SUSTAINABLE FRICTION STIR SPOT JOINING PROCESS FOR ALUMINUM ALLOY AA 4045 PARAMETER OPTIMIZATION AND MECHANICAL ASSESSMENT

M. M. Hamzah[1], S. M. Shnain[1], O. S. Barrak[2,3], S. Chatti[3*], M. A. Al-Obaidi[4]

[1]College of Engineering, Al-Iraqia University, Baghdad, Iraq
[2]Polytechnic College of Engineering – Baghdad, Middle Technical University, Baghdad, Iraq
[3]Laboratory of Mechanical Engineering, National Engineering School of Monastir, Monastir, Tunisia
[4]Technical Instructor Training Institute, Middle Technical University, Baghdad, Iraq
*Corresponding author's e-mail address: sami.chatti@udo.edu

ABSTRACT

This study aims to improve Friction Stir Spot Joining (FSSJ) parameters for AA4045 by examining their effects on energy use and mechanical strength. Also, it proposes a sustainable FSSJ strategy for AA4045 aluminum alloy through multi-parameter optimization and energy-based process evaluation. A Taguchi L9 experimental design was used to study how the rotational speed, plunge depth, and dwell time affect joint performance. Lap-shear tests showed that speeds between 900 and 1200 rpm with a plunge depth of 0.5 to 0.8 mm gave the best bonding. In contrast, a shallow plunge depth of 0.2 mm did not allow enough penetration, resulting in weak adhesion at the interface. Sample No. 9 (1200 rpm, 0.8 mm, 2 s) had the highest shear strength at 2.7 kN, while Sample No. 1 (600 rpm, 0.2 mm, 1 s) had the lowest. The sustainability assessment found that higher rotational speeds increased energy use from 0.06 to 0.11 MJ per weld, but 900 rpm gave the best strength-to-energy ratio. Life-Cycle Assessment (LCA) with ecoinvent data showed a Global Warming Potential (GWP) of 0.004–0.007 kg CO_2-eq per weld, confirming that FSSJ of AA4045 is a low-emission alternative to traditional spot welding. These findings show that FSSJ is an eco-efficient joining method for lightweight applications. This research offers a practical guide for using energy-efficient manufacturing in lightweight structures, which is important for reducing emissions in transport and supports SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). Optimised parameters not only lower environmental impact but also improve joint strength.

KEYWORDS: Friction Stir Spot Joining (FSSJ), sustainable manufacturing, Life-Cycle Assessment (LCA), AA4045, FSSJ parameters optimization, DOE

1. INTRODUCTION

Researchers are studying aluminum alloys such as AA 4045 from the Al-Si (4xxx) series because industries such as automotive, aerospace, and renewable energy require lighter, stronger materials. Aluminum alloy 4045 contains 9 to 11 percent silicon by weight, along with small amounts of iron and copper. It resists corrosion well, flows easily, and has high thermal conductivity (171W/m·K), making it useful for brazing and heat-transfer applications [1-2]. Its good wettability and low density (2.67 g/cm^3) also make it a good choice for joining and coating processes [3].

Welding is a key method for joining metals, and it influences how strong, reliable, and environmentally friendly the final product is. Traditional fusion welding methods like Resistance Spot Welding (RSW) and Gas Metal Arc Welding (GMAW) have drawbacks, including high energy consumption, distortion, porosity, and the formation of brittle intermetallic phases [4]. Because of these issues, solid-state welding methods are now more popular as greener, more environmentally friendly alternatives [5-6].

Friction Stir Spot Welding (FSSW), also known as Friction Stir Spot Joining (FSSJ), is a widely used method for joining aluminum sheets. It is environmentally friendly and uses less energy. In this process, a rotating, non-consumable tool generates frictional heat to soften the material at the joint without melting it [7].

After a brief pause, the tool is removed, creating

Date of submission/acceptance: 09.11.2025/15.12.2025 https://doi.org/10.35219/awet.2025.07

a strong bond. This technique reduces emissions and avoids common fusion issues, such as solidification cracks, because it does not require filler, shielding gas, or melting [8-9].

