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Friction Stir Extrusion: A New Process for Joining Dissimilar Materials

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Abstract

The need to join dissimilar materials such as aluminum and steel is prevalent in many industries. This paper investigates a new process called Friction Stir Extrusion(FSE) for joining aluminum and steel. The process uses Friction Stir Welding(FSW) to extrude aluminum into a premade concave groove cut into steel. FSE eliminates the concerns of intermetallic compounds and tool wear. This technique leads to a mechanically bound joint whose strength is determined by the mechanical bond between the steel and the extruded aluminum. Successful joints were created showing the FSE process has the potential for application to any combination of dissimilar materials.

Keywords

Friction Stir Welding; Dissimilar materials; Aluminum steel welding; Intermetallic bonds; Joining; Extrusion

1. Introduction

In many industries there is a need to join dissimilar materials. Joining modern alloys of aluminum and steel has been a challenge as most current welding methods do not work on these new alloys because of the disparate properties of the materials. Other joining processes such as adhesives, rivets, bolts, etc… have limitations in their use, application and/or strength.

Friction Stir Welding(FSW) has the advantage that the alloys are not melted, but efforts to use it so far have had limited success due to the creation of intermetallic bonds that weaken the weld (Liyanage, et al., 2009),and (Bozzi, et al., 2008) or severe tool wear that makes it cost prohibitive. (Gibson, et al., 2014) A good overview of the challenges associated with traditional FSW and FSSW for dissimilar welding of aluminum and steel can be found in (Haghshenas, et al., 2013). A limited amount of work has been used to extend FSW and FSSW processes to create dissimilar joints using prefabricated geometrical configurations (Evans, et al., submitted), (Nishihara, 2003), (Balakrishnan, et al., 2007) and (Lazarevic, et al., 2013). This contribution presents a new method for joining aluminum and steel by a process called Friction Stir Extrusion (FSE) which is an extension of the FSW technique.

2. Material and methods

In order to prove the concept, aluminum 6061 plates of 0.25 inch thickness are joined to 0.25 inch thick low carbon steel plates in a lap configuration using the Friction Stir Extrusion process. Prior to welding, a concave groove was cut along the length of a 0.25" steel plate as shown in Figure 1. The initial groove design was created by creating two cuts with a 1/32 inch slit saw at two perpendicular 45 degree angles. The middle section of the groove was then removed with a small end mill followed by 11/64 inch diameter end mill cutting at a depth of 0.07 inches. This particular setup proved difficult to reproduce consistently, so additional experiments were performed with an O-ring dovetail groove design. The dovetail groove had a neck diameter of 0.116 inches and a depth of 0.103 inches with an included angle of 48 degrees. A sheet of 6061 of equal length was placed on top of the steel sheet in a (FSW) lap weld configuration.

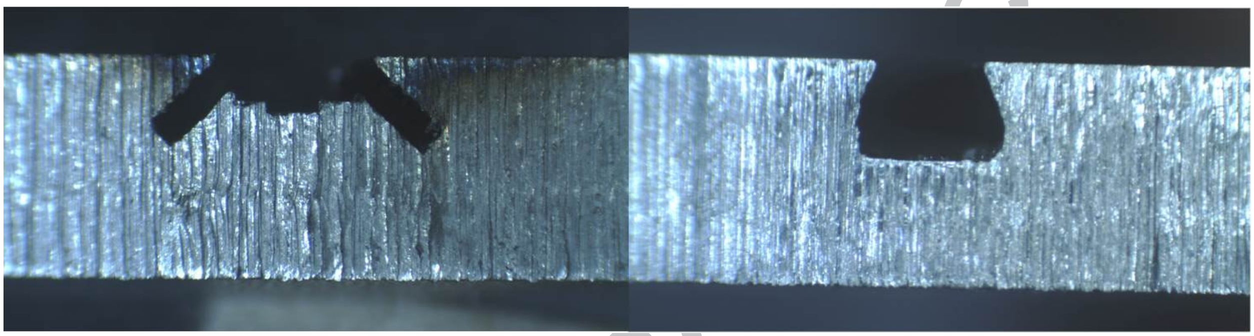

Figure 1 Groove patterns cut into base steel layer: slit saw and endmills(left), O-ring dovetail(right)

The tools used for FSE were the same as those used in standard FSW. In this case, tools were chosen with convex, scrolled shoulders and threaded probes to enhance the extruding process as shown in Figure 2. Tool A has a 0.25 inch diameter threaded probe of 0.18 inch length and a 7 degree convex shoulder with six scrolls. Tool B also has a 0.25 inch diameter threaded probe of 0.18 inch length, but the convex shoulder has a 12 degree slope and the scrolls are shorter in length.

