Spot Friction Welding for Sheet Aluminum Joining

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Abstract

Spot friction welding (SFW) is a new, solid-state spot joining process. It uses a rotating tool with a probe pin plunging into the upper sheet and a backing anvil beneath the lower sheet supporting the downward force. The rotating tool generates friction heat in the specimens. Then, heated and softened material adjacent to the tool deforms plastically, and a solid state bond is made between the surfaces of the upper and lower sheets. In this experiment, a displacement control methodology was studied. The pin tool, rotating at a constant speed, plunges into 6111-T4 specimens, 0.94 mm in thickness, in a lap-joint configuration. When a pre-determined insertion depth is reached, the process stops and the pin retracts. Various tool pin plunge depths, from 1.6 to 1.9 mm, were examined. The lap-shear strength of spot friction welded samples started low at the shallowest insertion depth, increased to a maximum value of over 3 KN at about 1.8 mm depth, then dropped to lower strength when the insertion depth was deeper. Test samples showed a failure mode of interfacial separation at shallow insertion depths, to a nugget-pull mode at the highest strength, then changing to a perimeter failure when the insertion was the deepest. In a second experiment, an embodiment was included on the surface of the anvil to make a decorative imprint on the surface of the lower sheet underneath the friction spot joint. This imprint can be applicable to a design feature, identification, and/or an effect of the joint strength.

Spot friction welding process

Similar to linear friction stir welding (FSW), spot friction welding (SFW) uses a cylindrical tool with pin tip centered on one circular face. The tool rotates circumferentially at room temperature and plunges into the sample to be joined with a normal force. There is a backing plate or an anvil on the bottom side of the sample to sustain the normal force. Unlike the linear FSW, which moves in the transverse direction to form a continuous linear joint, the SFW tool is not translated. Instead, it is retracted from the workpiece when the stirring process is finished at the particular spot. The process is schematically illustrated in Figure 1, and the cross-section of the metal stir zone is illustrated in Figure 2. The contacting metal interface is obliterated by the effects of heat and deformation caused friction from the rotational tool, and this forms a joint. The shaded area in Figure 2 corresponds to the stirred zone.

Within the parameters used to control the spot friction welding process, the most critical ones are tool rotational speed (rpm), process time, the normal load applied on the tool to the sample, tool insertion depth into the sample, and tool insertion rate into the sample. Surface details on the tool shoulder and pin may also be important. However, the most common design, with a cylindrical shank and a projection tip with smooth surfaces, is usually sufficient.

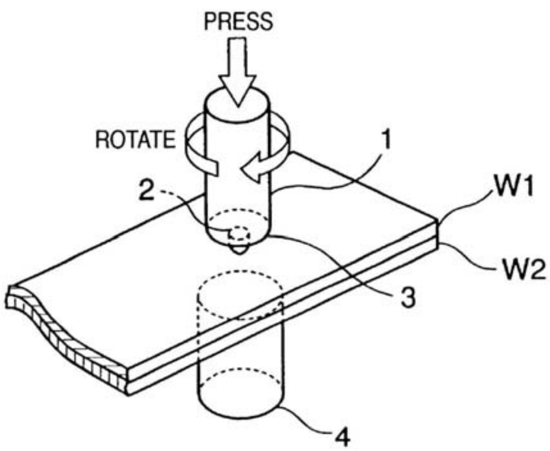


Figure 1: Spot friction welding process, with a rotational pin stirring from the top and a stationary anvil at the bottom. [1]

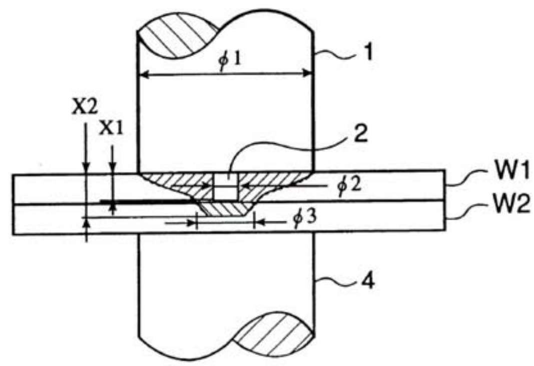


Figure 2: Spot friction welding pin tool and stirred zone in material to be joined. [1]

SFW machines can be designed with complex control systems to incorporate the above mentioned parameters. However, the controls of the process can be categorized into two major modes of operation: (1) displacement control (2) load control.