Many studies show that FSSW can match or even outperform RSW in mechanical properties, while using over 90% less energy [10]. It also makes manufacturing more sustainable by helping to reduce carbon emissions and use resources more efficiently [11-15]. Recent research focuses on improving FSSW's mechanical performance and energy efficiency in aluminum alloys by adjusting parameters, tool design, and process modelling [16-18].

Even with recent progress, there is still little research on the FSSJ of aluminum alloy AA 4045, especially regarding life-cycle and sustainability assessments. Although AA 4045 is often used as a brazing sheet and for cladding, it has not been widely studied for spot joining. Most previous studies have focused on alloys such as AA6061, AA2024, or AA7075 [19-21]. In addition, there is no clear link between environmental performance measures, such as energy use or CO_2 emissions, and joint mechanics, microstructure changes, and process settings [22-26].

Thus, by extending FSSJ sustainability and mechanical performance research to the less studied AA4045 alloy, the current study's findings close a significant knowledge gap. Therefore, through multi-objective process parameter optimization (tool rotation speed, dwell time, and axial force), thorough microstructural and mechanical characterization, and a sustainability evaluation based on life-cycle assessment (LCA), this study pursues to make a sustainable FSSJ process for AA 4045.

It is anticipated that the results will shed light on environmentally friendly joining techniques that balance sustainability and performance for next-generation lightweight manufacturing systems.

2. EXPERIMENTAL METHODS

2.1. Material Preparation

Aluminum alloy AA 4045 sheets with a nominal thickness of 2 mm were used for the experiment. These sheets were cut into 100 mm × 25 mm rectangular specimens. In table 1 is listed the alloy's nominal composition (in weight percentage) [1]. Because the sheets were delivered in the H14 state, a stable microstructure and an appropriate level of strain hardening were guaranteed.

To eliminate oxide coatings and impurities that could prevent bonding, all specimens were physically abraded with SiC sheets (up to 1000 grit), degreased in acetone, and washed with ethanol prior to the joining process [2].

In accordance with common configurations utilized in aluminum spot joining experiments, the joining configuration had a lap joint geometry with a 25 mm overlap between the two sheets [3].

Table 1. Chemical composition of AA4045

Elements	Si	Fe	Cu	Mn	Mg	Al
Standard ratio of AA4045	10	0.6	0.3	0.05	0.05	Bal.
Percentage of sample tested	9.78	0.59	0.0035	0.02	0.01	Bal.

Table 2. Mechanical properties of AA4045

Property of Material	Yield point σu, [MPa]	Tensile strength σy, [MPa]	Elongation [%]
Standard ratio of AA4045	64	120	3
AA4045 sample tested	79	128	7

2.2. Design of Tools and Equipment

A CNC-controlled friction stir spot joining (FSSJ) machine that can precisely control rotating speed, plunge depth, and dwell duration was used for the trials. The welding tool, which was made of H13 hardened steel, featured a short 0.3 mm probe made especially for thin-sheet joining and a cylindrical shoulder with a diameter of 12 mm. In order to support the study's goal of sustainable manufacturing, the tool design was chosen to encourage appropriate material flow and reduce excessive heat generation.

2.3. Process Parameters

There are three major process parameters were selected as a variable for optimization: Rotational Speed (A): 600, 900, and 1200 rpm; Plunge Depth (B): 0.2, 0.5, and 0.8 mm; Dwell Time (C): 1, 3, and 5 seconds. The experimental matrix was designed using a Taguchi L9 orthogonal array, which effectively balanced statistical significance and experimental cost.

To guarantee data reliability and reproducibility, each experimental condition was carried out three times. All of the parameters used by FSSJ to join the samples fall within the acceptance criteria of the spot welding procedure since they are based on the parameters mentioned in Table 3.

2.4. Welding Procedure

The specimens were positioned with a 25 mm overlap in a lap joint configuration. To prevent deformation or slippage, the lower plate was tightly fastened to the supporting plate. The spinning tool was inserted into the upper sheet at the designated depth during the FSSJ procedure, kept there for the predetermined amount of time, and then retracted. To mimic standard industrial procedure, all welds were performed in an ambient laboratory setting without the use of external cooling. Throughout each welding cycle, torque, axial force, and energy consumption were tracked and reported in real time. Figure 1 illustrates how the specimen was set up using fixtures.

