Joining Dissimilar Materials via Rotational Hammer Riveting Technique

Tianhao Wang, Scott Whalen, Piyush Upadhyay, and Keerti Kappagantula

Abstract

A robust, economically viable joining method for Mg/Al and Mg/CFRP could enable multi-material assemblies that decrease vehicle weight while offering more flexibility for designers. However, certain challenges exist for joining Mg/Al and Mg/CFRP. Mechanical joining, such as conventional riveting, clinching and bolting do not form a metallurgical bond between the fastener and metal sheet being fastened. Large differences in physical and mechanical properties of metals and polymers make joining Al or Mg to CFRP challenging via various welding techniques. For Mg/Al pair, solid-phase and fusion-based welding results in rapid formation of brittle intermetallic compounds at the interface leading to premature interfacial fracture under mechanical loading. In this study, a Rotational Hammer Rivet (RHR) technique was developed to fabricate Mg/CFRP and Mg/Al joints. With RHR technique, direct joining between Mg/Al and Mg/CFRP were replaced by joining Mg rivet head and top Mg sheet. Through heat generated by plastic deformation of an Mg rivet, RHR creates a metallurgical bond between rivet head and Mg sheet which seals corrosive electrolyte from penetrating around the rivet head.

Keywords

Riveting • Magnesium alloys • CFRP • Dissimilar joining • Light-weighting

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Introduction

As one of the oldest joining methods, riveting still plays a very important role in manufacturing industry. Especially, the increased use of multi-material and hybrid structures has boosted the requirement for joining dissimilar materials, and riveting is suitable for joining dissimilar materials [1]. In recent decades, requirements to improve fuel efficiency in the transport industries necessitate a higher usage of light-weight structural materials such as magnesium (Mg) and its alloys since their densities are around 65% of that of aluminum (Al) but with comparable strength [2]. As such, using Mg rivets in place of traditionally used steel or aluminum ones would augment vehicle light-weighting. However, while this has been explored in the past, literature shows that conventional cold driven riveting is not possible for Mg alloys due to its low formability [3]. Since Mg alloys are readily formable at elevated temperatures [4], hot driven riveting has been investigated for magnesium rivets [5]. But the prohibitively slow heating process and cycle time have been a barrier to industry adaptation. Therefore, in this study, a rotational hammer riveting (RHR) technique was developed and applied on magnesium studs to obtain rivet heads that are metallurgically joined to the underlying magnesium sheet. In contrast to hot and cold driven riveting where the only deformation is due to linear hammering, RHR takes advantage of heat generated by plastic shear deformation of Mg while a specially designed rotating tool plunges on an Mg stud.

Because of the desire to increase the use of lightweight structural materials such as aluminum alloys, magnesium alloys and carbon fiber reinforced polymers (CFRP) in industries, a mechanically robust joining method for combinations of these materials, namely Mg/Al and Mg/CFRP can enable decreased vehicle weight while offering more flexibility for vehicle designers [6, 7]. However, certain challenges exist for joining Mg/Al and Mg/CFRP. For example, mechanical joining methods such as conventional

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rivets, threaded fasteners and bolted joints cannot seal the interfaces between the rivet head and Mg sheet against penetration of corrosive electrolyte. With various welding techniques including solid-state and fusion welding methods, brittle intermetallic compounds Al_xMg_y formed rapidly at the Mg/Al interface, which facilitated a weak dissimilar joint [8]. Additionally, large differences of physical, chemical, and mechanical properties of metals and polymers make joining Al or Mg/CFRP challenging by applying conventional welding methods. The RHR technique addresses these challenges since metallurgical bonding formed between the rivet head and top Mg sheet. Tool design and process parameters including rotation rate and plunge speed were optimized based on microstructural characterization and mechanical performance of the dissimilar Mg/Al and Mg/CRFP joints.

