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REGULAR ARTICLE

Impact of Friction Stir Spot Welding Process Parameters on Weld Strength for Similar Aluminum Alloys

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Welding of aluminum alloys is an important process used in several industries, including automobile, shipbuilding and the aerospace. Welding aluminum alloys using traditional welding methods is difficult because of a various reasons, particularly melting of aluminum; however, friction stir welding (FSW) is a non-fusion solid-state welding technique, which can prevent bulk melting of aluminum during the process, hence acceptable joining approach for aluminum alloys. Friction stir spot welding (FSSW), a form of FSW, is a potential method for creating spot connections between Aluminum alloys. The weld quality and mechanical properties are affected by tool geometry and the process parameters utilized during FSSW. In this work, the friction stir spot welding techniques of aluminum 2024-T3 are successfully carried out utilizing a welding tool made of D3 steel. This experimental work utilizes process parameter such as spindle speed of 1500 rpm, 1750 rpm & 2000 rpm with dwell time of 2s, 4s and 6s. We investigated the effects of dwell period and spindle speed on shear stress while keeping the plunge rate and depth constant. The force exerted on the FSSW tool during the welding process is also investigated for the specified dwell time and spindle speeds. The highest tensile shear force was reported for a weld formed at 2000 rpm with a dwell time of 6 seconds.

Keywords: FSW, FSSW, Aluminum Alloys, Process Parameters, Welding Tool.

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1. INTRODUCTION

A lot of attention has been paid recently to study, how vehicle parts in the aerospace and automotive industries can be made lighter by substituting relatively light material like aluminum alloys for steel. Aluminum alloys are essential in modern industries due to their performance, aesthetics, technological advancement, economic and environmental impact or government regulatory requirements regarding carbon emission [1]. Since fusion welding process can intro-duce weld defects, which reduces the quality and integrity of aluminum alloys Therefore, new and innovative welding techniques are developed, such as friction stir welding (FSW) [2] and friction stir spot welding (FSSW) [3]. For welding aluminum sheets, the fusion welding (Resistance spot welding) was replaced by FSSW by Mazda Motors [4].

Since the FSSW method is a solid state, non-fusion and environmental friendly welding process, it is recommended for welding of aluminum alloys [5]. High-strength, fatigue and fracture-resistant aluminum alloys can also be successfully welded using it [6]. Since this process occurs at a temperature lower than the melting point of aluminum, the influence of heat on the microstructure and mechanical properties of aluminum alloys is minimal [7, 8].

All improvements in FSSW are aimed to produce defect-free, high-strength welds. The tool geometry and joining approach are being studied for potential enhancements. The pin and shoulder are the fundamental components of a non-consumable welding tool, and they contribute to welding strength. Pin contributes in material flow between work-piece and mixing in the stir zone, but shoulder provides most of the friction or deformational heat required to soften the upper surface of work-piece materials [9].

The core of current advances in FSSW are modifications of these components by adding new features or eliminating geometrical properties. The classifications of FSSW of aluminum alloys are shown in Fig. 1.

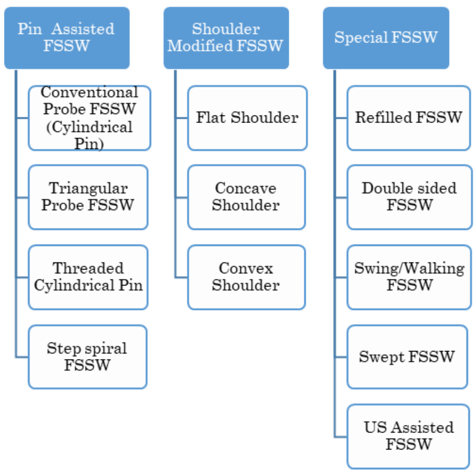

Fig. 1 – Various FSSW process developed

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It has been discovered that higher rotating speeds result in more frictional heating of the work samples [10], but high plunging rates result in insufficient ma-material churning and as a result, reduced heat generation [11]. Furthermore, the longer the dwell time, the more heat is transferred to the material [12].

The goal of the present study is to investigate the impact of rotation speed and dwell time, two key friction stir spot welding process parameters, on the shear strength of FSSW welds for aluminum 2024-T3 sheets of thicknesses of 1.6 mm and 2 mm [13-14]. The spindle speed and dwell time ranges from 1500 to 2000 rpm and 2 to 6 seconds respectively with plunging rate 15 mm/min & depth 2.3 mm has been taken in this analysis [15-16].

