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WHAT IF THEY ARE NOT WELD-ABLE?

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Abstract
Many light metals, such as aluminum and magnesium alloys, are promised to provide significant weight reduction for automobiles. However, the difficulties in welding these metals seriously hinder their large-scale applications. A new, hybrid mechanical joining process is proposed to avoid the inherited metallurgical complications in welding. By spinning and pressing a solid rivet into the metals, a joint is formed with the locking from the rivet, a stirred/mixed zone around the rivet, and solid bonding at the faying interface. This riveting process combines the actions of friction-stir welding in which metals of different sheets are mechanically mixed, and self-piercing riveting process which embeds a rivet in the sheets. Experiments have shown that such a friction-stir riveting process can produce joints of comparable strength to those created by other joining means, and can be applied to difficult-to-weld metals and dissimilar metals, such as aluminum-to-aluminum, magnesium-to-magnesium, and aluminum-to-magnesium.

Keywords
hybrid mechanical joining, friction-stir-welding, riveting, magnesium, aluminum.

Introduction

In addition to structural optimization, adopting new, light-weight materials is an effective means of reducing vehicles' weight, in order to lower emission and raise fuel efficiency. In the last two decades, aluminum alloys have been introduced to automobile body construction and significant weight savings have been achieved [1]. Unlike steels which have been used as automotive body structural materials since the birth of the automobile industry, aluminum alloys are relatively new to the automotive manufacturing, especially the welding process. Resistance spot welding, the most popular joining method in automobile body construction, of aluminum alloys has proven difficult to perform mainly because of their volatile physical properties. Aluminum has high thermal expansion in both solid and liquid states, and large volume expansion at melting. The high electrical conductivity of such alloys requires the use of low alloyed copper for electrodes which is usually soft with low wear resistance. In addition, the high electrical conductivity, together with the high thermal conductivity of aluminum, requires the use of high electric current in a short period of time in order to concentrate the Joule heat in the weld area. Consequently, welding aluminum alloys generally suffers short electrode life and inconsistent weld quality mainly due to expulsion which is ejection of liquid metal from the faying interface, and is inadequate for certain large volume productions. In general, welding aluminum requires much tighter process control than welding steels, and aluminum welding is often augmented with adhesives. Alternative joining methods to welding aluminum alloys have been developed, and the most noticeable is probably friction-stir welding, in which a rotating cylindrical-shouldered tool with a profiled probe advances into the metals to be joined. The mixed zone created by the stirring action of the probe forms a joint. This process has been fairly successful in joining aluminum and other metals. However, friction stir welding allows very little flexibility in the welding process and fixtures, making it difficult to be adopted in automobile assembly, especially for joining sheet metals. Another process, self-piercing riveting forms a joint by pressing a semi-tubular rivet into the sheets supported on a die. The rivet pierces and then flares into the sheets, forming a mechanical interlock between the sheets. The self-piercing riveted joints created through a dynamic pressing mechanism have similar or higher mechanical strengths than aluminum spot welds [2].

Magnesium alloys have similar electrical, thermal and mechanical properties as aluminum alloys and therefore, welding magnesium alloys is also a challenge. As a matter of fact, the electrode life is extremely short when welding certain magnesium alloys, and expulsion is nearly unavoidable [3]. In addition, their fairly low ductility makes self-piercing riveting process inapplicable to such alloys [4]. Although there are significant barriers to using Mg sheet materials in automobile body construction, it is predicted that the use of Mg will grow by at least an order of magnitude more in 10 years because of their high potential in vehicle light-weighting [5]. Therefore, developing a practical and reliable joining method is an essential step in enabling the use of Mg alloys for automobile weight reduction.

Based on a preliminary work of one of the authors [6], a new mechanical joining technique was developed. Taking the advantages of friction-stir welding and conventional mechanical riveting, the process involves spinning and pressing a solid rivet into two sheets of same or dissimilar metals. The embedded rivet provides a mechanical interlock between the sheets, augmented by a 'welded' portion of the sheets resulted from mechanical mixing, and a small amount of solid bonding at the faying interface.

Friction-stir riveting process

The most crucial part in friction-stir riveting is the rivet. Through a large number of trials on the shape and material of rivets, one robust design has been achieved. Figure 1 shows three different views of the identical friction stir rivet of this design: on the left is a top view revealing a plus sign that allows the driver to spin the rivet as it pushing the rivet into sheet metal; the middle one, as side view of the rivet, reveals the profile of the rivet; and the one on the right is a bottom view of the rivet.

Figure 2 shows the setup for a friction-stir riveting operation. At the beginning a steel plate serving as a clamp is tightly pressed against the sheets, in order to apply a downward force evenly to the metal sheets. The clamp transmits a compressive load to the sheet metal immediately surrounding the rivet to prevent sheet separation. Such a separation, created by squeezing the metal into the faying interfaces, is responsible for a loose joint. After the sheets are completely confined by the clamp and a die underneath, the rivet, pressed and spun by the driver, pierces into the sheets without a pilot hole. The important riveting parameters are spindle speed, feed rate, and feed depth.