The FSE is performed in a similar manner to a FSW. The center of the tool is placed 0.1 inches below the center of the groove on the advancing side of the weld. This location was chosen to prevent the probe from acting as a plug that would prevent the extrusion of material into the groove as was found to be the case in some FSSW welds performed by Lazarevic. (Lazarevic, et al., 2013) The tool is then plunged 0.215 inches into the aluminum and welds at a rate of 3 ipm and 1500 RPM. This ensures that the tool always remains in the aluminum and the majority of the shoulder is engaged in the weld. This mitigates one of the main issues in welding dissimilar materials which is the excessive tool wear caused by the harder material since the tool never touches the harder material. (Gibson, et al., 2014) However, instead of mixing the two lapped materials, the FSE process plasticizes the aluminum and extrudes it into the concave groove. The scrolled shoulder and threaded pin help in this process by stirring and forcing the material down into the groove. Once the material is extruded into the groove, the materials are fixed to each other due to the concave nature of the groove. The result is a strong, dissimilar joint created from a single pass of the FSW tool.

3. Results

FSE with tool A created a joint that appeared very smooth with an even surface and a small amount of flash on the edges of the weld. The surface finish looked the same as a traditional FSW. The aluminum was fully extruded into the groove and a joint between the two materials was created without any visible volumetric flaws.

Tool B was then used to perform the weld at the same parameters of 3 ipm and 1500 RPM. With tool B, the aluminum was partially extruded into the groove, but the process left a large void along the length of the weld. The weld was repeated at different traverse rates, plunge depths, RPM rates, while also adjusting the center line of the tool in relation to the center of the groove with similar results. The void was finally eliminated by placing the center of the probe 0.15 inches below the center of the weld on the advancing side, but the aluminum did not fully extrude into the bottom edges of the groove and the tool removed significantly more material from the advancing side creating a large amount of flash on the advancing side as seen in Figure 2.

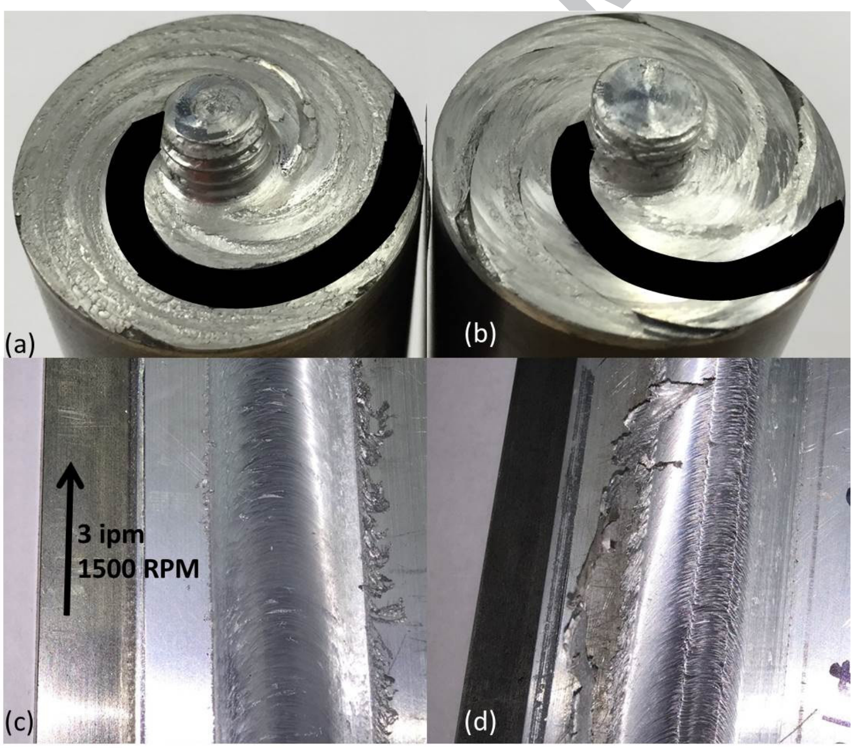

Figure 2 (a) Tool A with threaded probe and scroll pattern highlighted, (b) Tool B with threaded probe and scroll pattern highlighted, (c) Surface of Tool A, (d) Surface of Tool B

The welds made by tool A were cut into 1/2 inch wide samples for macrographic examination and tension-shear testing with a tensile tester as seen in Figure 4. The slit saw grooved joint had an average ultimate tensile shear load of 608 kgf for the three ½" samples tested. Failure of the joint occurred in the section of the joint on the side in tension(B) at about a 45 degree angle to the surface of the steel. The O-ring dovetail groove had an average ultimate tensile load of 488 kgf for the three ½" samples tested. Failure of the joint occurred across the neck of the groove parallel to the surface of the steel.