2. EXPERIMENTAL PROCEDURE

The base material plate with the necessary size was chosen for FSSW in lap joints. The friction stir spot welds were manufactured using a CNC linear friction stir welding machine with an in-house developed welding tool. The fracture load for FSSW welds was determined using a lap-shear tensile test on the universal testing machine (UTM).

2.1 Weld Specimens

The specimens for FSSW were cut from the aluminum alloy sheets (AA2024-T3) purchased from the standard supplier. The selected dimensions of Specimen are approximately as per ASTM E8M-13. The schematic diagram and material properties of work-piece is shown in Fig. 2 and Table 1 respectively.

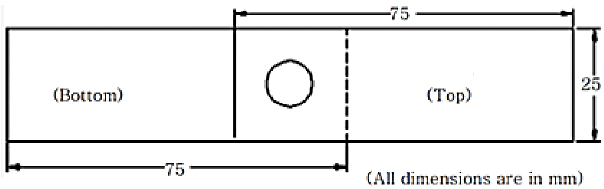

Fig. 2 – The schematic diagram of weld sample

Table 1 – Material properties (Al 2024-T3)

Mechanical properties		Chemical composition (wt.%)							
Tensile strength (MPa)	Elongation (%)	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti
435	17	93.11	0.07	0.14	4.5	0.65	1.5	0.01	0.02

2.2 Friction Stir Spot Welding Tool

A welding tool (D3 Tool steel) with a shoulder diameter of 10 mm, a pin length of 2.3 mm and a pin diameter of 3 mm was developed using a CNC Lathe machine, with tool geometry and specifications substantially identical to those previously described [17]. The characteristics of welding tool material is shown in Table 2.

Table 2 – Material properties of D3 tool steel

Mechanical properties			Chemical composition (wt.%)				
Tensile strength (MPa)	Elongation (%)	Machinability (%)	C	Mn	Si	Cr	V
435	17	45-50	2.15	0.40	0.40	12.25	0.25

2.3 FSSW Set-up and Welding Technique

The FSSW procedure was carried out using a 40 kN CNC linear friction stir welding machine. The rotational speed, feed rate, tool's forward and reverse motion and dwell time were all controlled. A visual representation of FSSW machine is shown in Fig. 3.

The welding process begins with a perpendicular downward motion of the welding tool with a preset feed rate. The tool movement continues till the shoulder touches the upper plate, after which it stirs for an extended amount of time than welding tool retracts and the welding operation is completed. The FSSW manufactured welds are shown in the Fig. 4.

Fig. 3 – CNC linear friction stir welding machine

Fig. 4 – Manufactured FSSW specimen

In this welding process, dwell time and spindle speed were set as 2, 4 & 6 seconds and 1500, 1750 & 2000 rpm respectively, while maintaining a constant plunge rate 15 mm/m and plunge depth 2. 3 mm. The forces exerted during welding process are shown in the Table -3.

Table 3 – Force exerted on tool during FSSW process

Spindle speed (revolution per minutes)	Dwell Time (seconds)	Force (Newton)
1500	2	3671.35
	4	3990.96
	6	3835.29
1750	2	3226.72
	4	3360.85
	6	3336.84
2000	2	3547.15
	4	3694.33
	6	3550.67

2.4 Measurements of Weld Strength

A Universal testing machine (UTM) with a capacity of 60 kN was used to determine the tensile force at fracture for base materials with the same dimensions as the weld specimen, and the tensile force at fracture was 24 kN for 2 mm and 14.6 kN for 1.6 mm thick sheets. To determine the tensile strength of the weld connection, a lap shear tensile test was performed in the universal testing machine.

3. RESULTS AND DISCUSSION

3.1 FSSW Tool

Heat treatment is a metallurgical process used to increase the hardness of the metal; hence developed welding tool is uniformly heated to 850 °C, and then slowly cooled, first in the furnace at a rate of 25 °C per hour to 650 °C then air cooled. This resulted in a tool hardness of 52.7 HRC; however the color of the tool surface changed from metal polish to black, as illustrated in Fig. 5.