Figure 3 illustrates schematically the basic operation of a displacement-controlled SFW process. After the tool starts rotating, it is driven into the sample at a controlled plunging rate to reach a pre-determined maximum depth. The process then stops and the tool retracts. The normal force, recorded as an output starts with a relatively low value when the pin initially plunges into the sample, then it increases to a higher value when the shoulder of the tool touches the sample.

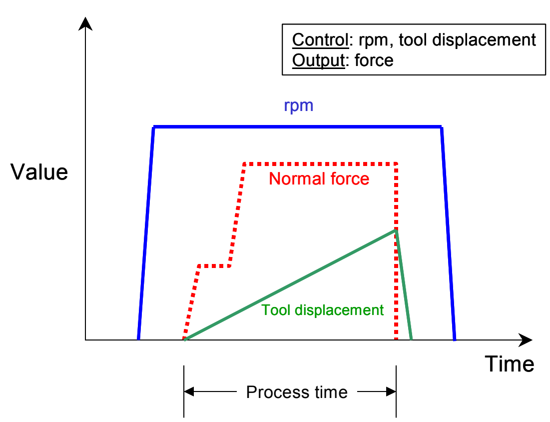


Figure 3: Schematic diagram of a displacement-controlled spot friction welding process.

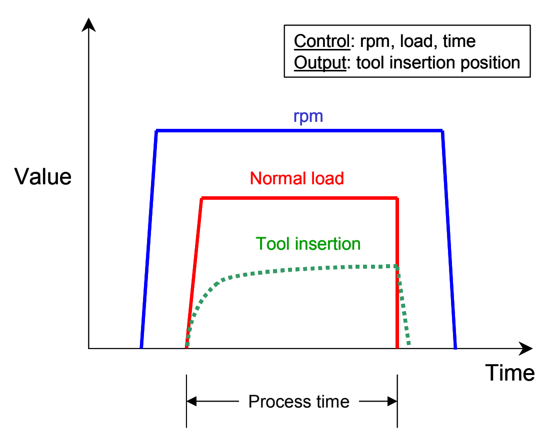


Figure 4: Schematic diagram of a load-controlled spot friction welding process.

Figure 4 illustrates schematically the basic operation of a load-controlled SFW process. In this case, after the tool begins rotating the pin is driven into the sample by controlling the rate at which the force on the pin tool increases. The tool keeps plunging into the sample, until a pre-set time is reached. Then the process stops and the pin retracted.

Displacement-controlled experiment and results

Experiments were carried out using a purpose-built friction stir welding system (MTS Systems Incorporated) at Oak Ridge National Laboratory. The machine is capable of simultaneous force-controlled or displacement controlled operation of three independent axes with adjustable, adaptable pin tools for on-the-fly mode switching between fixed, adjustable and self-reacting welding modes. It also handles computer controlled operations and key process parameter monitoring with the capability of making non-linear, variable thickness, and double curvature welds. In this experiment, only the displacement-control mode is used.

Specimens of aluminum alloy 6111-T4, 25.4 mm in width, 101.6 mm in length, and 0.94 mm in thickness, were used. A lap-shear geometry with 25.4 mm overlap was constructed. A spot friction welding tool, made of H13 tool steel, was used under a constant rotational speed of 2,000 rpm. The displacement was set between 1.6 and 1.9 mm from the tip touching the top sample surface. Several repeats were made for tensile lap shear testing and micrographic cross-sectioning.

Figure 5 shows the lap shear tensile results of samples made between 1.6 and 1.9 mm in depth. Initially the joint strength increased with the plunge depth. It reached a maximum value and then dropped off as plunge depths were further increased. The maximum lap-shear strength exceeded 3KN at about 1.8 mm plunge depth.

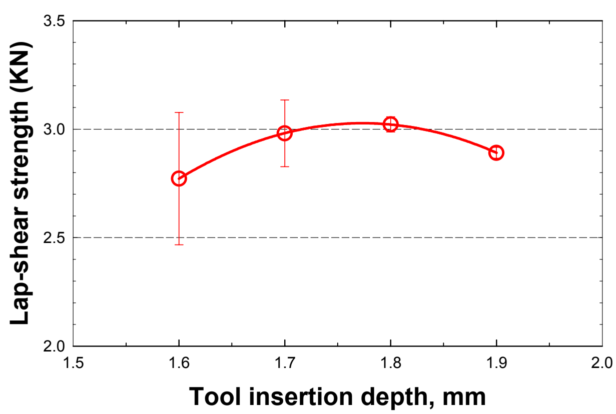


Figure 5: Lap-shear strength of spot-friction welded 6111-T4 samples with varying tool insertion depths using by a displacement-controlled process.

