Journal of Manufacturing Processes 23 (2016) 115–121

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Two-sided friction stir riveting by extrusion: A process for joining dissimilar materials

William T. Evans[a,*], Chase Cox[b], Brian T. Gibson[c], Alvin M. Strauss[a], George E. Cook[a]

[a] Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37235, United States
[b] Schlumberger, 1121 Buschong St., Houston, TX 77039, United States
[c] Oak Ridge National Laboratory, Materials Processing and Joining Group, One Bethel Valley Road, P.O. Box 2008, MS-6140, Oak Ridge, TN 37931-6140, United States

ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 28 May 2016
Accepted 1 June 2016
Available online 25 June 2016

Keywords:
Dissimilar materials joining
Aluminum steel welding
Friction stir extrusion
Friction stir spot welding
Friction stir forming
Rivet

ABSTRACT

Two-sided friction stir riveting (FSR) by extrusion is an innovative process developed to rapidly, efficiently, and securely join dissimilar materials. This process extends a previously developed one sided friction stir extrusion process to create a strong and robust joint by producing a continuous, rivet-like structure through a preformed hole in one of the materials with a simultaneous, two-sided friction stir spot weld. The two-sided FSR by extrusion process securely joins the dissimilar materials together and effectively locks them in place without the use of any separate materials or fasteners. In this paper we demonstrate the process by joining aluminum to steel and illustrate its potential application to automotive and aerospace manufacturing processes.

1. Introduction

With the development of new and lightweight materials to satisfy the demand for lighter and stronger structures and systems, there is a need for new joining methods. These new materials are being integrated into current systems, but they must interface and connect with other parts that are of a dissimilar material such as steel to aluminum. Their dissimilar nature makes joining with traditional welding methods costly or ineffective.

1.1. Background and challenges of joining dissimilar materials

FSW of aluminum and steel has been used in the manufacture of certain vehicle components such as the trunk hinge on the Mazda MX-5 [1] and the hybrid steel/aluminum sub frame introduced by Honda on the 2013 Accord [2]. While these examples are promising, there are still three major difficulties that arise in the application of the FSW of aluminum to steel: (1) the rate of wear of the FSW tool, (2) the formation of an intermetallic compound (IMC) layer at the weld interface, and (3) the difficulty of reliably creating a bond between the two metals.

Significant wear of the FSW tool can occur because of the hardness of the steel. Common tool materials used for joining aluminum wear out very quickly when in operational contact with a wide variety of steels and harder, more robust tool materials are expensive and much more difficult to machine. One way of avoiding wear is through the use of pinless tools that contact only the aluminum, or tools with short pins along with position control that keep the pin within the aluminum only [3–5].

The second issue that must be considered in joining aluminum to steel is the formation of IMC layers which can weaken the joint. Bozzi has shown that some IMC layer is necessary in traditional FSW to create a bond, but that it will weaken the joint if it is too thick [6]. Another study has shown a significant increase in strength when the IMC layer is less than 1.5 μm [7]. Watanabe has shown that the thickness of the IMC is proportional to the square root of the dwell time, so it becomes important to limit the amount of dwell time [3].

The third and greatest challenge in welding steel and aluminum is the great difference in their material properties which makes it very difficult to create a bond between the surfaces. In fact, most of the current studies attribute the majority of the strength of the weld to factors other than welding of steel to aluminum. In the

* Corresponding author. Tel.: +1 6158759438.
E-mail addresses: William.T.Evans@Vanderbilt.edu (W.T. Evans), CCox4@slb.com (C. Cox), gibsonbt@ornl.gov (B.T. Gibson), Al.Strauss@Vanderbilt.edu (A.M. Strauss), George.E.Cook@Vanderbilt.edu (G.E. Cook).

http://dx.doi.org/10.1016/j.jmapro.2016.06.001
1526-6125/

FSSW study by Lee where the probe only entered the aluminum, the conclusion was that the strength of the bond was entirely attributed to the formation of IMCs and that no mixing of the aluminum and steel occurred [5]. In another study of FSSW that penetrated into the steel layer, it was concluded that the strength of the joint was due mainly to a mechanical interlocking produced by a "hanging" section of displaced steel similar to a hook and the greatest tensile strength reached was 407 kgf [8]. Other experiments in FSW have found that the use of a zinc coated steel helps to form a stronger bond because of the better bonding between the zinc and Al due to a brazing effect of the melted zinc [4,9,10].

Other authors seeking to join dissimilar materials have attempted to bypass the material properties issue by creating preformed mechanical features such as Lazarevic for an aluminum and steel joint, Balakrishnan for joining nylon to aluminum, Nishihara with aluminum and steel, and Evans with aluminum to steel [11–14]. Yet another alternative has been proposed of introducing a third material by using a combination of friction stir welding (FSW) and riveting. Two main processes following this research have emerged called friction stir blind riveting (FSBR) as proposed by Gao [15], Min [16], and Lathabai [17] and friction-stir riveting as presented by Ma and Durbin [18]. These processes use friction stir welding to plasticize the material to be joined so that an actual rivet made of a different material can be driven into and left behind in the materials to be joined.