(a) (b)

Fig. 5 – Tool (a) Before and (b) After heat treatment

3.2 FSSW of Aluminum 2024-T3

The impact of dwell time and spindle speed on force exerted during the FSSW process has been examined and illustrated in Fig. 6 and Fig. 7.

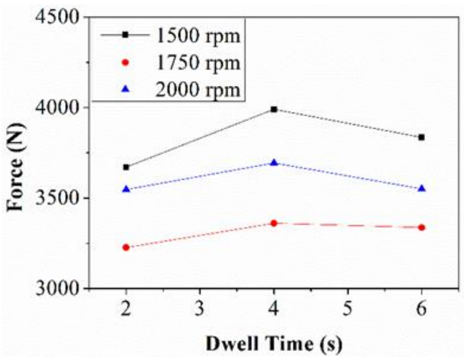

Fig. 6 – Force on the tool vs. dwell time (t = 1.6 mm)

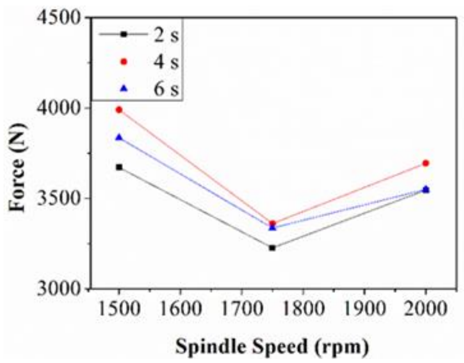

Fig. 7 – Force on the tool vs. spindle speed (t = 1.6 mm)

The graph in Fig. 6 shows that force increased with an increase in dwell time from 2s to 4s, then declined for 6s while keeping the rotational speed constant. In all three spindle speeds, the highest force value is observed with a dwell period of 4 seconds and the maximum force exerted on the FSSW tool is 3990.96 N at 1500 rpm.

Similarly, from the Fig. 7, it is observed that the force value is minimum at spindle speed of 1750 rpm and maximum at 1500 rpm for all the three dwell times.

3.3 Lap Shear Strength of the Weld

The tensile strength is determined experimentally in a universal testing machine at room temperature and the effect of dwell time and tool rotating speed on weld strength was studied. The greatest lap shear force obtained is 11.91 kN for 1.6 mm and 16.5 kN for 2 mm thick plates at rotational speed of 2000 rpm and dwell time of 6 seconds hence better weld strength achieved. Figure 8 depicts the effect of dwell time and rotating speed on the tensile force at fracture.

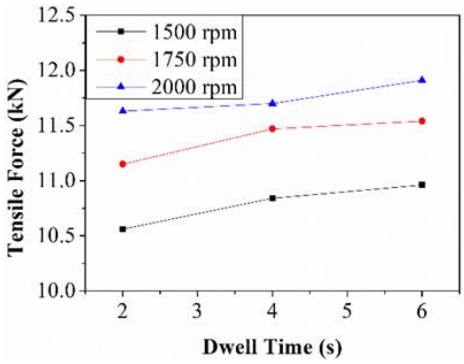

Fig. 8 – Tensile load vs. dwell time (t = 1.6 mm)

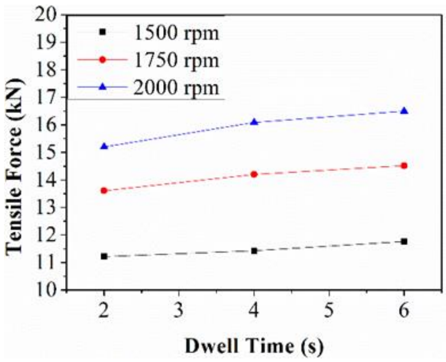

Fig. 9 – Tensile load vs. dwell time (t = 2 mm)

Fig. 8 and Fig. 9 show that the tensile shear forces steadily increases as the dwell time increases from 2s to 6s; the results are consistent with prior studies (18). It is important to remember that the upper work-piece is pressed onto the lower work-piece underneath the welding tool to start the welding process. As the temperature increases, softened materials get trapped in the weld zone between the two plates, generating a weld ring and causing the plates to fuse together to form a welded joint.

It ought to be noted that the reported tensile force at 1500 rpm is low, which could be explained by the slow rotating speed; there is minimal frictional heat produced and passed to the materials.