Experiments and Methods

Base Materials

In this study, Mg (AZ31), CFRP and Al (AA7055) sheets with thickness of 2.4, 3.1 and 2.5 mm, respectively, were used. The CFRP, commercially available as Ultramid Advanced N XA-3454, is a 40% short carbon fiber reinforced grade of PA9T obtained from BASF Corporation. Mechanical properties of AZ31, CFRP, and AA7055 are listed in Table 1.

Tool Design

Two H13 tools utilized in this study are shown in Fig. 1. Both the tools were 12.7 mm in diameter with concavity of 10° (tool#1) and 20° (tool #2). The detailed schematic of tool geometry including dimensions used to calculate cap volume (volume within tool concavity) and AZ31 insert volume is shown in Fig. 2a, b shown. According to the diameter (D_{tool}) and concave degree (θ) of the RHR tools, cap volume (V_{cap}) and cap-height (H_{cap}) were calculated via Eqs. (1) and (2). On the other hand, the height (H_{insert}) and volume (V_{insert}) of AZ31 insert were related by Eq. (3). For tool #1 (θ = 10°), H_{cap} of 0.5 mm and V_{cap} of 29.4 mm^3 were obtained. For tool #2 (θ = 20°), H_{cap} of 1.1 mm and

Table 1 Mechanical properties of base materials

Materials	Tensile strength (MPa)	Elongation (%)
AZ31	260	15
CFRP	274	1
AA7055	640	10

Fig. 1 Pictures of RHR tools #1 and #2

V_{cap} of 60.8 mm^3 were obtained. In addition, a coefficient of α (≥ 1) is used to balance V_{ex} and V_{cap} as shown in Eq. (4). This is because insert height can guarantee enough material for fully forming a rivet head. In this study, it was found that α should be greater than 2.

$$V_{cap} = \frac{\pi D_{tool}^3 \cdot (2 + \cos\theta)(1 - \cos\theta)^2}{24(\sin\theta)^3} \quad (1)$$

$$H_{cap} = \frac{D_{tool} \cdot (1 - \cos\theta)}{2\sin\theta} \quad (2)$$

$$V_{insert} = \frac{\pi}{4} D_{insert}^2 \cdot H_{insert} \quad (3)$$

$$\alpha \cdot V_{insert} = V_{cap} \quad (4)$$

Experimental Setup and Process Parameters

Ø 5 mm holes were predrilled on the AZ31, CFRP and AA7055 sheets and center to center spacing of 15 mm. AZ31 inserts were penetrated through bottom sheet, and the height of AZ31 inserts was designed such that they contained sufficient volume to form a rivet head during the joining process as discussed in Fig. 2. Setup for riveting AZ31/CFRP sheets with AZ31 inserts is shown in Fig. 3. As for riveting AZ31/AA7055 sheets with AZ31 inserts, the bottom CFRP sheet was replaced with AA7055 sheet. For riveted AZ31/CFRP and AZ31/AA7075 sheets obtained with tool #1, the rotation rate was 1000 RPM with varying plunge speed.

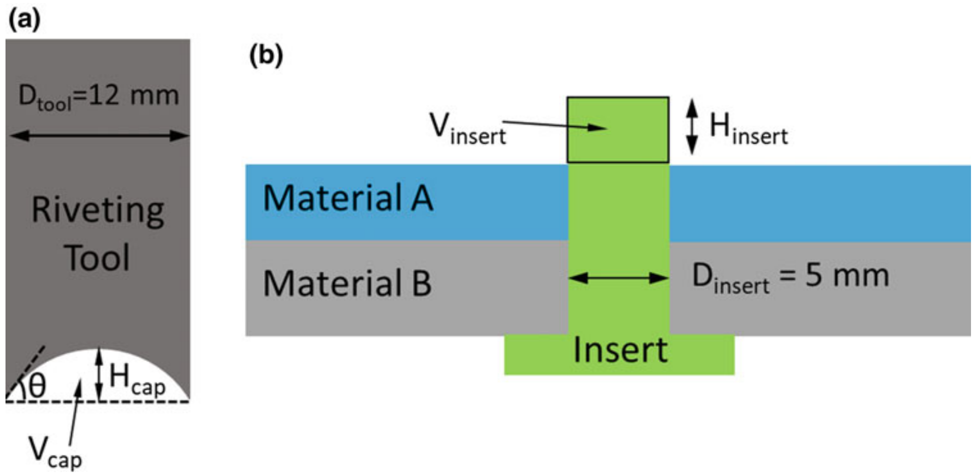

Fig. 2 Schematic of volume calculation of the **a** tool dimensions and **b** insert dimensions

