

Development of Friction Stir Clinching Process for Alclad 2024-T3 Aluminum Sheets

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ABSTRACT

A concept of combining friction stir spot welding (FSSW) and clinching, denoted as friction stir clinching (FSC), was proposed to join alclad 2024-T3 aluminum sheets. A tool, having a smooth probe and a flat shoulder, and a die, having a circular cavity and a round groove, were used to make FSC joints. The failure loads and fatigue lives of FSC joints made by various punching depths, rotational speeds, and dwelling times, were evaluated to obtain the admissible processing parameters. Optical micrographs of the FSC joints, before and after failure, were examined to understand the effects of processing parameters on the mechanical interlock and alclad layer distribution, which strongly correlate to the failure load, failure mode, and fatigue life of FSC joints. Finally, the static and fatigue performance of FSC joints made by the admissible processing parameters was obtained. The feasibility of the FSC process for alclad 2024-T3 aluminum sheets was confirmed.

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INTRODUCTION

Resistance spot welding (RSW) is the most commonly used joining technique for body-in-white parts made of steel sheets. However, RSW of aluminum sheets is likely to produce poor welds due to numerous voids and defects inside the nugget. A friction stir spot welding (FSSW) process is therefore developed for joining aluminum sheets [1,2]. Importantly, in contrast with conventional welding processes, the FSSW process makes joints without melting the base metal. A comprehensive literature review of the FSSW process can be found in Pan [3].

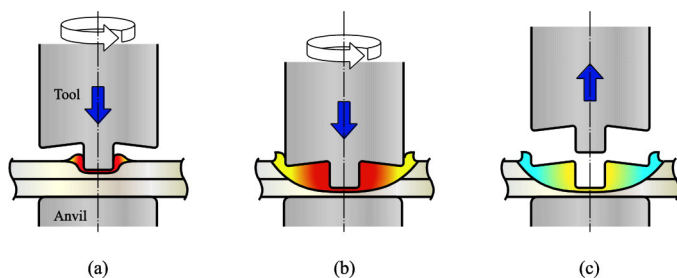


Fig. 1. Schematics of the FSSW process: (a) plunging, (b) dwelling, (c) drawing out.

As shown in Fig. 1, the FSSW process is applied to join the two metal sheets. A rotating tool with a probe is first plunged into the upper sheet. When the rotating tool contacts the upper sheet, a downward force is applied. The downward force and rotational speed

of the tool are maintained for an appropriate time to generate the frictional heat. Then, the heated and softened material adjacent to the tool deforms plastically, and a solid state bond is made between the upper and lower sheets. Finally, the tool is drawn out of the sheets.

In the aerospace and automotive industries, the surface-treated aluminum sheets are widely used to avoid the corrosion problem. Various surface treatments, such as alclading, anodizing, and alodining, are adopted for different applications. Conventionally, the solid rivets are widely used to join the surface-treated aluminum sheets in the industry since they could provide stable and reliable mechanical performance. However, the riveting process is quite time-consuming and operator-dependent due to pre-drilling and alignment of rivet holes.

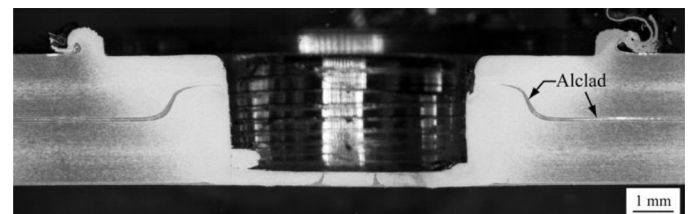


Fig. 2. A micrograph of the cross-section of a FSSW in alclad 2024-T3 aluminum alloy (AA2204-T3) sheets.

For conventional fusion welding and solid-state welding processes, such as RSW [4], FSSW, and refill FSSW/FSpW [5,6], the surface-treated layers between the upper and lower sheets can be considered as a tough and ductile barrier, which eliminates the weld strength significantly. Fig. 2 shows a micrograph of the cross section of a FSSW in alclad 2024-T3 aluminum alloy (AA2204-T3) sheets. Inside the stir zones, the alclad layers made of 1230 aluminum alloy (AA1230) cannot be stirred as small debris due to high ductility. A similar phenomenon can be seen in the stir zones of alclad AA7xxx refill FSSWs, as reported in Shen et al. [5] and Zhao et al. [6]. Note that the strength of the alclad layer is relatively low compared to that of the base metal. Thus, the fracture surface or fatigue crack tends to propagate along the alclad layer. This fact results in a poor mechanical performance for alclad AA2024-T3 FSSWs.

Recently, Swept-FSSW, a variation of FSSW, was suggested to join surface-treated aluminum sheets, reported by Tweedy et al. [7], Brown et al. [8,9] and Su et al. [10]. Su et al. [10] indicated that the surface-treated layers can be easily stirred as small debris and scattered inside the stir zone by the sweeping motion of the tool. Although the mechanical performance of Swept-FSSWs could be significantly improved, the processing time is too long compared to other spot joining processes.