Table 3. Process parameters used for joining AA 4045 by FSSJ

Sample No.	Rotational speed [RPM]	Plunge depth [mm]	Dwell time [s]
1	600	0.2	1.0
2	600	0.5	1.5
3	600	0.8	2.0
4	900	0.8	1.0
5	900	0.5	1.5
6	900	0.2	2.0
7	1200	0.2	1.0
8	1200	0.5	1.5
9	1200	0.8	2.0

Fig. 1. Joining process: a) fixtures of the specimen; b) the specimen

2.5. Mechanical Testing

To evaluate the mechanical integrity of the spot joints, lap shear tensile testing was conducted using a universal testing machine (UTM) at a crosshead speed of 1 mm/min. The failure mode and maximum load were recorded for each specimen.

2.6. Sustainability and Life-Cycle Assessment (LCA)

To include sustainability into the process evaluation, Life-Cycle Assessment (LCA) relied on data on energy consumption throughout each welding cycle as its primary input. "Cradle-to-gate" definition of the system boundaries includes tool fabrication, machine operation, and energy consumption per weld. The open LCA program and the ecoinvent database were used to conduct the LCA, which focused on three main effect categories: Global Warming Potential (GWP, kg CO_2-eq), Cumulative Energy Demand (MJ), and Resource Depletion. The results were analyzed under several process settings in order to determine the best sustainable parameter combination that balanced environmental impact and mechanical performance.

The ecoinvent datasets in this study match the process variables needed to convert measured per-weld energy use into environmental impact values. Used these datasets, along with machine operation data, within cradle-to-gate boundaries to keep LCA calculations consistent and reproducible.

3. RESULTS AND DISCUSSION

3.1. Mechanical Performance

The FSSJ joints' lap-shear test results showed a definite dependence on the chosen process parameters. The maximum shear strength was seen in sample No. 9 (2.7 KN) that having the following parameters (RPM = 1200 rpm, plunge depth= 0.8 mm and dwell time = 2 sec). At contrast side the minimum shear strength was seen at sample no. 1 which have the following welding process parameters (RPM = 600rpm, plunge depth= 0.2 mm and dwell time = 1 sec). Figure 2 shows the shear force results of the 9 specimens which are welded by FSSJ.

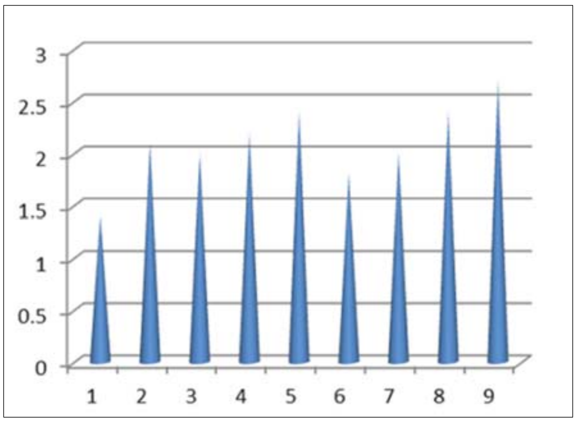

Fig. 2. Shear force results of the specimens

Because of improved plasticized material flow and appropriate intermixing between the top and lower sheets, the shear strength significantly improved when the rotational speed was increased from 600 rpm to 900 rpm and continue to 1200 rpm. Another significant factor was the plunge depth: a moderate depth (0.5 mm) created the strongest joint, while shallow penetration (0.2 mm) led to inadequate bonding.

Material expulsion, or "flash," was seen at deeper penetration (0.8 mm), which decreased the effective bonding area. By regulating the thermal exposure, the dwell time had an impact on the joint integrity. Two seconds was determined to be the ideal dwell time, striking a balance between adequate material flow and negligible over-aging effects. Figure 3 shows the main effects plot for means which indicate the effect of every process parameter on shear force. The analysis of failure revealed two major modes: (1) nugget pull-out failure, which occurred in high-strength welds joint (900–1200 rpm, 0.5–0.8 mm plunge depth), and (2) interfacial shear failure, mostly observed in weak welds joint created at shallow penetration (0.2 mm).