Figure 6 shows the photos of the fractured specimen surfaces after lap-shear testing. The sample with the shallowest plunge depth failed in an interfacial manner, with corresponding joint strength of 2.77 KN. At the 1.8 mm plunge depth, the failure mode was similar to the nugget pull-out commonly observed when testing resistance spot welds. The pull-out failure mode was also associated with higher joint strength, exceeding 3 KN. When the plunge depth increased to 1.9 mm, the circumference of the tool depression on the top surface of the specimen became the main failure location, indicating a thinning of the upper sheet around the weld peripheries. This failure mode corresponds to lower joint strengths.

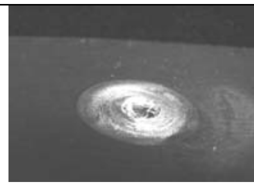
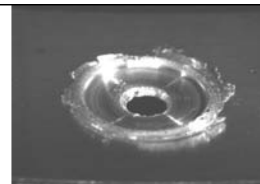
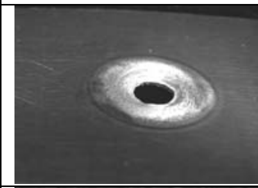
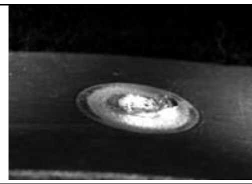
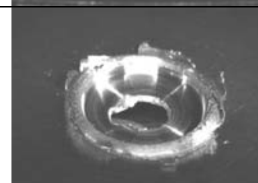
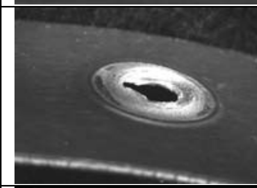
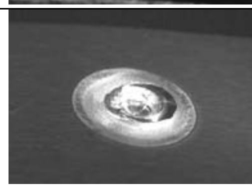
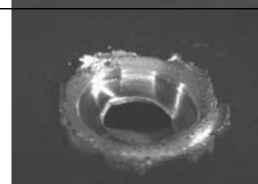
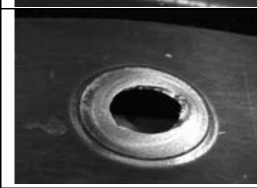
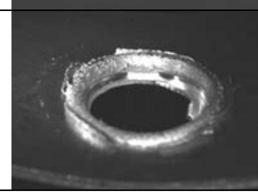
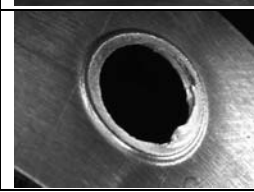
Insertion Depth (mm)	Lap shear strength (KN)	Lower specimen	Upper specimen	Underside of the upper specimen
1.6 mm	2.77			
1.7 mm	2.98			
1.8 mm	3.02			
1.9 mm	2.89			

Figure 6: Photographs of failure surface of lap-shear tested 6111-T4 specimens with different tool insert depths.

Figure 7 shows a micrograph of the cross-section of a sample with a plunge depth of 1.7 mm. It shows a stirred zone next to the tool pin, with a fine microstructure. Figures 8(a) and (b) show a magnified micrograph in the parent material region and stirred zone, respectively, in Figure 7. The grain size in the stirred zone is about 3-5X smaller than that in the parent material.

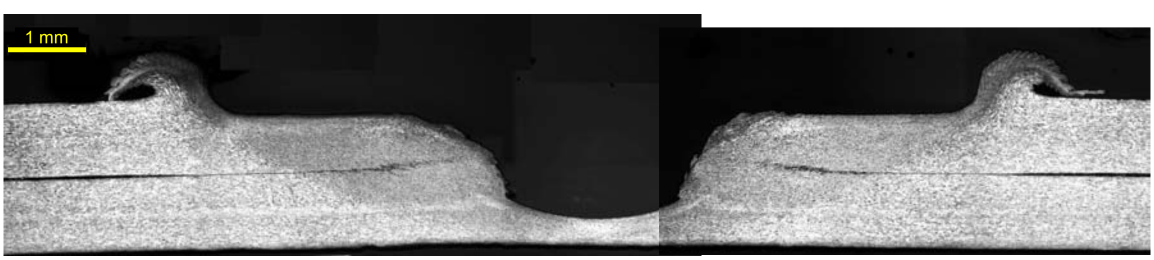


Figure 7: Micrograph of spot-friction welded 6111-T4 specimen with 1.7 mm tool insertion using a displacement-controlled process.