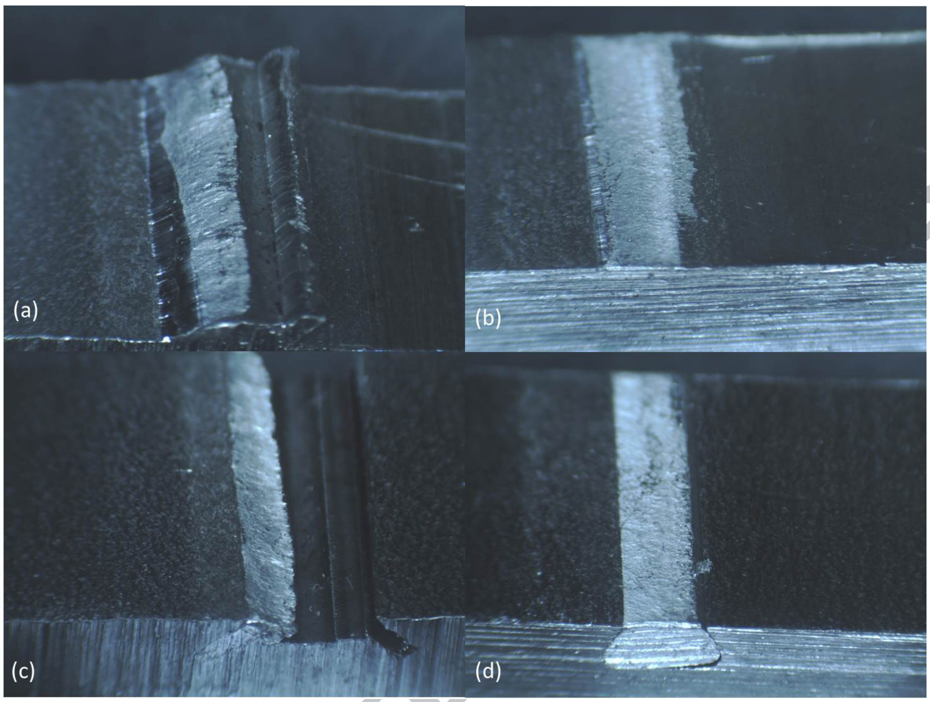

Figure 3 (a),(c) Fracture pattern of slit saw groove (b), (d) Fracture pattern of O-ring dovetail groove

Figure 4 Experimental results of FSE for two groove types

4. Discussion

FSE created strong joints between the aluminum and steel and offers a new way of joining dissimilar materials. The two tools tested were very similar in design, but the resulting joints differed greatly in their surface appearance and in the amount of extrusion. The larger shoulder angle of tool B necessitated making a deeper plunge to fully engage the shoulder which placed the probe closer to the surface of the groove. It is likely that this inhibited the flow of aluminum into the groove. As the probe was moved further away from the groove, it allowed the space for the aluminum to extrude, but also moved the most active part of the stir zone further from the groove, thus leading to only partial extrusion into the groove. Additional experimentation will be needed to determine the optimum tool for industrial applications, but tool A seems to be an excellent starting point.

The major contribution of strength of the FSE joint comes from the cross section of aluminum that is extruded into the groove. The two types of grooves in this experiment had different geometries, but the cross section of the fractured area was very similar. The higher ultimate tensile strength of the slit saw cut can be attributed to the extra contribution from the opposed slit slit saw groove that acted as an anchor on the back side of the joint (Figure 4, point A). The slit on the back side of the joint kept the larger neck diameter in line with the shear force of the tester until it pulled out and the resulting failure happened on a section of lesser width than the neck. Other groove shapes such as slit saw cuts without the use of an endmill in the middle, circular shaped grooves, or other geometries will likely improve joint strength. Also, a cutter that would allow for a larger radius on the top surface of the steel would be preferred as it would reduce the stress concentration of the sharp angle present at the neck.

5. Conclusions

FSE provides an effective way to join dissimilar materials such as aluminum and steel. It eliminates the need for costly tools and tool replacement since traditional FSW tools used for welding aluminum can be used in the FSE process and the tool never touches the steel plate. Initial experimentation showed a large difference in the quality of the joint based on tool selection. Tool A performed very well, but would likely need to be optimized for the intended application. FSE also creates a strong mechanically bound joint that eliminates many of the concerns of intermetallic bonding that occur in traditional FSW of aluminum and steel. Since the process creates a mechanical joint, it could potentially be extended to other materials from plastics to super alloys.

Acknowledgements

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