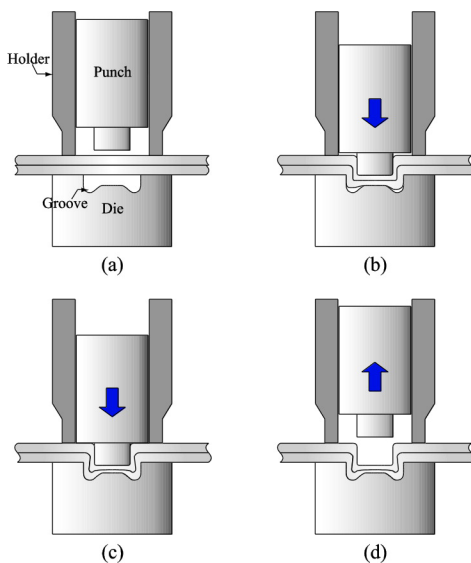


Fig. 3. Schematics of the clinching process: (a) clamping, (b) punching, (c) interlocking, (d) drawing out.

In order to overcome the aforementioned problems caused by surface-treated layers, the clinching process, one type of mechanical fastening methods, is first considered here. Fig. 3 shows the schematics of the clinching process. In Fig. 3(a), two metal sheets are clamped by a holder and a die. Then, in Fig. 3(b), a round punch presses the overlapping sheets into the die. The upper and lower sheets are severely deformed as two buttons. Note that the inner and outer buttons belong to the upper and lower sheets, respectively. In Fig. 3(c), as the downward force continuously increases, the material of the inner button is forced to expand outward and the material of

the outer button is then squeezed into the groove of the die until a given force is reached. Note that the expanded part of the inner button is denoted as undercut, which could provide strong mechanical interlock between the two buttons. Finally, the punch is drawn out of the sheets and a round clinch joint is made, as shown in Fig. 3(d).

Comparing to the other joining processes, such as RSW and FSSW, the clinch joint provides joining strength by mechanical interlock, not by fusion bonding or metallurgical bonding. Consequently, the problems caused by the surface-treated layers can be avoided easily. However, the sheet metals should be severely deformed during the clinching process. From this viewpoint, the sheet metals with low ductility, such as advanced high strength steels and high strength aluminum alloys, may not be applicable since the local high-stress areas of clinch joints could fracture easily. Additional preheating process is needed to improve the material ductility.

This work proposes a concept of combining FSSW and clinching, denoted as friction stir clinching (FSC), to join alclad AA2024-T3 sheets. A tool, having a smooth probe and a flat shoulder, and a die, having a circular cavity and a round groove, are used to make FSC joints. The failure loads and fatigue lives of FSC joints made by various punching depths, rotational speeds, and dwelling times, are evaluated to determine the admissible processing parameters. Optical micrographs of the FSC joints, before and after failure, are examined to understand the effects of processing parameters on the mechanical interlock and alclad layer distribution. Finally, the static and fatigue performance of alclad AA2024-T3 FSC joints made under the admissible processing parameters is evaluated.

FRICITION STIR CLINCHING (FSC) PROCESS

For alclad AA2024-T3 sheets, the alclad layers and the low ductility may cause many problems or difficulties for conventional joining processes. In order to overcome these problems, a new spot joining process, denoted as friction stir clinching (FSC) in Fig. 4, is proposed here to join alclad AA2024-T3 sheets based on a concept of combining the clinching and FSSW processes. In this process, the FSSW tool and the clinching die are used together to make FSC joints.

Fig. 4 shows the schematics of the FSC process. In Fig. 4(a), two metal sheets are clamped tightly by a steel holder and a die. In Fig. 4(b), a rotating tool with a probe presses the upper and lower sheets into the die. When the rotating tool contacts the upper sheet, the downward force is applied. The rotational speed and downward force of the tool are applied through the whole process to generate frictional heat. Then the heated and softened sheets nearby the tool are deformed plastically as two buttons. Note that the inner and outer buttons belong to the upper and lower sheets, respectively. In Fig. 4(c), when the tool is fed to the given depth, the materials of the inner and outer buttons are squeezed into the groove of the die and then deformed as undercut. Finally, the tool is drawn out of the sheets and a FSC joint is made as in Fig. 4(d). Note that the undercut between the inner and outer buttons can provide strong mechanical interlock

for FSC joints. In addition, under high pressure and temperature conditions, the alclad layers between upper and lower sheets can be bonded as well. The mechanical interlock and metallurgical bond of FSC joints not only overcome the aforementioned problems but also provide good joining strength.