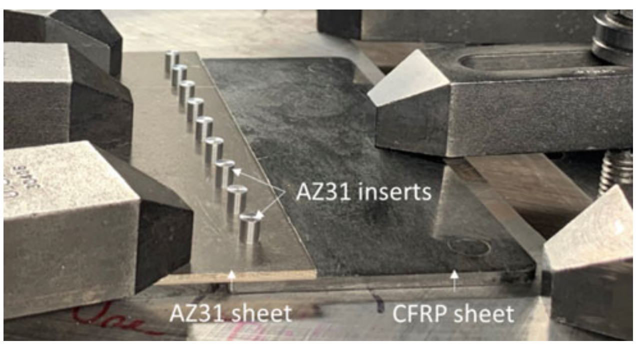

Fig. 3 Setup of RHR process

Sample Preparation and Characterization

Riveted AZ31/CFRP and AZ31/AA7055 joints were cut along the centerline of AZ31 inserts. Specimens for microstructural analysis were mounted in epoxy and polished to a final surface finish of 0.05 μm using colloidal silica. Optical microscopy was performed on cross-sections of the samples. In order to perform lap shear tensile testing, riveted AZ31/CFRP joints and AZ31/AA7055 joints were prepared such that the width of the specimens was about 15 mm with the AZ31 insert located at the center. Lap shear tensile tests were performed at room temperature using an MTS test frame at an extension rate of 1.27 mm/min. The lap shear tensile test configuration of AZ31/CFRP with AZ31 insert is shown in Fig. 4.

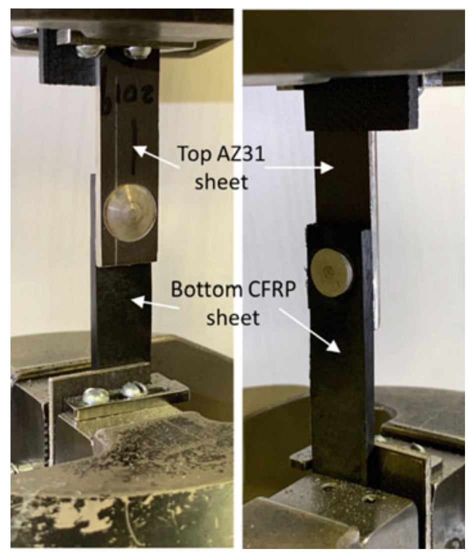

Fig. 4 Picture of lap shear tensile test configuration of AZ31/CFRP with AZ31 insert

Results and Discussion

Mechanism of RHR

Schematic of RHR process is shown in Fig. 5. Friction between the rotating tool and AZ31 insert produces heat, which softens Mg insert. Under the combined effect of heat

