

Friction Stir Spot Welding for Structural Aluminum Sheets

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ABSTRACT

The Friction Stir Spot Welding (FSSW) process is a derivative of the friction stir welding (FSW) process, without lateral movement of the tool during the welding process. It has been applied in the production of aluminum joining for various Mazda and Toyota vehicles. Most of the applications and published studies were concentrated in aluminum sheet in the range of 1.0 to 1.5 mm, suitable for non-structural automotive closure applications. The objective of this study is to study the feasibility of FSSW process for automotive structural aluminum joining, up to 3 mm in thickness, for potentially replacement of self-piercing rivets (SPR) process. Joining thicker aluminum with FSSW tooling with a typical smooth concave shoulder and threaded probing pin, requires long process time, which would not be appropriate in mass-production automotive body construction. In this paper, an innovative FSSW tool with grooved shoulder was developed. Results were demonstrated on FSSW of 2 mm 5754 alloy which reached 4 kN of lap-shear strength in 1.4 sec. Critical process parameters, including rotational speed (up to 4,500 rpm) and applied load (up to 15 kN), were studied to achieve higher joint strength and reduced process time. Cross-section micrographs were analyzed to investigate the joining mechanism. It was found that grooved-shoulder tool helped in agitating materials at interface and forming bonded joint larger and quicker

than smooth-shoulder tool. Higher rotational speed and applied load were beneficial in reducing joining time.

INTRODUCTION

Automotive companies are increasingly replacing conventional steel with advanced high strength steel (AHSS), aluminum, magnesium, and composite materials to reduce weight and, thereby, improve fuel economy. Although steel has long dominated automotive structure, aluminum alloy is not totally new to automotive manufacturing. Audi led the modern history toward aluminum for production car bodies, with their A8 luxury sedan introduced in 1994 and later, A2 in 1999. The A8 and A2 used a skeleton frame of alloy extrusions between cast aluminum joints as their basic load bearers, and covered the body with aluminum sheet skins.

Jaguar XJ, arrived in showrooms in 2003, is the first all aluminum vehicle with monocoque design. In addition to small amounts of extrusions and castings, about 85% of the body and chassis parts are aluminum stampings for the structural parts (load-bearing) and closures (non-load bearing, such as door and engine hood) panels [1,2]. Aluminum 5754 alloy was extensively used for non-cosmetic interior structure in thickness of 2 to 3 mm. Due to the difficulties of resistance spot welding (RSW) in aluminum spot joining [3,4], self-piercing rivets (SPRs)

and adhesives were the main joining processes utilized to provide both tensile strength and torsion and bending stiffness. About 3,200 rivets and 102 meters of adhesive bonding were used in XJ production.

However, SPR process is not perfect. SPR requires a supply of steel rivets, which add to the cost of the process and weight, and make recycling more complex because the steel rivets have to be removed before the aluminum can be recycled [5].

At the same time when Jaguar was using SPR and adhesives in production, Japanese auto makers were implementing a competitive technology for aluminum sheet joining – friction stir spot welding (FSSW; or spot friction welding, SFW; friction spot joining, SFJ, which are the same technology but different terminologies used by different companies). The fundamental mechanism of the FSSW process is shown schematically in Figure 1. The rotating tool with a pin at its tip, usually with a threaded pattern, is plunged into the overlapping sheets. The friction heat is generated between the tool and the work pieces and softens the work pieces. The pin, with the aid of thread, causes plastic flow of material. A strong compressive forging pressure is generated when the tool shoulder contacts the sheet surface and then moves down further into the overlapping sheets. The tool is retracted at the end of the process. At this point, a solid state bond is formed at the interface between the two sheets, shown in Figure 1. The FSSW process is a derivative of the friction stir welding (FSW) process, with the important difference being no lateral movement of the tool during FSSW [6]. FSSW has been applied in the production of automotive aluminum body panels. The most noticeable application is the production of all-aluminum rear doors and hood on the Mazda RX-8 since 2003 [7]. It also is known that Toyota uses same FSSW technology to produce the decklid and hood for Prius gasoline/electric hybrid vehicles [8]. Thin 6xxx aluminum sheets were the materials used in both cases. The thickness was between 1 to 1.5 mm. Mazda [7] has claimed the benefits of using FSSW of aluminum for RX-8 production, including reduced energy consumption, less equipment investment, no weld spatter and reduced vapor emissions as in RSW, long tool life, no foreign substances and consumables as in SPR, and short cycle time compared to SPR.

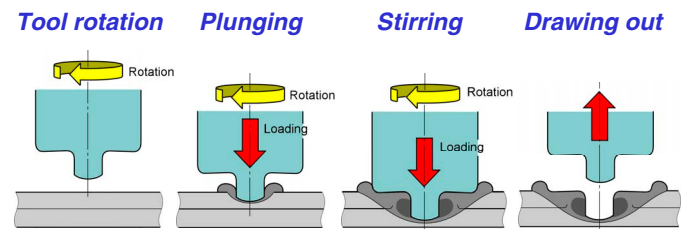


Figure 1. Schematics of FSSW process. (Courtesy of Kawasaki Heavy Industries)

OBJECTIVES OF THIS STUDY

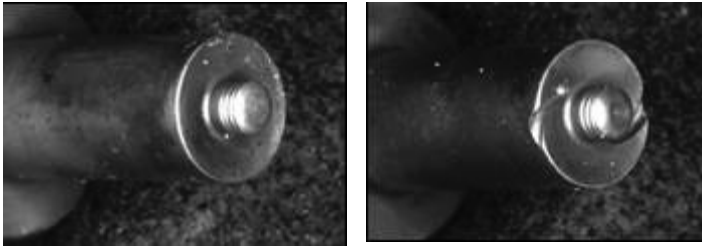
Knowing that SPR has been used in structural aluminum joining on XJ, and FSSW has been implemented in aluminum closure joining with great advantages, a question to challenge the technical community is: can FSSW be applicable for structural aluminum joining such as 2-3 mm in thickness? The objective of this study is feasibility of FSSW for 2-mm thick aluminum alloy 5754. An internal target was set to achieve a lap shear joint strength of 4 kN in less than 2 sec process time on 2mm/2mm Al 5754 [9]. As a reference, a Japanese industrial standard has specified a minimum spot weld strength of 3.2 kN for 2 mm 5754 alloy [10]. The study involves tool designs, and the process parameters, such as joining time, rotational speed and applied load.