These three issues make the welding of aluminum directly to steel difficult and the complexity of the problems increase with the introduction of high strength alloys.

1.2. The two-sided friction stir riveting by extrusion process

This paper presents a new method of joining dissimilar materials such as aluminum and steel by applying the friction stir spot welding process to a new setup that creates a bond between multiple layers of dissimilar materials while creating a solid riveted pin at the same time. This process has been termed two-sided friction stir riveting by extrusion to help differentiate it from other processes with similar names. The result is a combination of three sheets that are joined and strengthened by a solid, rivet-like feature that joins the materials together with no additional processing needed, no weight added, no bulges, and no chance for crevice corrosion as must be dealt with when using traditional rivets.

Two-sided FSR by extrusion is here presented as an innovative method of quickly and effectively joining dissimilar materials while creating strong joints in a process that is easily implemented at minimal cost. Also, unlike other joining processes, a strong bond is achieved at every location with no missed or defective spots. Two-sided FSR by extrusion has broad applications to a variety of materials, but this study has been focused on one particularly challenging problem of joining high strength aluminum alloys and steel as these materials are widely used in many industrial and manufacturing processes.

Two-sided FSR by extrusion combines elements of friction stir extrusion (FSE) [14] and rotating anvil friction stir spot welding (RAFSSW) [19]. The FSE process is a single-sided, linear friction stir weld that extrudes material into a preformed cavity to create a mechanical interlock. Two-sided FSR by extrusion uses this idea of extruding material by friction stirring, but does so at a single spot using the two sided RAFSSW process. The setup, as shown in Fig. 1, is unique because it creates a triple lap configuration of Al/steel/Al with a predrilled hole in the steel which serves to create an area where the aluminum can be extruded and joined together. The aluminum is joined to the steel by diffusion bonding, while at the same time the process plastically deforms the aluminum within the stir zone of the top and bottom aluminum sheets and extrudes the aluminum into the preformed through hole. As it is extruded, it joins together at the junction of the two channels of extruded aluminum. This creates a solid-state aluminum joint that effectively locks the aluminum plates into the steel via the through hole. The resulting joint will join the three sheets (Al-Steel-Al) in a manner similar to a mechanical fastener such as a rivet. The final friction stir extrusion rivet is a solid, joined connection between the sheets that also prevents crevice corrosion and creates a hermetic seal.

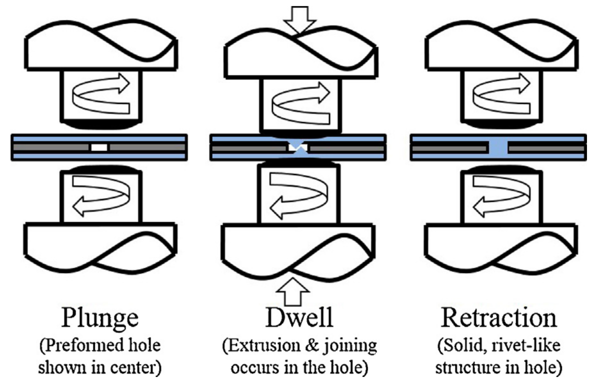

Fig. 1. Two-sided friction stir riveting by extrusion process.

1.3. Joining tools

The two-sided FSR by extrusion process uses two pinless FSSW tools which feature a convex taper with scroll-like features that are cut into O1 tool steel and then hardened. The extrusion tool has a maximum overall diameter of 25.4 mm and features a scrolled, spherically tapered (convex) shoulder and a 10.2 mm flat as pictured in Fig. 2.

1.4. Sample preparation

For all experiments, 1 mm Al 6061 was used for the top and bottom aluminum plates and 1.5 mm low-carbon steel for the middle steel plate. The aluminum was in the T6 heat treated condition exhibiting a yield strength of 276 MPa, Rockwell hardness B 60 and the low-carbon steel had a yield strength of 413 MPa and Rockwell hardness B 80. Initial samples were prepared without a through hole to determine the baseline strength of the aluminum/steel bond. For the rest of the samples, the center of the extrusion/welding zone was marked and a through hole was punched into the steel plate. The effect of dwell time, hole size, and number of holes was explored by varying these parameters. The diameters of the hole sizes chosen for the single hole samples were 2.38 mm, 3.18 mm, 3.97 mm, 5.56 mm. For the two and three hole samples, a hole size of 3.18 mm was chosen. There was a

Fig. 2. Pinless FSSW tool with a spherically tapered shoulder.