demonstrates the interaction effect of laser power, laser speed, and pass number on load for the Spiral profile strategy, Figure. 15.a shows that as the laser power increases, the load increases. Whereas increases in laser speed negatively influence load, this relationship is tied to the laser power setting settings. The laser speed has a greater influence on the load at high power than at low laser power. As the pass number increases, the connection between the laser speed and load shifts from dropping to growing. Meanwhile, laser power has the same effect on the load independent of the pass number settings. See Figure. 15.b. This result confirms the influence of interaction between process parameters on responses, as indicated in Table 3. As a result, high-demand loads might be accomplished utilizing a high laser power combined with a low laser speed at a single pass number. However, with a high pass number, the maximum load may be achieved by employing a high laser power and speed setting.



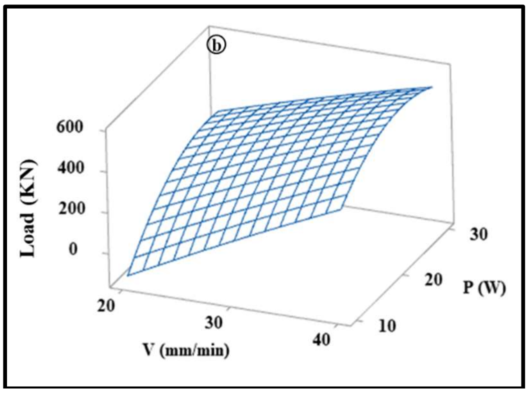


Figure 15: The effect of laser power, speed, and pass number on load for Spiral profile.

5. Conclusions

This study used RSM modeling based on BBD to evaluate the effectiveness and quality of TLW of PMMA. The impact of three variables - the response (maximum load) to the laser's power, speed, and pass number - was examined. The experimental and RSM approaches were used to calculate and assess the influence and percentage contribution of each process parameter on weld strength and stress-strain. This resulted in the following conclusions.:

1- The Box profile BBD-RSM model indicates that power has the greatest effect and percentage contribution on load (81.40%). This is followed by the number of laser passes (17.16%) and laser speed (1.43%).

2- In Spiral, power contributes the most to load (77.29%), followed by speed (22.62%), and laser passes (0.082%).

3- For Box profile LTWs, the highest joint strength can be achieved with high laser power, low laser speed, or a combination of both during numerous welding passes.

4- The spiral profile offers optimum joint strength. It was found that the LTWs products with the highest load may be achieved with the employment at a single welding pass, high laser power and low laser speed or high laser speed and power at many welding passes can be used.

5- Most trials indicate that the spiral profile results show superior welding strength compared to the box profile results with the lowest laser power, this is a result of the spiral's welding lines being closer to one another, which produces a stronger weld and closer passes.

References

[1] Acherjee, B. (2021). State-of-art review of laser irradiation strategies applied to laser transmission welding of polymers. Optics & Laser Technology, 137, 106737
[2] Acherjee, B., 2017. Selection of optimal parameters for laser transmission welding of polycarbonate using desirability function analysis. Materials Today: Proceedings, 4(8), pp.7161-7170.
[3] Acherjee, B., 2020. Laser transmission welding of polymers–A review on process fundamentals, material attributes, weldability, and welding techniques. Journal of Manufacturing Processes, 60, pp.227-246.
[4] Anwer, G. and Acherjee, B., 2022. Laser polymer welding process: Fundamentals and advancements. Materials Today: Proceedings, 61, pp.34-42. https://doi.org/10.1016/j.matpr.2022.03.307
[5] Anwer, G. and Acherjee, B., 2022. Laser Welding Innovations for Polymers and Hybrid Structures. Lasers in Engineering (Old City Publishing), 53.
[6] Bachy, B. (2017). Experimental lnvestigation, Modeling, Simulation and Optimization of Molded lnterconnect Devices (MID) Based on Laser Direct Structuring (LDS). Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU).
[7] Bachy, B., Süß-Wolf, R., & Franke, J. (2018). On the quality and the accuracy of the laser direct structuring, experimental investigation and optimization. Journal of Laser Applications, 30(2).
.
[8] Chabert, F., Garnier, C., Sangleboeuf, J., Asseko, A. C. A., & Cosson, B. (2020). Transmission laser welding of polyamides: Effect of process parameter and material properties on the weld strength. Procedia Manufacturing, 47, 962-968.
[9] Chen, Z., Zhou, H., Wu, C., Han, F. and Yan, H., 2022. A cleaner production method for laser transmission welding of two transparent PMMA parts using multi-core copper wire. Journal of Materials Research and Technology, 16, pp.1-12.
[10] da Silva, L. F., El-Zein, M. S., & Martins, P. A. (Eds.). (2020). advanced joining processes: welding, plastic deformation, and adhesion. Elsevier.
[11] Dave, F., Ali, M. M., Mokhtari, M., Sherlock, R., McIlhagger, A., & Tormey, D. (2022). Effect of laser processing parameters and carbon black on morphological and mechanical properties of welded polypropylene. Optics & Laser Technology, 153, 108216.
[12] Fernandes, F. A., Pereira, A. B., Guimarães, B., & Almeida, T. (2020). Laser welding of transmitting high-performance engineering thermoplastics. Polymers, 12(2), 402.
[13] Hassan, S. S., & Bachy, B. S. (2023). On the Laser Micro Cutting: Experimentation and Mathematical Modeling based on RSM-CCD. Journal of Engineering, 29(6), 98-113
[14] Ilie, M., Stoica, V., Cicala, E. and Kneip, J.C., 2020. Experimental design investigation of through-transmission laser welding of dissimilar polymers. In Journal of Physics: Conference Series (Vol. 1426, No. 1, p. 012045). IOP Publishing.
[15] Junke, J.I.A.O., Jihao, X.U., Chenghu, J.I.N.G., SHENG, L., Haolei, R.U. and Hongbo, X.I.A., 2023. Laser welding process and strength enhancement of carbon fiber reinforced thermoplastic composites and metals dissimilar joint: A review. Chinese Journal of Aeronautics.
[16] Kordass, T., Bachy, B., Weisser, M., & Franke, J. (2017). Laser-assisted selective activation of injection molded chip packaging devices with thermoset substrate materials for intelligent connectivity systems in automobiles. Procedia CIRP, 63, 101-106
[17] Kucukoglu, A., Yuce, C., Sozer, I.E. and Karpat, F., 2023. Multi-response optimization for laser transmission welding of PMMA to ABS using Taguchi-based TOPSIS method. Advances in Mechanical Engineering, 15(8), p.16878132231193260.
[18] Kumar, D., Sarkar, N.S., Acherjee, B. and Kuar, A.S., 2022. Beam wobbling effects on laser transmission welding of dissimilar polymers: Experiments, modeling, and process optimization. Optics & Laser Technology, 146, p.107603.
[19] Long, Q., Qiao, H., Yu, X., Liu, Y., & Wang, C. (2022). Modeling and experiments of the thermal degradation behavior of PMMA during laser transmission welding process. International Journal of Heat and Mass Transfer, 194, 123086.
[20] Mandal, R.K., Bandyopadhyay, A. and Das, S., 2014. An experimental investigation on laser beam welding of acrylics. Indian Welding Journal, 47(4).
[21] Montgomery, D. C. (2017). Design and analysis of experiments. John wiley & sons.
[22] Pereira, A.B., Fernandes, F.A., de Morais, A.B. and Quintão, J., 2019. Mechanical strength of thermoplastic polyamide welded by Nd: YAG Laser. Polymers, 11(9), p.1381.
[23] Ramachandramoorthy, R., 2011. Laser transmission welding of thermoplastic tubes and plates using laser refraction. McGill University (Canada).
[24] Shaker, F. M., AL-Khafaji, M. M., & Hubeatir, K. A. (2020). Effect of different laser welding parameter on welding strength in polymer transmission welding using semiconductor. Engineering and Technology Journal, 38(5), 761-768.
[25] Sopeña, P., Wang, A., Mouskeftaras, A., & Grojo, D. (2022). Transmission laser welding of similar and dissimilar semiconductor materials. Laser & Photonics Reviews, 16(11), 2200208
[26] Weglowska, A., 2008. Modern methods of laser-welding of plastics. Welding International, 22(2), pp.100-104.
[27] Zhou, Z., Gao, X. and Zhang, Y., 2022. Research Progress on Characterization and Regulation of Forming Quality in Laser Joining of Metal and Polymer, and Development Trends of Lightweight Automotive Applications. Metals, 12(10), p.1666.

