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Technical Paper

Energy input during friction stir spot welding

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ABSTRACT

Friction stir spot welding is performed on thin plates of an aluminum alloy. This paper presents the results on how the number of tool rotations affects the quality of the resulting spot weld. Different combinations of rotation rate and dwell time are investigated. A linear relationship was found to exist between the number of tool rotations completed during the spot weld and the resulting tensile shear strength. Spot welds that only completed 10 rotations were 177% stronger than those created at 50 tool rotations. The energy generated during the welding operation was quantified and also found to have a linear relationship with tensile shear strength. A modified open-loop position control system is proposed that monitors and limits the energy generated during friction stir spot welding by adjusting the dwell time.

1. Introduction

Rising fuel costs have placed a demand on automobile manufactures to produce vehicles with better fuel economy. One approach to achieve this goal is to replace structural and cosmetic components in the vehicle made of steel with lighter aluminum alloys. However traditional spot welding processes can prove problematic when joining metals like aluminum. Friction stir spot welding (FSSW) is a solid-state joining process capable of joining lightweight metals with high thermal conductivity such as aluminum, making it an attractive process for manufacturers. In FSSW, the joint is created by plunging a rotating tool into a weldment until the tool's shoulder reaches a desired penetration depth. It will remain at this 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 [1]. For these reasons FSSW can be considered a "green technology". Technologies like self-piercing rivets can afford manufacturers some of the same advantages of FSSW but adds to the overall complexity and weight of the design and increases overhead for production.

Several parameter studies have been performed in FSSW in order to quantify the effects they have on the quality of the spot weld. Karthikeyan et al. investigated the effects rotation speed, plunge speed, plunge depth, and dwell time have on the strength of the spot weld. They concluded that the plunge rate was the most critical factor in determining weld quality, followed by plunge depth, dwell time, and tool rotation speed [2]. The inclusion of a pin in the welding tool design makes the plunge rate an important process parameter. The additional time required to plunge the rotating welding tool into the workpiece can generate too much heat such that the quality of the weld is negatively affected before the spot weld is even formed. In this study a pinless FSSW welding tool will be used. Tozaki et al. found that increasing the rotation rate from 1000 rpm to 2000 rpm was detrimental to the quality of the spot weld. Tozaki also reports that for a given rotation rate there exists an optimal dwell time for creating a quality spot weld [3]. The combination of rotation rate with dwell time can instead be considered in terms of tool rotations. Previous work found that welding at higher rotation rates (1500–2000 rpm) and long dwell periods (4–6 s) resulted in a weld zone that was too hot and prone to defect formation [4].

It is the primary objective of this work to understand how many tool rotations it takes to create a friction stir spot weld in an aluminum alloy. Understanding this relationship could be a critical step for the advancement of FSSW in manufacturing. The secondary objective of this work is to quantify the energy generated during

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Table 1
Experimental welding parameters.

RPM	Dwell time (s)	Tool turns	Plunge rate (mm/s)	Plunge depth (mm)
800	0.75	10	0.21	0.2
1200	0.5	10	0.21	0.2
1200	1	20	0.21	0.2
1600	0.75	20	0.21	0.2
1800	1	30	0.21	0.2
1200	1.5	30	0.21	0.2
1600	1.5	40	0.21	0.2
1200	2	40	0.21	0.2
1500	2	50	0.21	0.2

welding for the purpose of identifying a process parameter that may be related to weld quality.

2. Experimental

Spot welds are made using 1 mm × 50 mm × 76.2 mm sheets of Al 6061 T6. A lap joint configuration is used to create the weld joint. The spot welding parameters are listed in Table 1. Combinations of rotation rate and dwell time were selected such that spot welds would be made with 10, 20, 30, 40, and 50 turns of the welding tool. A constant plunge depth and plunge rate of 0.2 mm and 0.21 mm/s respectively are used for each spot weld.

One identified drawbacks of this process is that the tooling leaves a keyhole (the size of its dynamic volume) in the weld during retraction that requires removal via either post-processing or costly, highly specialized tool design. As such, pinless tool designs have been identified in the literature as a low-cost alternative in this situation [5,6]. In this work, a pinless FSSW tool is used. The spot welding tool is made from O1 tool steel and is then hardened. The welding tool has a maximum overall diameter of 25.4 mm (1 in.) and features a scrolled, spherically tapered (convex) shoulder of 76.2 mm radius with a 10.2 mm flat (Fig. 1a). During spot welding the workpiece is rigidly mounted to a backing anvil. A macrosection of a spot weld made using this tool design can be seen in Fig. 1c.