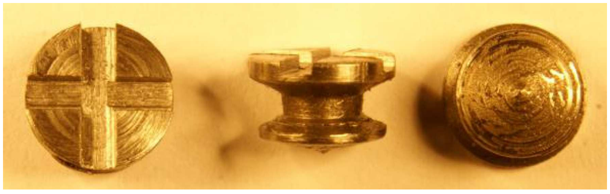


Fig. 1. Views of a friction stir rivet.

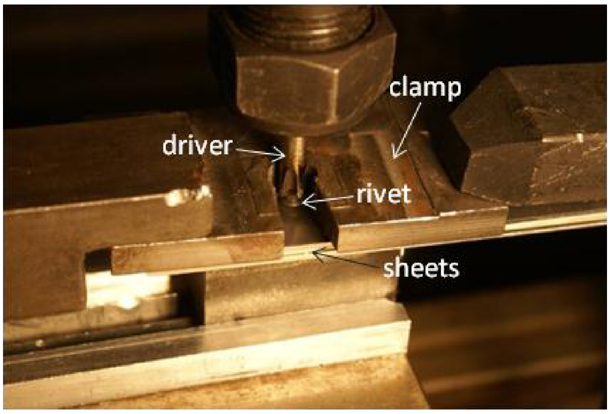
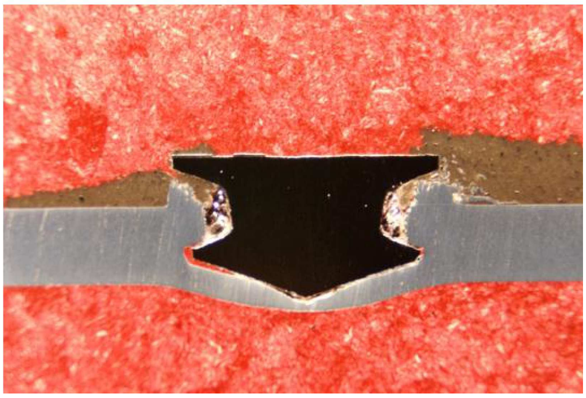


Fig. 2. Friction-stir riveting setup.

Figure 3 shows a progressive view of the friction-stir riveting process through the intermittent steps as the rivet entering the sheets of an aluminum alloy. A thrust force is exerted on the steel rivet by a spindle with a Philips cross head, and the spinning rivet penetrates into the sheets. As seen in Fig. 3a, the rivet extrudes the metal in the top sheet, which is softened by the spinning action through friction heating. The first batch of the extruded metal goes out of the surface of the top sheet, and the subsequently squeezed metal curls into the opening on the back side of the rivet head.

Once the rivet pierces through the top sheet, it extrudes into the bottom one, and at the same time the bottom sheet is pushed into the die cavity. The bottom sheet in Fig. 3b clearly shows the confined deformation of the sheet supported by the die. A mixed zone is formed behind the rivet head as the stirred metal being squeezed into the openings around the rivet trunk, which is compressed by the rivet tail as it enters the sheet stack-up. A reasonable joint is formed as the rivet settles at a designated depth, as seen in Fig. 3c, with the interface ends near the center of the rivet, and with a compacted mixed zone.

a)



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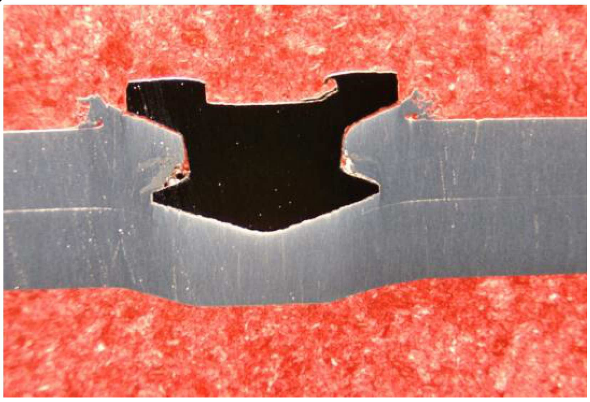

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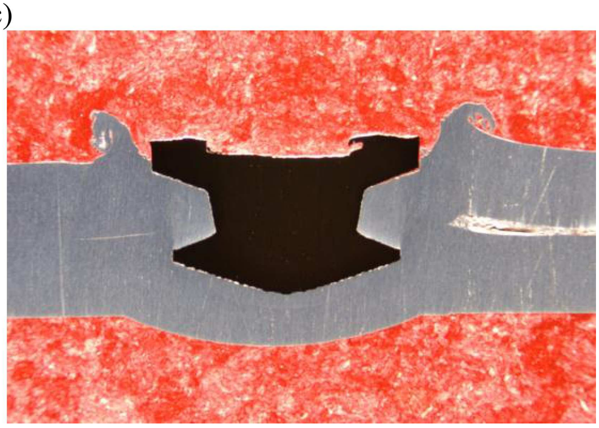

Fig. 3. Sequence of friction-stir riveting.

