Joining of Lightweight Dissimilar Materials by Friction Self-Piercing Riveting

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Abstract In this work, we employed a unique solid-state joining process, friction self-piercing riveting (F-SPR), to join carbon fiber composites to the low-ductility magnesium alloy AZ31B. The localized frictional heat generated between the rotating rivet and the underside of the magnesium sheet softened and prevented crack generation in AZ31B. A consumable joining rivet was designed to join the selected material stacks by F-SPR. Lap shear tensile testing was used to assess the joint quality of specimens produced by F-SPR. The joint interface from the cross-sectioned F-SPR specimen was evaluated by optical microscopy.

Keywords Friction self-piercing riveting · Carbon-fiber-reinforced polymer AZ31B

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Introduction

Multi-material lightweight vehicles have been targeted by the automotive industry as a way to comply with government regulations while producing safer, more fuel efficient, and more durable vehicles. One general approach to achieving this goal is to integrate high specific strength (i.e., strength divided by density) materials—-such as aluminum, magnesium alloys, carbon fiber (CF) composites, and advanced high-strength steels—into the unified vehicle structure. However, joining of the individual materials has been a critical challenge because of the physical and chemical incompatibilities between the materials.

Extensive research has been conducted on joining dissimilar lightweight materials using fusion welding, solid-state joining, and mechanical fastening [1–5]. Although hybrid vehicle structures using CF composites and magnesium alloys have good potential for future lightweight vehicle applications, only limited work has been reported for joining CF-reinforced composites (CFRCs) to magnesium alloys [6]. For this reason, the authors focused on developing a process for joining CFRCs to the magnesium alloy AZ31B. Magnesium has low ductility and formability at room temperature [7], so it is hard to achieve the required plasticity even for mechanical fastening, such as self-piercing riveting. To overcome the issue of low ductility at room temperature, we employed a unique friction self-piercing riveting (F-SPR) process. This process has recently been used for joining dissimilar materials, such as joining aluminum to magnesium alloys [8, 9] and aluminum to steel [10].

Experiment

Materials

For a top sheet material, a 3-mm-thick thermoplastic CF-reinforced polymer (polyamide [PA] 66 with 40% random and short CFs) was provided by BASF. Another top sheet was purchased for this work—a 1.86-mm-thick thermoset CF-reinforced polymer (Clearwater Composites, Minnesota, USA) with G-83 prepreg laminated reinforced with 50 wt% of unidirectional CFs (T700, Toray). The stacking sequence of the CF layers was (0°/90°) with nine plies. A 2.3-mm-thick AZ31B alloy sheet was used as the bottom material. Figure 1 shows a magnified cross-sectional view of both the thermoplastic and thermoset CF composites. For the F-SPR process, 5.3 mm diameter special semi-tube rivets with hexagonal heads were designed and fabricated. The rivet shank length was 6 mm. The rivets were made of Japanese Industrial Standard G3507-2 carbon steel without heat treatment or coating. Table 1 shows the chemical compositions of AZ31B and the rivets. The mechanical properties of both materials are summarized in Table 2. Finally, a DZ series pip die with a 1.7 mm cavity depth was used, based on previous work [8].

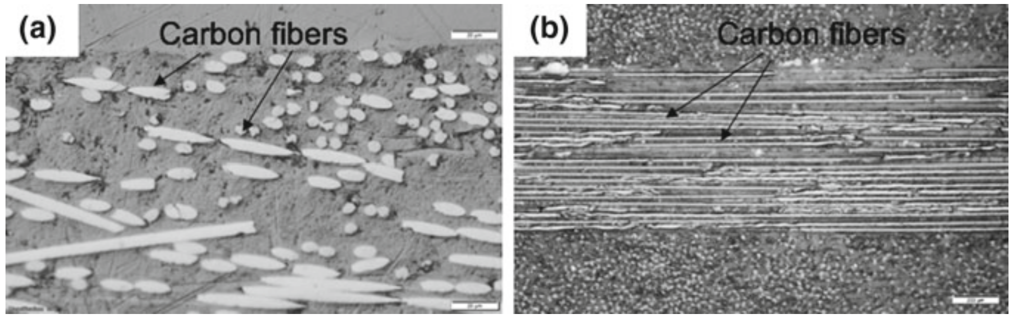

Fig. 1 Magnified cross-sectional optical image of **a** thermoplastic CFRP (PA66-40% CF), **b** thermoset CFRP with (0°/90°) CF layers

Table 1 Chemical compositions of AZ31B and rivet

Element	C	Al	Zn	Mn	Ca	Cu	Fe	Ni	Si	P	S	Others	Mg
AZ31B	–	2.5–3.5	0.7–1.3	0.2–1.0	0.04	0.05	0.005	0.005	0.05	–	–	0.4	Balance
Rivet	0.14	0.0005	–	0.71	–	–	Balance	–	0.04	0.011	0.004	–	–