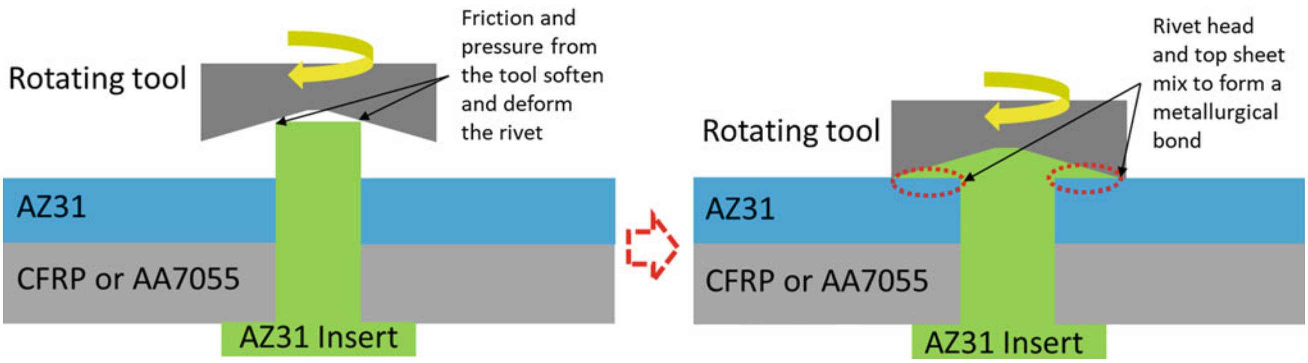

Fig. 5 Mechanism and schematic of rotational hammer riveting technique

and pressure from the tool, AZ31 insert head is plastically deformed and mixed with the top AZ31 sheet to form a metallurgical bond while simultaneously creating a traditional rivet head. With various bottom sheets used in this study, AZ31/CFRP and AZ31/AA7055 joints were both obtained with RHR of AZ31 inserts, as shown in Fig. 5.

Rivet Appearance and Microstructure

For riveted AZ31/CFRP sheets obtained with tool #1, the rivet surface is smooth and completely formed (Fig. 6a). The cross-section of riveted AZ31/CFRP shows that the rivet head is mixed optimally with the top AZ31 sheet while some deflection of CFRP sheet is observed (Fig. 6b). Comparably, for riveted AZ31/AA7055 sheets obtained with tool #1, the rivet surface is shiny and completely formed (Fig. 6c). The cross-section of riveted AZ31/AA7055 shows that the rivet head is mixed sufficiently with the top AZ31 sheet (Fig. 6d).

Riveting AZ31/CFRP sheets with tool #2 were also investigated. It is, however, difficult to find stable riveting parameters due to the higher concavity. Figure 7a shows the rivet appearance with constant rotation rate of 1000 RPM and plunge speed of 60 mm/min. It shows that rivet head has a propensity to stick on the tool after riveting. Figure 7b shows the cross-section of the rivet that displayed a good surface appearance. The head is