The spot welding experiments are conducted using a modified Milwaukee Model K milling machine which is retrofitted with advanced motors and instrumentation. The weld control computer executes the FSSW routine by simultaneously sending the welding parameters to both the vertical drive and spindle motors. The control computer interfaces with the vertical drive motor via a Compumotor KH Brushless Servo Drive and with the spindle motor via a Cutler-Hammer SVX9000 variable frequency drive. As the vertical servomotor begins to raise the welding stage, the control system monitors the vertical position of the spot welding sample. At the same time the spindle begins to rotate. Once the spot welding tool reaches the desired plunge depth within the weld sample the vertical motion of the table is halted. After the specified number of tool turns is completed, the welding stage is lowered and the spindle rotation is stopped (Fig. 2). During spot welding the spindle torque and axial force are monitored via a custom built wireless force dynamometer. The quality of the resulting spot welds is evaluated using tensile shear tests. The tensile shear tests are performed on the as welded joints such that the loading direction is parallel to the original joint line using a cross head speed of 5 mm/min.

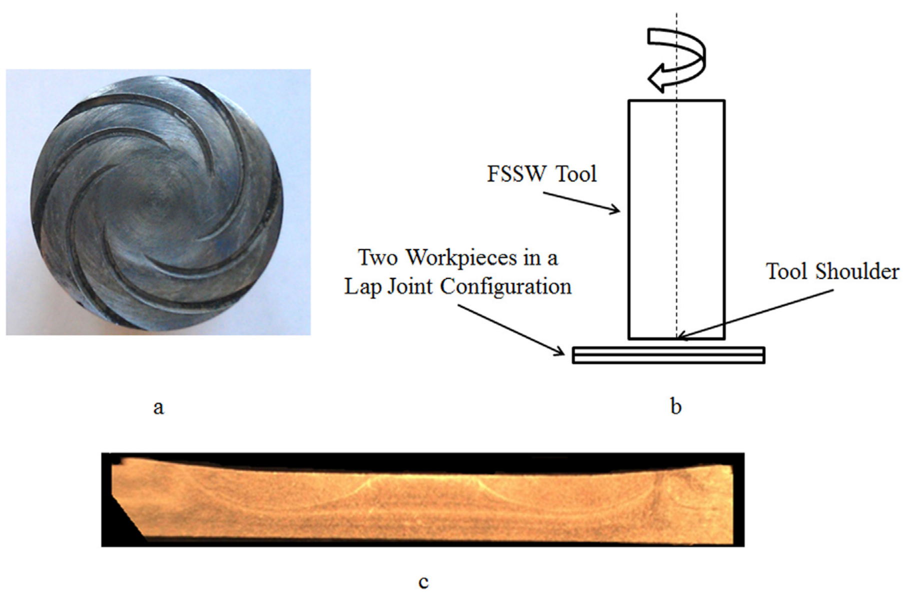

Fig. 1. (a) Pinless FSSW tool with a spherically tapered shoulder. (b) Diagram of the FSSW tool and workpiece orientation. (c) A macrosection of an FSSW spot weld made with good quality.

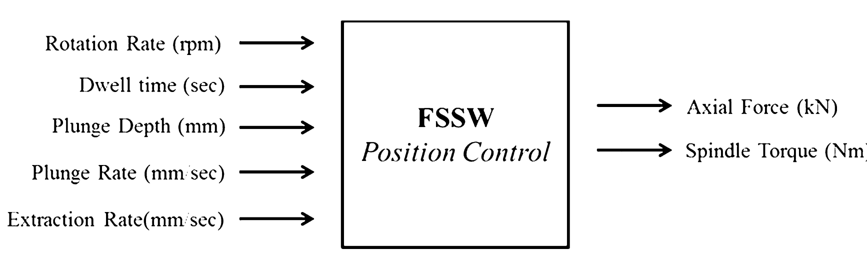

Fig. 2. Open-loop position control system used for this experiment. The rotation rate, dwell time, plunge depth, plunge and extraction rates are inputs. The plunge depth and dwell time are the limits in this system. The resulting axial force and spindle torque are monitored during welding.