With increased spindle speed, the heat generated by friction increases, as does the area of the welding ring, resulting in increased weld strength. The results are similar with previous studies (19-20). It is also observed that, the weld failure of the FSSW connections is influenced by dwell time; various failure modes observed is shown in the Fig. 12.

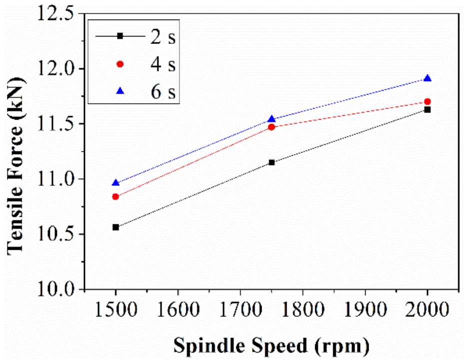

Fig. 10 – Lap shear force vs. spindle speeds (t = 1.6 mm)

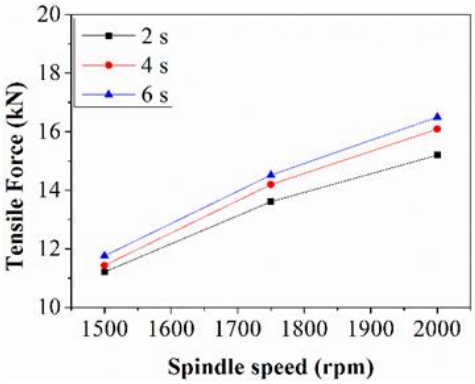

Fig. 11 – Lap shear force vs. spindle speeds (t = 2 mm)

Fracture Mode	Upper Part	Lower Part
Interfacial Shear Fracture		
Upper or Lower Sheet Fracture		
Nugget Pull out Fracture		

Fig. 12 – Different failure modes of FSSW weld

4. CONCLUSIONS

An FSSW study was undertaken to investigate the effect of welding parameters, specifically rotating speed and dwell time, on weld fracture load. Based on the obtained results, the following conclusions can be drawn:

– Increasing rotating speed and dwell time improves weld strength for the specified process parameters.

– Friction Stir Spot Welding of 1.6 mm thick plate achieves 81 % efficiency, whereas 2 mm thick sheet achieves 61 %. The tool employed may not be suitable for welding a 2 mm thick plate, resulting in poorer efficiency.

– To obtain high-strength FSSW joints, control the tool geometry and welding parameters (rotational speed and dwell time) based on the plates being welded.

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Вплив параметрів процесу точкового зварювання з перемішуванням тертям на міцність зварного шва для алюмінієвих сплавів

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Зварювання алюмінієвих сплавів є важливим процесом, який використовується в кількох галузях промисловості, включаючи автомобільну, суднобудівну та аерокосмічну. Зварювання алюмінієвих сплавів традиційними методами зварювання утруднено з різних причин, зокрема плавлення алюмінію; однак зварювання тертям з перемішуванням (FSW) — це техніка твердотільного зварювання без розплавлення, яка може запобігти об'ємному плавленню алюмінію під час процесу, отже прийнятний підхід для з'єднання алюмінієвих сплавів. Точкове зварювання тертям із перемішуванням (FSSW), різновид FSW, є потенційним методом створення точкових з'єднань між алюмінієвими сплавами. На якість зварювання та механічні властивості впливає геометрія інструменту та параметри процесу, що використовуються під час FSSW. У даній роботі успішно реалізована технологія точкового зварювання алюмінію 2024-Т3 тертям з перемішуванням з використанням зварювального інструменту зі сталі Д3. У цій експериментальній роботі використовуються такі параметри процесу, як швидкість шпинделя 1500 об/хв, 1750 об/хв і 2000 об/хв з часом витримки 2 с, 4 с і 6 с. Ми досліджували вплив періоду витримки та швидкості шпинделя на напругу зсуву, зберігаючи швидкість занурення та глибину постійними. Сила, що діє на інструмент FSSW під час процесу зварювання, також досліджується для заданого часу витримки та швидкості шпинделя. Найбільша сила зсуву при розтягуванні була зареєстрована для зварного шва, сформованого при 2000 об/хв з часом витримки 6 секунд.

Ключові слова: FSW, FSSW, Алюмінієві сплави, Технологічні параметри, Зварювальний інструмент.