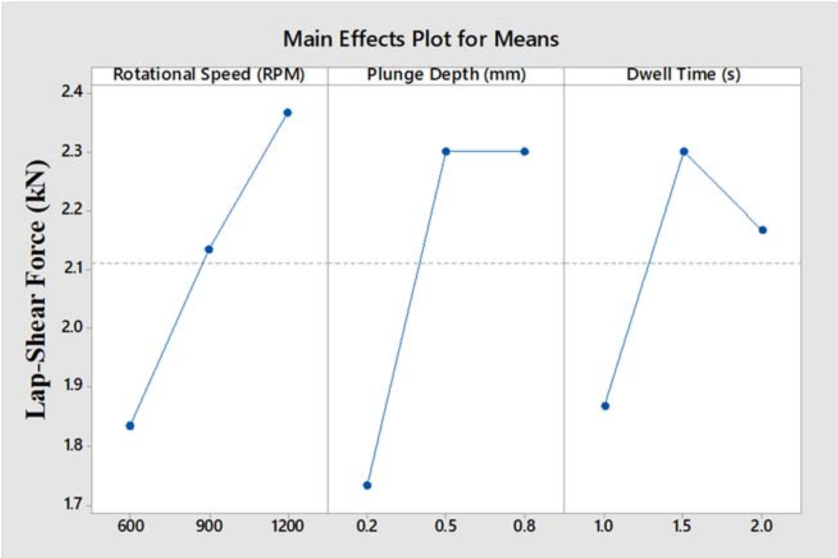

Fig. 3. The main effects plot for means

Figure 4 indicating the Minitab programs were used to analyse the shear force of the test data using the Pareto Chart of the Standardized Effect. This plot, which looks at each parameter's effect on the shear force separately. The chart shows that the plunge depth is the effective parameter then the rotational speed and then come the remaining parameters.

Table 4 indicates the Percentage Contribution of Factors of the process parameters on the joint strength by using Statistical Analysis (ANOVA).

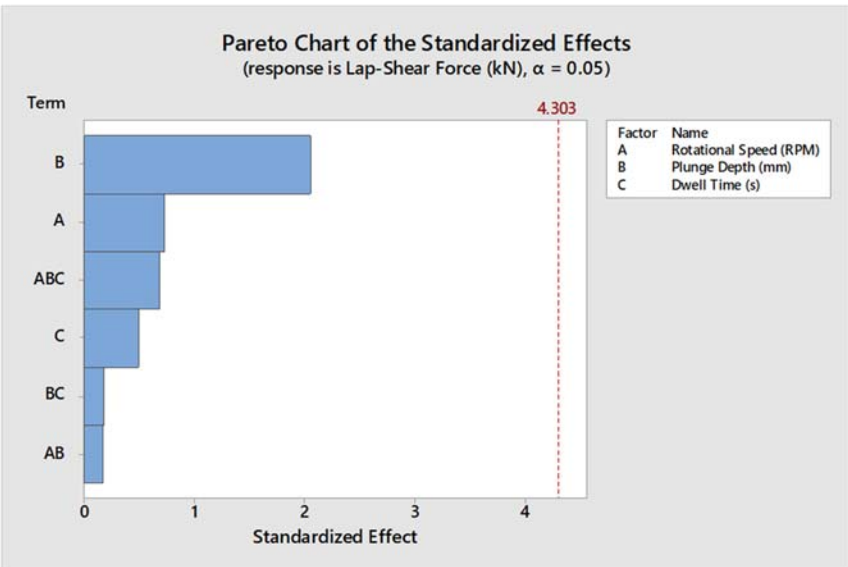

Fig. 4. Pareto chart of the standardized effect

Table 4. Percentage Contribution of Factors

Factor	Contribution [%]
Rotational Speed (A)	31.7%
Plunge Depth (B)	61.0%
Dwell Time (C)	4.0%
Error	3.3%

3.2. Sustainability and Life-Cycle Assessment

Energy consumption per weld and related environmental effect parameters were incorporated into the sustainability evaluation. Energy consumption increased linearly with rotational speed, from 0.06 MJ/weld at 600 rpm to 0.11 MJ/weld at 1200 rpm, according to measured power data. However, the 900 rpm condition had the optimum performance-to-energy ratio when taking into account both mechanical strength and energy economy.

