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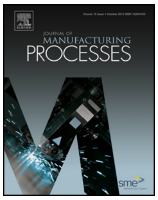

Technical paper

A method for double-sided friction stir spot welding

Chase D. Cox[a,*], Brian T. Gibson[a], David R. DeLapp[a], Alvin M. Strauss[a], George E. Cook[b]

[a] *Department of Mechanical Engineering, Vanderbilt University, 2400 Highland Avenue, 101 Olin Hall, Nashville, TN 37212, United States*
[b] *Department of Electrical Engineering and Computer Science, Vanderbilt University, 400 24th Avenue South, 254 Featheringill Hall, Nashville, TN 37212, United States*

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ABSTRACT

A rotating anvil similar to a pinless friction stir welding (FSW) tool can be applied to friction stir spot welding (FSSW) of thin metal plates. FSSW is a solid-state joining process that is currently being used by automotive manufacturers as an alternative to rivets and traditional resistance spot welding. The principal detractor of this process is the keyhole left by pin extraction, which can be detrimental to the weld strength. A pinless tool can be used to eliminate the keyhole. However, this approach is limited to joining thin sheet ($\leq$1 mm). Using a rotating anvil with the FSSW process permits the joining of thicker cross sections, improves the mechanical strength of the spot weld and reduces the reaction forces on the spot welding frame. A numerical model of the process, tensile shear tests and macrosection analysis are used to evaluate the spot welds.

Macrosection and numerical analysis reveals that the material flow between the pinless tool and rotating anvil is complex and unique to this process. It has been found that the use of a rotating anvil for FSSW is a viable means to create quality spot welds in thicker weldments.

1. Introduction

Automotive manufacturers are facing challenging issues related to creating light weight automobiles in an effort to improve fuel economy. One approach to reducing the weight of their vehicles is to use lighter materials in the design of the structure such as aluminum in lieu of steel. However traditional joining processes such as resistance spot welding are difficult to implement on metals like aluminum due to their higher thermal conductivity. Using technologies like self-piercing rivets affords manufacturers some of the same advantages of FSSW but adds to the overall complexity and weight of the design and increases the overhead for production.

Friction stir welding (FSW) was invented by Wayne Thomas at The Welding Institute (UK) in 1991. As a solid-state joining process capable of joining light-weight metals with lower melting points, FSW quickly received the attention of many researchers around the world. Friction stir spot welding (FSSW) is a more recent application of the FSW process. The initial development of FSSW was performed by Sumitomo Light Metal Industries, Ltd., Mazda, Kawasaki Heavy Industries, Ltd., and Norsk Hydro. In 2003, Mazda implemented FSSW in the assembly of the rear door panel of their RX-8, the first noted application of the process [1].

In FSSW, the joint is created by plunging a rotating tool into a weldment until the welding tool's shoulder reaches a desired penetration depth. It will remain at this plunge depth for a specified length of time, at which point the tool is retracted. Unlike fusion welding, FSSW does not melt the parent material, require consumables such as filler rod, shielding gas, or welding sticks, and uses 99% less energy to create the weld [2]. For these reasons FSSW can be considered a "green technology". The FSSW process can be characterized by three main parameters: rotation rate, plunge depth, and dwell time. Compared to the multitude of parameters involved in resistance spot welding, FSSW presents the operator with a simpler, more controllable process.

One identified drawback of this process is that the welding tool leaves a keyhole (the size of its dynamic volume) in the spot weld during retraction that requires removal via either post-processing or costly, highly specialized tool design (Fig. 1). On such method is the refill FSSW process developed by GKSS in 2003. In refill FSSW, a purpose-built machine is used to create a spot weld without a keyhole that is nominally flush with the original workpiece surface. This is accomplished by actuating the three components of the system, a clamp ring, shoulder, and pin, independently during welding. The process begins with the clamp firmly holding the weldment in place. The rotating shoulder then makes contact (the probe at this point is completely retracted) and begins to heat the workpiece. Once the temperature of the workpiece is sufficient for welding, the probe is extended into the workpiece. As the probe penetrates the workpiece, the shoulder retracts enough to create a

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* Corresponding author. Tel.: +1 6153223322.
E-mail address: Chase.D.Cox@Vanderbilt.edu (C.D. Cox).

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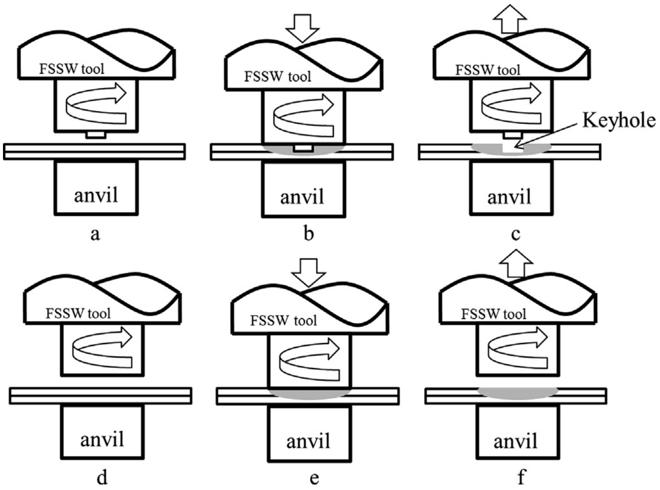

Fig. 1. The friction stir spot welding process. (A–C) Traditional FSSW process using a tool with a pin. The resulting keyhole defect is illustrated. (D–F) FSSW process using a pinless tool. The lack of the keyhole defect is illustrated.

reservoir that will allow for the material displaced by the probe to be contained. When the probe retracts the shoulder is lowered back toward the workpiece, forcing the expelled material back into the weld zone, filling the keyhole. The weld is completed when the pin is completely retracted back into the shoulder. Alternatively, pinless tool designs have been identified in the literature as a low-cost alternative in this situation [3,4]. However, the pinless tool design is limited by the thickness of the weldment in which it can create a spot weld of good quality ($\leq$1 mm).