Abbreviations

ABS	Acrylonitrile Butadiene Styrene

ANOVA	Analysis of Variance	RSM	Response Surface Methodology
BBD	Box-Behnken Design	TOPSIS	Technique for Order of Preference by Similarity to I Solution
CAD	Computer-Aided Design	V	Scanning Speed
CAM	Computer Aided Manufacturing	x	Input Parameter
CB	Carbon Black	y	Process's Responses (Output)
CCD	Central Composite Design	β	Regression Equation Constant
F-value	Fisher's Ratio	ε	Residual Error
k	Number of Variables		
LCD	Liquid Crystal Display		
LTW	Laser Transmission Welding		
Nd: YAG	Neodymium-Doped Yttrium Aluminum Garnet		
P	Laser Power		
P. No.	Laser Pass Number		
PMMA	Polymethylmethacrylate		

تقييم قوة اللحام النافذ بالليزر في لحام مادة بولي ميثيل ميثاكريلات

*سجى عدنان حسين[1] *، باسم شاهين بجاي[2]*

[1]قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بغداد، العراق/بغداد

[2]قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بغداد، العراق/بغداد

* الباحث الممثل: سجى عدنان حسين، *saja.adnan2103m@coeng.uobaghdad.edu.iq*

نشر في: 31 كانون الاول 2024

الخلاصة – تقدم هذه الدراسة دراسة تجريبية عن عملية اللحام النافذ بالليزر (LTW) لمادة البولي ميثيل ميثاكريلات (PMMA) باستخدام استراتيجيتين مختلفتين للحام: مسار لحام على شكل Box وعلى شكل Spiral. وتم فحص تأثير بارامترات اللحام الليزري، مثل قوة الليزر، وسرعة اللحام، وعدد تمريرات الليزر، على قوة اللحام بتطبيق منهجية الاستجابة السطحية (RSM) وفقاً لمنهجية تصميم Box-Behnken (BBD) في تصميم التجارب. وتم اجراء عدة تجارب اولية لإعداد النموذج الرياضي الذي يوضح كيفية ارتباط الاستجابات وبارامترات العملية وتم تقييم هذا النموذج باستخدام أداة تحليل التباين ANOVA. وتم اجراء اختبار الشد بعد اللحام لتقييم تأثير نوع المفاصل واللحام على قوة اللحام. أظهرت النتائج أنه تم إنتاج اللحامات عالية الجودة في التجربة رقم 8 (V=10 mm/min, P=20 Watt and one passes number) في اللحام نوع ال Box بينما في اللحام نوع Spiral ظهرت في التجربة رقم 4 (V=40 mm/min, P=30 Watt and two passes number).

الكلمات الرئيسية – اللحام النافذ بالليزر، مادة ببولي ميثيل ميثاكريلات، الاختبارات الميكانيكية، قوة المفصل.