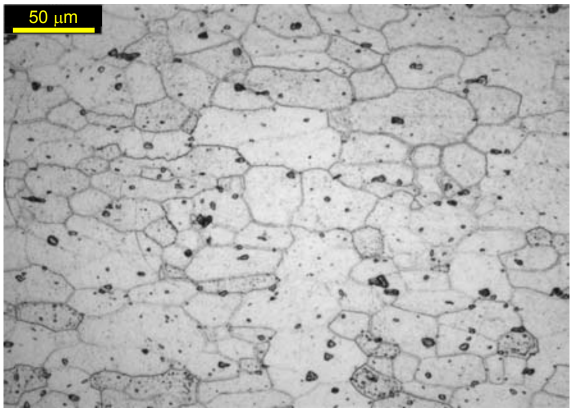


Figure 8(a): Micrograph of the parent material from the sample in Figure 7.

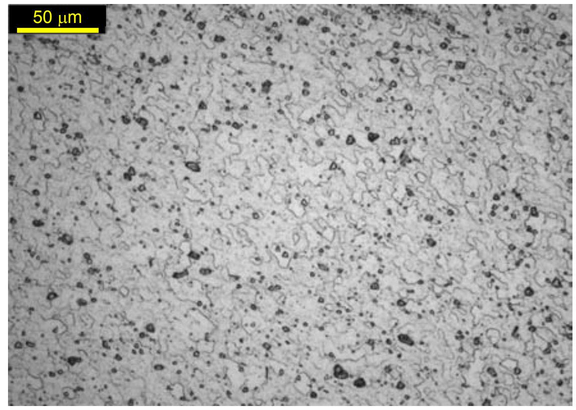


Figure 8(b): Micrograph of the stirred zone from the sample in Figure 7.

Load-controlled process

Previous experiments [2-5] have demonstrated the process and the results of load-controlled SFW process and showed similar results as in the displacement-controlled process.

Decorative joints

Spot friction welding uses a stationary anvil on the opposite side of the spinning tool. A typical anvil has a 12.7 mm circular head with a flat surface. After the welding process, a flat dimple is left on the opposite side of the pin hole. As an alternative, an embodiment can be included on the surface of the anvil (as shown in Figure 9), to make a decorative imprint or logo on the friction spot joint, as shown in Figure 10.

Figure 9: An example of decorative anvil for the spot friction welding process.

Decorative spot joints can be added as design features (as in this experiment trial), as identification (such as VIN), or as personalized features (customer could choose any letters or designs as long as they can fit in the surface area of the anvil). Higher joint strength may also be achieved with patterns on the anvil. A similar concept has been proposed in other spot joining methods. [6]

Conclusions

A displacement control spot friction weld process was studied in this experiment. Sheets of 6111-T4 aluminum, 0.94-mm-thick, were joined in a lap-shear configuration using a cylindrical a pin tool plunged to pre-determined depths of 1.6, 1.7, 1,8 and 1.9 mm. Micrographs of the joint cross-section showed a semi-circular stirred zone around the pin and shoulder of the tool, with a fine microstructure in the stirred zone. The lap-shear strength of spot friction welded samples was about 2.7 KN at the shallowest insertion depth (1.6 mm), increased to a maximum value of over 3 KN at about 1.8 mm depth, then fell off when the insertion depth was deepest. A nugget-pull failure mechanism corresponded to the highest lap shear strength.

In a second experiment, an embodiment was included on the surface of the anvil to make a decorative imprint on the surface of the lower sheet underneath the friction spot joint. This feature can be applied to design, identification, and/or an effect of the joint strength.

Figure 10: Spot friction welded sample with the normal pin hole on the top sheet, but with a decorative imprint on the bottom surface of the lower sheet.

Acknowledgements

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