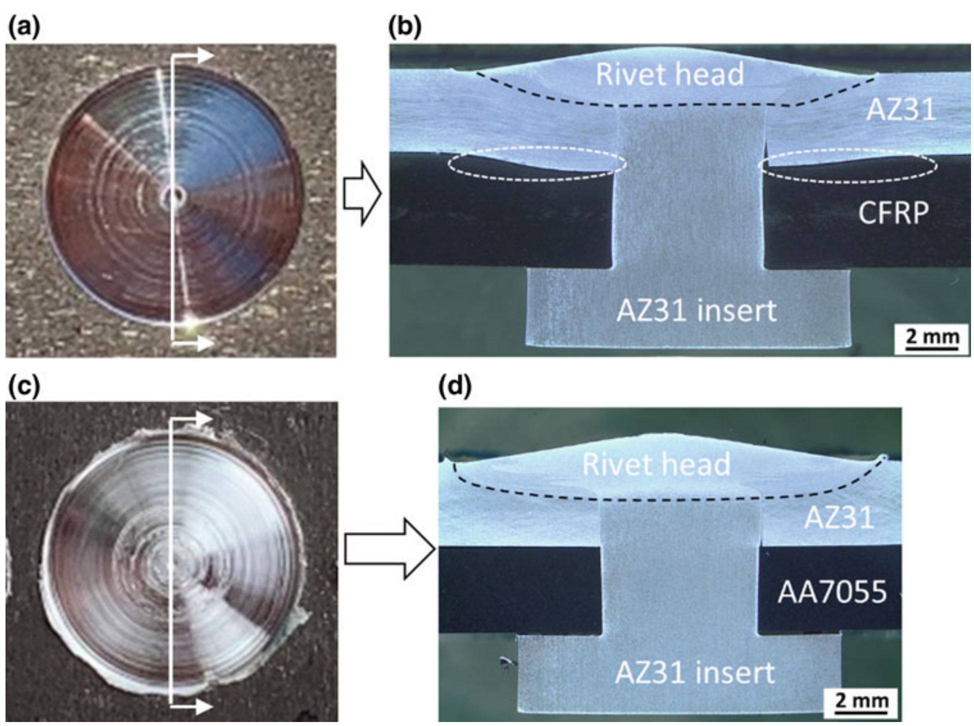

Fig. 6 **a** Rivet head top view and **b** cross-section of riveted AZ31/CFRP sheets with AZ31 insert (Tool #1), and **c** rivet head surface and **d** cross-section of riveted AZ31/AA7055 sheets with AZ31 insert (Tool #1). Black dotted lines are approximate representations of metallurgical bonding between the formed rivet head and stop AZ31 sheet. (**b**) and (**d**), and deflection of CFRP in labelled with white dotted ellipses in (**b**)

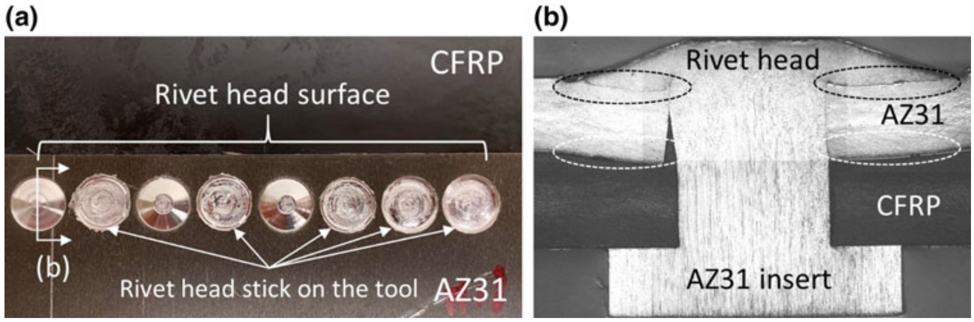

Fig. 7 **a** Rivet head appearance and **b** cross-section of riveted AZ31/CFRP sheets with AZ31 insert via tool #2. Note that the unmixed region between rivet head and top AZ31 sheet is labelled with black dotted ellipses in (**b**), and deflection of CFRP is labelled with white dotted ellipses in (**b**)

not completely mixed with top AZ31 sheet and deflection of CFRP is more severe than the joints obtained with tool #1 (Fig. 6a–b). The higher concavity tool face appears to have impeded mixing at the head/sheet interface.

Mechanical Characterization

Lap shear tensile tests were conducted on riveted AZ31/CFRP joints and riveted AZ31/AA7055 joined by tool #1. Fracture modes varied for riveted AZ31/CFRP and riveted AZ31/AA7055 joints. As shown in Fig. 8a_{1-2}, riveted AZ31/CFRP joints break through the CFRP from the edges of the pre-drilled holes. As shown in Fig. 8b_{1-2}, riveted AZ31/AA7055 joints break through the AZ31 insert shank. Lap shear tensile tests show that peak load of riveted AZ31/CFRP was ∼1.2 kN and peak load of riveted AZ31/AA7055 is ∼2.5 kN.