Based on the open LCA simulation using ecoinvent data, the Life-Cycle Assessment (LCA) results indicated that the Global Warming Potential (GWP) varied from 0.004 to 0.007 kg CO_2-eq per weld. A similar pattern was seen in the Cumulative Energy Demand (CED). The modified parameters created a good balance between strength and energy use, which improved mechanical performance and reduced environmental impact. The LCA results clearly show that FSSJ is better for the environment than traditional Resistance Spot Welding (RSW).

4. CONCLUSIONS

The experimental analysis showed that plunge depth is the most important factor in joint integrity and failure mode. Rotational speed and dwell time are also important, but to a lesser extent. The optimal welding window was identified within 900-1200 rpm, 0.5-0.8 mm plunge depth, and ~2 s dwell time, producing nugget pull-out failure, which indicates strong metallurgical bonding. The maximum measured lap-shear force of 2.7 kN was produced by this combination (Sample No. 9). Enhanced material flow, better metallurgical bonding, and sufficient heat generation without excessive flash creation are all credited with the strength enhancement.

Sustainability analysis demonstrated that FSSJ can be achieved with <0.12 MJ of energy and a GWP below 0.007 kg CO_2-eq per weld, making it significantly greener than fusion-based resistance spot welding. Therefore, FSSJ of AA4045 offers a technically reliable and environmentally aligned pathway for lightweight manufacturing, especially in thermal management, automotive panels, and heat exchanger structures.

Future work should focus on fatigue durability mapping, digital process twin modeling, and CO_2-based cost–benefit integration to accelerate industrial adoption.

ACKNOWLEDGEMENTS

The Middle Technical University (MTU) provided the laboratory space and technical assistance needed to carry out the FSSJ studies, for which the authors are very grateful. We also thank the staff of the Polytechnic College of Engineering – Baghdad for their help with data collection, testing, and specimen preparation.

REFERENCES

[1] **Kaufman J. G.**, *Introduction to Aluminum Alloys and Tempers*, ASM International, 2000.

[2] *** ASM International, *Metals Handbook - Welding, Brazing, and Soldering*, vol. 6, ASM International, 2022.

[3] **Pan T.**, *Friction Stir Spot Welding (FSSW) - A Literature Review*, SAE Technical Paper, 2007-01-1702.

[4] **Ji S.**, **Wang Y.**, **Li Z.**, **Yue Y.**, **Chai P.**, *Effect of tool geometry on material flow behavior of refill friction stir spot welding*, Transactions of the Indian Institute of Metals, 2017, vol. 70, iss. 6, pp. 1417-1430.

[5] **Hamzah M. M.**, **Hussein S. K.**, *Effect of surface pretreatment on hot press lap joining of high density polyethylene to stainless steel alloy AISI 304L*, IOP Conference Series: Materials Science and Engineering, 2020, vol. 745, pp. 012058.

[6] **Ma Z. Y.**, **Feng A. H.**, **Chen D. L.**, **Shen J.**, *Recent advances in friction stir welding/processing of aluminum alloys: microstructural evolution and mechanical properties*, Critical Reviews in Solid State and Materials Sciences, 2018, vol. 43, iss. 4, pp. 269-333.

[7] **Barrak O. S.** et al., *Joining of Polymer to Aluminum Alloy AA1050 By Friction Spot Welding*, Journal of Technology, 2023, vol. 5, iss. 4, pp. 88-94.

[8] **Barrak O. S.**, **Hamzah M. M.**, **Hussein S. K.**, *Friction stir spot welding of pure copper (C11000) with pre-holed threaded aluminum alloys (AA5052)*, Journal of Applied Science and Engineering, 2022, vol. 26, iss. 8, pp. 1103-1110.