Table 2 Mechanical properties of each material

Material	Tensile strength (MPa)	Elongation (%)
CFRP (PA66-40%CF)	154	–
CFRP (G-83 prepreg)	827	–
AZ31B	285	8
Rivet	463	26.4

A water jet was used to cut all sheets into coupons of 25 mm wide and 100 mm long for lap shear coupons. A 25 mm overlap was used for the lap shear coupons. Then, acetone, followed by isopropyl alcohol, was used to clean the surfaces of both sheets before joining. The material stacks for F-SPR were 3-mm-thick CFRP (PA66-40% CF) joined to 2.3-mm-thick AZ31B, and 1.86-mm-thick CFRP (G-83 prepreg) joined to 2.3-mm-thick AZ31B.

Friction Self-Piercing Riveting

In the F-SPR process, a semi-hollow rivet is rotated and plunged into the top and bottom materials to create a joint, as illustrated in Fig. 2. Frictional heat is generated by the rotating rivet and underneath the material, leading to local softening of the material. This local heating can produce a crack-free joint for a low-ductility material such as a magnesium alloy. Finally, mechanical interlocking between the rivet and bottom sheet is achieved by outward flaring of the rivet leg based on the geometry of the supporting die. The joint quality is governed by the interlock distance and the remaining material thickness of the bottom sheet. Figure 3 shows a specially

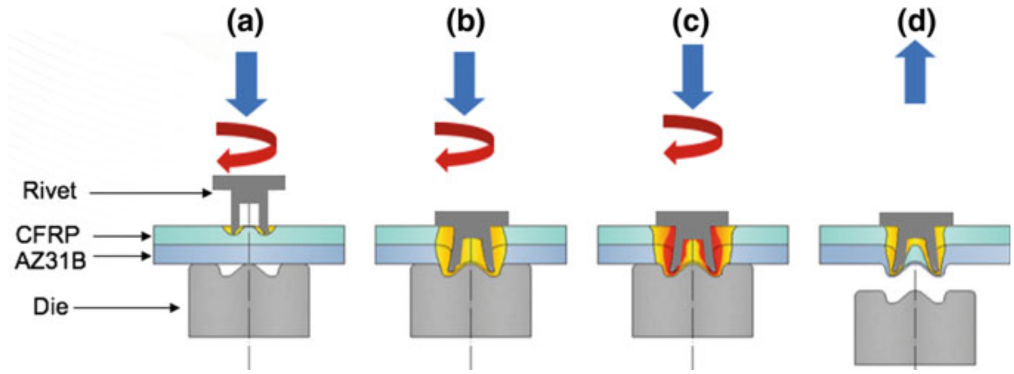

Fig. 2 Schematic of F-SPR process

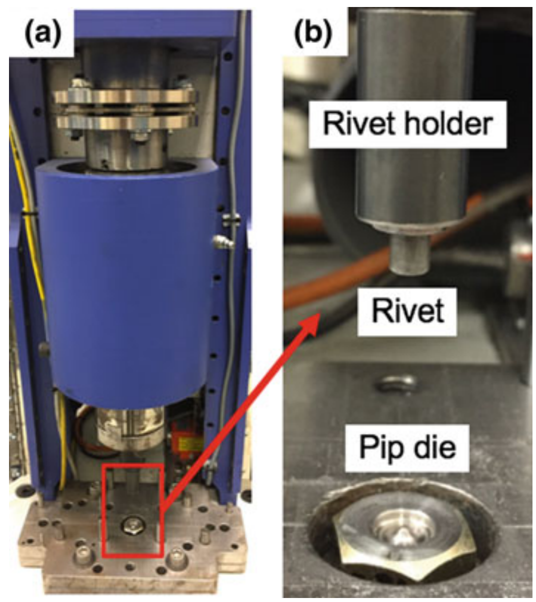

Fig. 3 **a** Overview of friction self-piercing riveting machine. **b** Magnified image showing rivet holder, steel rivet, and pip die

Table 3 Summary of F-SPR process parameters for each material stack

Material stack	Spindle speed (rpm)	Z-axis plunge depth (mm)	Z-axis plunge speed (mm min^{-1})
CFRP (PA66-40%CF)—AZ31B	2000	6.7	101.6
CFRP (G-83 prepreg)—AZA31B	2000	6.65	101.6

designed piece of welding equipment for the F-SPR process along with a rivet, its holder, and the pip die. The F-SPR process parameters initially used for the material stacks are summarized in Table 3.

Mechanical Testing

To evaluate the joint integrity of F-SPR specimens, lap shear tensile testing was performed using an MTS tensile machine with a constant crosshead speed of 10 mm min^{-1} at room temperature. Spacers were used to grip the lap shear coupons to align them.