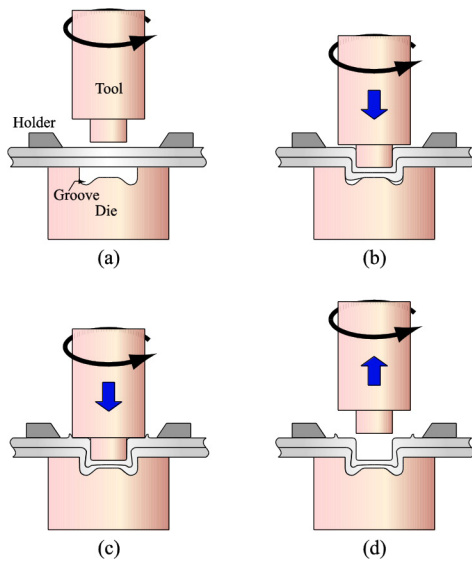


Fig. 4. Schematics of the FSC process: (a) clamping, (b) punching, (c) interlocking, (d) drawing out.

EXPERIMENTS

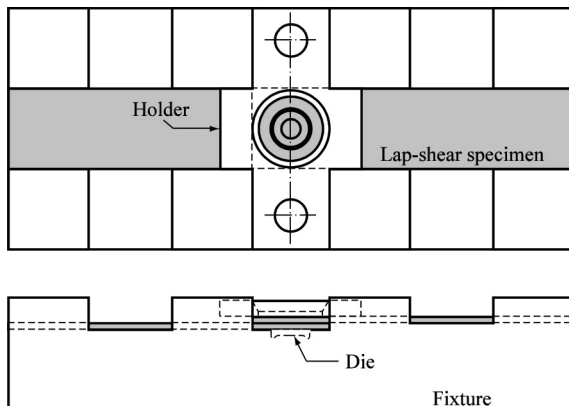


Fig. 5. A schematic of a lap-shear specimen in a fixture clamped by a holder.

Alclad AA2024-T3 sheets with a thickness of 1.6 mm were used in this work. AA1230 layers, having a thickness of 0.05 mm, were cladded on the surfaces of AA2024-T3 sheets to avoid corrosion problems. In the FSC process, a tool, having a flat shoulder and a smooth probe, and a die, having a circular cavity and a round groove, were used together. The FSC tool has a shoulder diameter of 12 mm, a probe diameter of 6 mm, and a probe length of 3.8 mm. The FSC die has a diameter of 10 mm and a nominal depth of 2.6 mm.

Lap-shear specimens were made by using two 25.4 mm by 101.6 mm sheets with a 25.4 mm by 25.4 mm overlap area. Two doublers were made by folding two square parts of the sheets near the ends (25.4

mm $\times$ 25.4 mm). During the FSC process, the lap-shear specimen was clamped by a fixture as in Fig. 5 and then joined by a CNC milling machine (Mazak AJV-25/405N) under displacement-controlled conditions.

Next, the mechanical properties of FSC joints in lap-shear specimens made by different processing conditions were examined by a MTS servo-hydraulic testing machine under quasi-static and cyclic loading conditions. Lap-shear specimens were first tested at a monotonic displacement rate of 5.0 mm per minute. The tests were terminated when specimens separated. The average failure load obtained from three tested specimens could be taken as the reference load to determine the load ranges applied in the fatigue tests. The lap-shear specimens were then tested with the load ratio R of 0.1 and the test frequency of 10 Hz. The tests were terminated when specimens separated or the displacement of the two grips exceeded 5 mm.

EFFECTS OF PROCESSING PARAMETERS ON MECHANICAL PROPERTIES

In order to check the feasibility of the FSC process for joining alclad AA2024-T3 sheets, the effects of each important processing parameter on the failure load, failure mode and fatigue life of FSC joints should be carefully examined. Similar to FSSW, the processing parameters of FSC include the punching depth, rotational speed, dwelling time and punching rate. Based on the experimental observations, the effects of the punching rate on the mechanical properties of FSC joints are quite weak compared to the other three. Therefore, only the first three parameters are considered in the following.

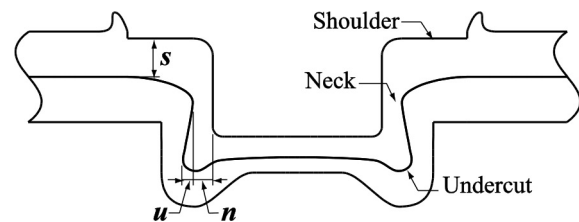


Fig. 6. Schematic of the close-up view near a FSC joint.

Fig. 6 schematically shows the close-up view near a FSC joint. The shoulder, neck and undercut of the inner button are marked by small arrows. The minimum shoulder thickness is denoted as s . The neck thickness and undercut length are denoted as n and u , respectively. Based on the research works of clinch joints [11,12], the shoulder thickness, neck thickness, and undercut length of the inner button, as shown in Fig. 6, have strong correlation with the mechanical performance of clinch joints. In addition, the above geometric parameters are strongly affected by the processing parameters. Therefore, the effects of the punching depth, rotational speed, and dwelling time on the geometric parameters and mechanical performance of FSC joints will be studied in the following. Then the admissible processing parameters for FSC joints in alclad AA2024-T3 sheets will be obtained.