It is commonplace in the FSW community to utilize a double-sided tool design for welding. The inclusion of a pin on these double-sided welding tools may have prevented this application from being implemented for spot welding. Using a pinless tool in a double-sided welding configuration may present a means to increase the thickness of the weldment used in FSSW. Traditionally in FSSW, the anvil (Fig. 1) is used to support the massive forging loads incurred during welding. For the proposed double-sided spot welding method (rotating anvil for friction stir spot welding) the anvil will be rotated during welding.

In this study a computational fluid dynamic (CFD) model is created to examine how the use of rotating anvil in FSSW may affect the spot welding process. A rotating anvil is designed, implemented and evaluated on the FSSW machine located in the Vanderbilt University Welding Automation Laboratory (VUWAL). The results of the CFD model and experimental tests are presented using macro-section analysis and tensile shear tests.

2. Numerical model

A 2-dimensional axisymmetric computational fluid dynamic model was created to simulate the RAFSSW process using COMSOL. Two workpieces of different thicknesses are considered in two separate simulations; a 2 mm thick solid disk with a radius of 14 mm and a 4 mm thick solid disk with a radius of 28 mm. The workpieces in the simulations represent 1 mm and 2 mm thick plates in a lap joint configuration. In Fig. 2 it can be seen that contact condition between the tool and rotation anvil are simulated to be plunged 0.13 mm beneath the top and bottom surfaces of the workpiece. The simulation is performed in two successive steps. A transient thermal model is created to simulate the temperatures within the workpiece during welding. The temperature dependent material flow field is then computed for a specified instance in time. For simplicity, material deformation associated with plunging the welding tool into the workpiece is not considered. Additionally, the workpiece is restricted from any out-of-plane deformation and the model will not account the formation of weld flash, hooking defects or lack of bonding. The material simulation will be used in this application to better understand the flow characteristics within the stir zone during FSSW when using a pinless tool.

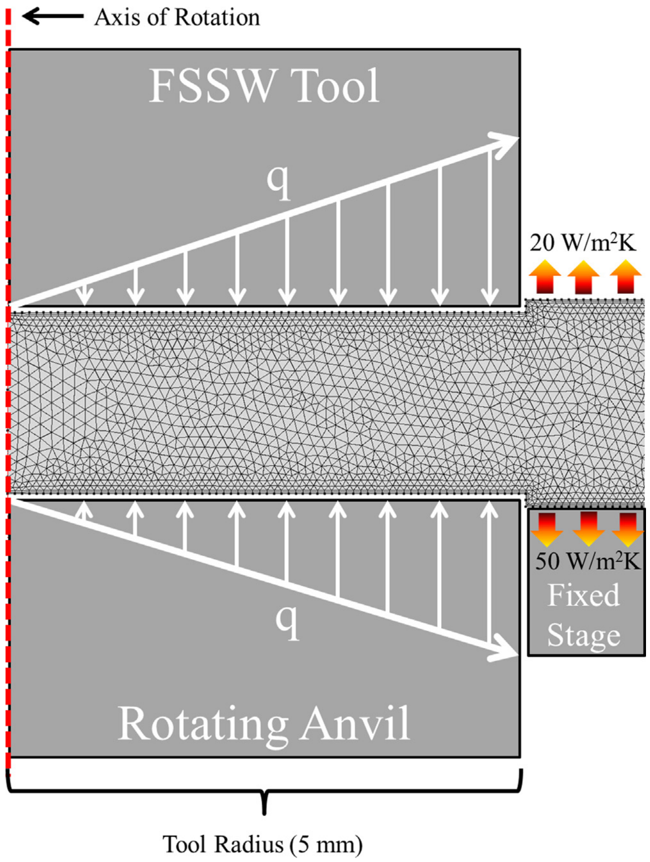

Fig. 2. Thermal boundary conditions and mesh used for the workpiece in the FSSW simulation.

2.1. Thermal model

The FSSW tool and rotating anvil are modeled as a heat flux boundary condition for both thermal simulations; they are not physically modeled in order to improve computation time. The effective diameter of the tool (length of the boundary is 5 mm) is 10 mm. The heat flux across the tool/workpiece and rotating anvil/workpiece boundary was adjusted to be at its maximum value at the edge of the tool and a minimum value at the center of the tool. The power input into the weld can be determined using the rotational speed of the tool and the weld torque

$$P = M \times \omega \tag{1}$$

where P is the weld power (W), M is the weld torque (Nm), and ω is the welding tool's angular velocity (rad/s) [5,6]. A rotational rate of 1000 rpm was used for both the welding tool and rotating anvil. A previously obtained experimental torque (single-sided FSSW) value of 27.8 Nm (obtained using 1000 rpm, 3 s dwell) is used, resulting in a calculated heat input of $\approx$2900 watts for both the welding tool and rotating anvil. The heat input was distributed across the weld interface between the welding tool and workpiece as well as the boundary between the rotating anvil and workpiece by applying the heat locally in proportion to the local tangential velocity. The initial workpiece temperature before welding is set to be 293 K. The heat input along the tool/workpiece and rotating