Results and Discussion

Figure 4 shows an example of thermoset CFRP (G-83 prepreg) joined to AZ31B by F-SPR. No surface damage was observed on the CFRP when the rivet is plunged into the top sheet. In addition, visual observation of the backside of the AZ31B after F-SPR showed no crack formation on the low-ductility magnesium alloy. Frictional heat generated during F-SPR softened the AZ31B so that crack formation was avoided. Previous work also demonstrated that preheating AZ31B up to 200 °C before self-piercing riveting effectively prevented cracking [11].

Load and displacement curves from lap shear tensile testing of the different material stacks are plotted in Fig. 5. The peak failure load for the thermoplastic CFRP (PA66-40%CF)–AZ31B stack was 3.2 kN, and a failure load of 5.12 kN was obtained for the thermoset CFRP (G-83 prepreg)–AZ32B stack. Note that the lap shear peak load obtained was comparable to that found in previous reported work (~1.5 kN) for AZ31B joined to a polyphenylene sulfide CF composite by friction spot welding [6]. The peak loads obtained for the different material stacks were normalized using the cross-sectional area of the rivet shank diameter (5.3 mm), resulting in load values of 145.1 MPa and 231.96 MPa for the thermoplastic CFRP–AZ31B and the thermoset CFRP–AZ31B, respectively. The normalized tensile shear strengths for both cases were close to the tensile strengths of the base materials, such as thermoplastic CFRP (PA66-40%CF) and AZ31B, respectively.

Different failure modes were observed for each material stack. Net tension failure of the CFRP was observed for the CFRP (PA66-40%CF)–AZ31B specimen, as shown in Fig. 6a. The failure could be due to stress concentration around the hole produced by the F-SPR process. In the CFRP (G-83 prepreg)–AZ31B specimen, a large hole was observed in the AZ31B sheet because the mechanical interlock pulled out from the bottom magnesium sheet, as seen in Fig. 6b. From the cross-sectional view, the

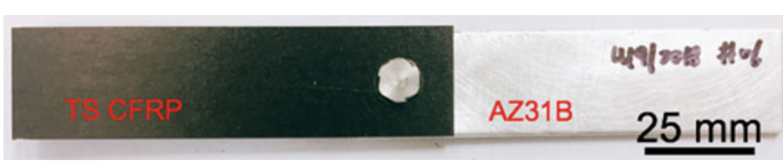

Fig. 4 Example of thermoset CFRP joined to AZ31B by friction self-piercing riveting

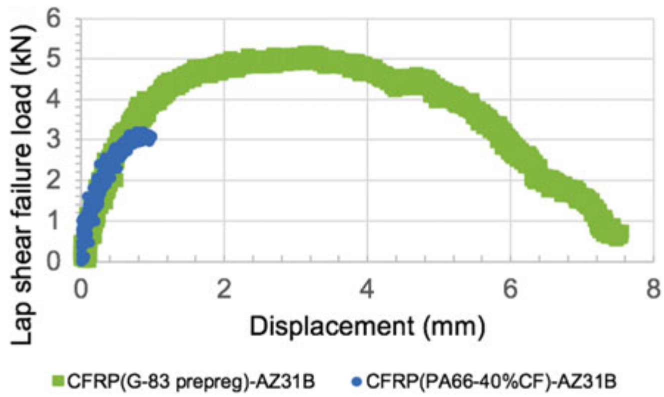

Fig. 5 Load and displacement curves of different material stacks

Fig. 6 **a** Fractography of thermoplastic CFRP (PA66-40%CF) joined to AZ31B by friction self-piercing riveting, showing net tension failure of the composite (red-dotted circle). **b** Fractography of thermoset CFRP (G-83 prepreg) joined to AZ31B showing pullout from the AZ31B

mechanical interlock was measured at around 0.4 mm. This failure mode can indicate good mechanical interlocking between the rivet and the magnesium alloy.

Conclusions

In quick summary, F-SPR was successfully demonstrated for joining CF composites to the magnesium alloy AZ31B. No cracking of AZ31B was found after the joining process, because localized friction heat generated during F-SPR softened the magnesium alloy, leading to improved ductility and formability of the material. Lap shear tensile peak loads of 3.2 kN and 5.12 kN, respectively, were achieved for thermoplastic CFRP (PA66-40%CF) joined to AZ31B and thermoset CFRP (G-83 prepreg) joined to AZ31B. Net tension failure was observed for the thermoplastic CFRP joined to AZ31B, and mechanical interlocking pullout from the bottom magnesium sheet was seen for thermoset CFRP joined to AZ31B. In future work, other process parameters should be further studied for optimization of the F-SPR process.

Acknowledgements This research was financially sponsored by the US Department Energy, Vehicle Technologies Office, as part of the Joining Core Program. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the US Department of Energy under Contract DE-AC05-00OR22725. The authors would like to thank to Kevin Simmons at Pacific Northwest National Laboratory for an optical microscopy of carbonfiber composites.

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