[9] **Rached S.**, **Chaabene A.**, **Chatti S.**, *Enhancing friction stir welding performance: Finite element simulation study using filler material*, Annals of „Dunarea de Jos" University of Galati, Fascicle XII, Welding Equipment and Technology, 2024, vol. 35, pp. 79-92.

[10] **Zou Y.**, **Li W.**, **Shen Z.**, **Su Y.**, **Yang X.**, *Refill friction stir spot welding of aluminum alloys: state-of-the-art and perspectives*, Welding in the World, 2023, vol. 67, iss. 8, pp. 1853-1885.

[11] **Savio Lewise K. A.**, **Raja Dhas J. E.**, *FSSW process parameter optimization for AA2024 and AA7075 alloy*, Materials and Manufacturing Processes, 2022, vol. 37, iss. 1, pp. 34-42.

[12] **Saad M. L.**, **Sar M. H.**, **Barrak O. S.**, **Hussein S. K.**, **Hussein A. K.**, *Fuzzy logic model analysis of shear force in aluminium/polyethylene lap joined by hot press*, IOP Conference Series: Materials Science and Engineering, 2019, vol. 518, iss. 3, pp. 032007.

[13] **Abduljaleel Y. W.** et al., *Compressive strength prediction of recycled aggregate concrete based on different machine learning algorithms*, Al-Iraqia Journal of Science and Engineering Research 2024, vol. 3, iss. 3, pp. 25-36.

[14] *** ASTM International, *ASTM E407-07 Standard Practice for Microetching Metals and Alloys*, ASTM International, 2023.

[15] **Sonomura H.** et al., *Interface microstructure observation for welds of an alumina ceramics and an aluminum alloy with friction stir spot welding*, Journal of the Ceramic Society of Japan, 2019, vol. 127, iss. 2, pp. 127-130.

[16] **Prabhakar D. A. P.** et al., *A review of optimization and measurement techniques of the friction stir welding process*, Journal of Manufacturing and Materials Processing, 2023, vol. 7, iss. 5, pp. 181.

[17] **Muhammad N.** et al., *Optimization and modeling of spot welding parameters with simultaneous multiple response consideration using multi-objective Taguchi method and RSM*, Journal of Mechanical Science and Technology, 2012, vol. 26, iss. 8, pp. 2365-2370.

[18] **Sar M. H. et al.**, *Friction stir spot welding (FSSW) of dissimilar aluminum alloys (AA5052 with AA6061)*, AIP Conference Proceedings, 2024, vol. 3105, pp. 020025.
[19] ***, *AWS D17.3/D17.3M Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications*, 2021.
[20] **Saravanakumar R.** et al., *Mechanical and microstructural characteristics of underwater friction stir welded AA5083 armor-grade aluminum alloy joints*, Journal of Materials Engineering and Performance, 2022, vol. 31, iss. 10, pp. 8459-8472.
[21] **Yapici G. G.**, **Ibrahim I. J.**, *On the fatigue and fracture behavior of keyhole-free friction stir spot welded joints in an aluminum alloy*, Journal of Materials Research and Technology, 2021, vol. 11, pp. 40-49.
[22] **Zhang Z. et al.**, *Sustainability in FSW-based technologies: a review*, Journal of Manufacturing Processes, 2023, vol. 85, pp. 121-138.
[23] **Abduljaleel Y. W.**, *High-temperature effects on punching shear performance of hybrid reinforced concrete slabs*, Al-Iraqia Journal of Science and Engineering Research, 2025, vol. 4, iss. 1, pp. 46-60.
[24] **Derringer G.**, **Suich R.**, *Simultaneous optimization of several response variables*, Journal of Quality Technology, 1980, vol. 12, iss. 4, pp. 214-219.
[25] **Huang C. M.**, **Romero J. A.**, **Osterman M.**, **Das D.**, **Pecht M.**, *Life cycle trends of electronic materials, processes and components*, Microelectronics Reliability, 2019, vol. 99, pp. 262-276.
[26] **Hussein A. K.**, **Barrak O. S.**, **Hamzah M. M.**, **Hussein S. K.**, *Friction stir welding AA6061-T6 with multi-objective optimization of parameters*, Advanced Science and Technology Research Journal, 2025, vol. 19, iss. 10, pp. 162-172.