EXPERIMENTS

TOOLS

Typical FSSW tool has a probing pin, which is used to penetrate into the specimen and a shoulder, which is used to generate frictional heat and spreads the metal in the stir zone. The shape of the shoulder, usually flat or concave, controls the material flow around the pin and shoulder. The probing pin usually has reversed (left-handed) thread which has been shown to be associated with higher strength joints [11-13].

Two kinds of tools were used in this study. One is a “benchmark” tool with a concave shoulder and reverse thread on probing pin. It has 14-degree concavity on shoulder surface, 10 mm in shoulder diameter, 3.6 mm in pin diameter, and 2.4 mm in pin length, as shown in Figure 2(a). Second tool added two additional grooves on the shoulder surface, as shown in Figure 2(b). The rest of the dimensions are the same as smooth-shoulder tool. Both were made of H13 tool steel with heat treatment to provide hardness of R_c 47~50.



(a) FSSW tool with smooth shoulder and threaded pin used as a benchmark tool (b) FSSW tool with two additional grooves on shoulder. The rest of dimensions are the same as in (a)

Figure 2. Photos of FSSW tools used in this study.

MATERIALS

NG grade aluminum 5754 sheets from ALCAN, with a thickness of 2.0 mm, were used. The material is not heat-treatable. Material properties are listed in Table 1 [14]. Lap-shear specimens were made by using two 25.4 mm by 101.6 mm (1 inch by 4 inches) sheets with a 25.4 mm by 25.4 mm (1 inch by 1 inch) overlap area. The surface contains a Cr-free pre-treatment PT2 and the forming lubricant AL070 [2]. The function of the chemical pre-treatment is to eliminate, through an etching process, the unstable oxide layer on the aluminum and to replace it with a stable chemical layer. The layer improves the long-term durability of adhesive bond, which is the production method of joining XJ body along with SPR. Both PT2 and AL070 are compatible with the adhesive used in the XJ production and are not removed in the manufacturing. Consequently, both materials were kept (not cleaned) on the sample surface for FSSW in this study.

EQUIPMENTS

Three types of FSSW equipments were used in this study, all are load-control system (as explained in [15]).

First is a robotic, production-ready, system manufactured by Kawasaki Heavy Industries (KHI), to achieve maximum applied normal load of 5.88 kN, and rotational speed of 3,000 rpm.

Table 1: Composition and mechanical properties of NG5754 alloy.

MECHANICAL PROPERTIES				
Young's Modulus (GPa)	Tensile strength (MPa)	Elongation	Hardness (HV)	
70	240	22%	63.5	
nominal composition(Balance Al)				
Si	Fe	Cu	Mn	Mg
0-0.40	0-0.40	0-0.10	0-0.50	2.60-3.60

Second is a production-ready, pedestal-type system, also made by KHI, equipped with the same 3.1 kW motor, and is capable of applying maximum load of 5.88 kN and a rotational speed of up to 4,500 rpm.

Third is a prototype system at KHI, which was used to conduct some sample preparations at 15 kN normal load and 1,500 rpm.

LAP SHEAR TESTING

Lap shear strength is a standardized way of measuring the FSSW joint strength. Specimens were tested using an Instron® model 4502 machine. The crosshead displacement was set at a rate of 10 mm per minute. No spacer was used during testing to compensate for the offset created by the lap joint. The maximum failure load or lap shear joint strength were recorded from the test.

From authors' previous experiences, the variations of the lap shear strength of FSSW aluminum samples were very small. The standard deviation was about 7% of the average strength [16] which was very good compared to typical industrial joining methods. It was decided to have no repetitive sample during the testing, since feasibility was the main focus in this study.

TEST PROCEDURES AND RESULTS

A preliminary study was carried out with a smooth-shoulder tool. Process parameters of 5.88 kN load, maximum allowed by the robotic system, and rotational speeds of either 2,000 or 3,000 rpm were applied. Figure 3 shows the results of lap shear strength of samples made with joining time between 1 to 5 sec and at 2,000 and 3,000 rpm. The results showed increased joint strength with joining time, and higher strength at 3,000 rpm vs. 2,000 rpm. Sample made at 3,000 rpm for 5 sec reached a joint strength of 3.98 kN, near the target of 4 kN. The trend of increasing strength with time is consistent with previous papers [15,17]. The strength would decrease with joining time longer than an optimal period, which was caused by excessive penetration of tool. It is apparent that the optimal strength was not achieved using smooth-shoulder tool with up to 5 sec. Longer time would be needed to further increase the joint strength. However, the long process time was not desirable.

A subsequent test was conducted using a grooved-shoulder tool at 5.88 kN applied load, and 3,000 rpm. Figure 4 shows the lap shear strength results, with joint strength increased with time, achieving 4 kN at about 2.5 sec, reaching a maximum of 4.8 kN at about 3.1 sec, then decreasing with longer joining time.