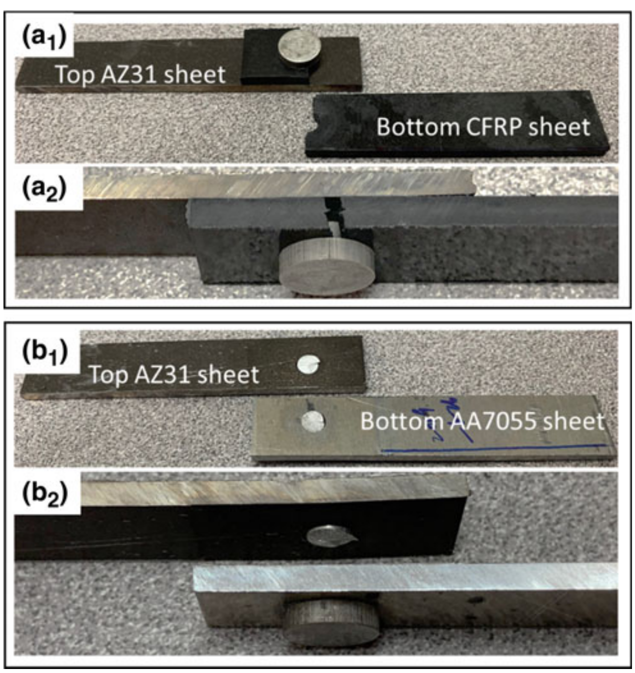

Fig. 8 Pictures of $\mathbf{a_{1-2}}$ fractured joint of AZ31/CFRP and $\mathbf{b_{1-2}}$ fractured joint of AZ31/AA7055

Conclusion

A novel riveting method—RHR—was developed and applied to join AZ31/CFRP and AZ31/AA7055 assemblies with AZ31 rivets. The mechanism of RHR process was also provided which addresses challenges inherent to cold and hot riveting with Mg alloys. With RHR, the deforming rivet head forms a metallurgical bond with the top sheet being fastened. Different tool designs were investigated for their rivet head surface appearance and cross-section morphology. Tool #1 with 10° concavity demonstrated and better mixing between rivet cap and top AZ31 sheet compared to tool #2 with 20° concavity. Mechanical response of riveted AZ31/CFRP and AZ31/AA7055 was studied via lap shear tensile testing. Riveted AZ31/CFRP displayed a peak load of ∼1.2 kN with fracture at the CFRP predrilled hole, while riveted AZ31/AA7055 displayed a peak load of ∼2.5 kN with fracture through AZ31 insert shank. RHR process has demonstrated promise in utilizing low formability materials like magnesium that can enable multi-material design. The process robustness, cycle time and performance of joints in different loading conditions will be investigated in future work.

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References

1. Martinsen, K., Hu, S.J. and Carlson, B.E., 2015. Joining of dissimilar materials. CIRP Annals, 64(2), pp. 679–699. https://www.sciencedirect.com/science/article/pii/S0007850615001456?via%3Dihub
2. Luo, A.A., 2002. Magnesium: current and potential automotive applications. jom, 54(2), pp. 42–48. https://link.springer.com/article/10.1007/BF02701073
3. Kaiser, F., Letzig, D., Bohlen, J., Styczynski, A., Hartig, C. and Kainer, K.U., 2003. Anisotropic properties of magnesium sheet AZ31. In Materials Science Forum (Vol. 419, pp. 315–320). Trans Tech Publications Ltd., Zurich-Uetikon, Switzerland. https://www.cheric.org/research/tech/periodicals/view.php?seq=1254083
4. Trang, T.T.T., Zhang, J.H., Kim, J.H., Zargaran, A., Hwang, J.H., Suh, B.C. and Kim, N.J., 2018. Designing a magnesium alloy with high strength and high formability. Nature communications, 9(1), p. 2522. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6023917/#CR3
5. Gann, J.A., 1931. Magnesium Industry's Lightest Structural Metal (No. 310044). SAE Technical Paper.https://www.sae.org/publications/technical-papers/content/310044/
6. Cole, G.S. and Sherman, A.M., 1995. Light-weight materials for automotive applications. Materials characterization, 35(1), pp. 3–9. https://www.sciencedirect.com/science/article/pii/1044580395000631
7. JC, H. and Chen, M., 2003. Fabrication of high performance magnesium/carbon-fiber/PEEK laminated composites. Materials Transactions, 44(8), pp. 1613–1619. https://www.jstage.jst.go.jp/article/matertrans/44/8/44_8_1613/_article/-char/ja/
8. Liu, L., Ren, D. and Liu, F., 2014. A review of dissimilar welding techniques for magnesium alloys to aluminum alloys. Materials, 7(5), pp. 3735–3757. https://www.mdpi.com/1996-1944/7/5/3735/htm