The quality of a friction-stir riveted joint is directly determined by its structure. The structural characteristics of an aluminum joint is shown in Fig. 4. The end of the interface of the sheets at the mixed zone indicates the thicknesses of attachment of the sheets, d_t and d_b for the top and bottom sheets, respectively, to the joint. A small d_t or d_b means that a small fraction of the top or bottom sheet is connected to the joint and therefore, a low load-bearing capacity of the joint. A balanced combination of d_t and d_b is preferred to fully utilize the sheets in bearing loads. The size of the mixed zone, w, is related to the diameter of the cohesive part of the joint. w also promotes d_t and d_b values, so a large w is preferred. However, experiments have shown that its value varies in a very narrow range of the diameter of the rivet head, which is responsible for creating the mixed zone through the stirring action. The friction heat generated during the riveting process is very high, and the shrinkage of the mixed zone can be significant to affect the integrity of the joint. Such a thermal effect is measured by the gap at the end of the rivet-top sheet interface, s.

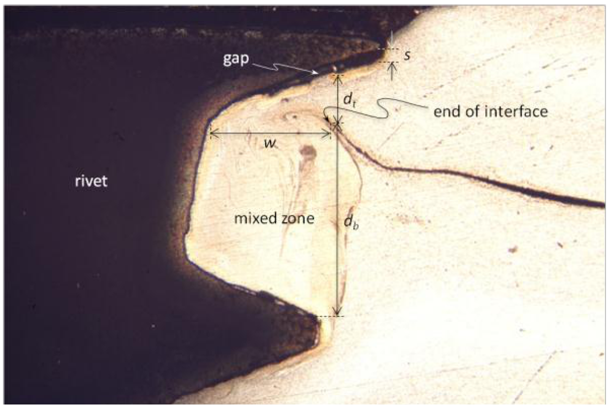

Fig. 4. Metallographic section of a friction-stir riveted joint, and dimensions and various zones for characterizing the joint.

The flow of stirred and softened metal plays an important role in the formation of a joint. If much of the initially squeezed metal goes out of the top surface, there might be insufficient amount of metal to fill the cavity created by the advancing rivet head. In addition, a continuous upward flow of squeezed metal pushes the interface between the two sheets too close to the top surface of the joint, which implies very little resistance to separation of the top sheet from the joint. A die with a partial sphere cavity was used to control the material flow. This die allows the sheets to bend, which effectively reduces the amount of metal squeezed out of the top surface at the beginning of riveting. In addition to the material flow, the location of the interfaces ending at the mixed zone is also a strong function of the depth of the rivet embedded in the sheets, or feed depth.

Experimental results

The characteristic dimensions shown in Fig. 4 were measured on a number of aluminum joints made using ten combinations of spindle speed and feed rate. Because the spindle speed promotes friction heating, and feed rate is inversely proportional to the dwell time of the rivet along the path of riveting, the ratio of spindle speed to feed rate is related to the rate of heat generation, and therefore, is used as an indicator of heat input, hereafter called heating ratio.

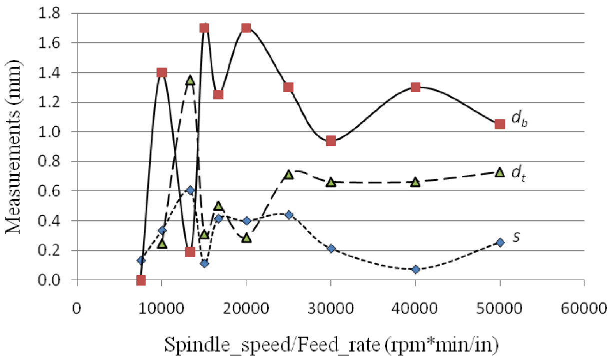

Fig. 5. The characteristic dimensions of joints created using different spindle speed to feed rate ratios.

The depth of feed was kept approximately the same in the experiment. The characteristic dimensions of the joints, as defined in Fig. 4, are plotted in Fig. 5 as a function of the heating ratio. Note that d_t and d_b values are opposite in trend, with their sum close to a constant value. The geometric features of a riveted joint depend strongly on the heating rate. When the heating rate is low, the measurements fluctuate violently, indicating an unstable process. As a quality joint requires a large d_t, a large but comparable d_b, and a small s, the best combination of these three appears to be around the heating ratio of 40000 (rpm*min/in). When increasing the depth of feed, it is possible to obtain a better joint at this combination.

The friction-stir riveting process has been applied to three material combinations: Al-Al, Mg-Mg, and Al-Mg (including Al (top)-Mg (bottom) and Mg (top)-Al (bottom) stack-ups). Figure 6 shows an Mg-Mg joint, created using a spindle speed of 1500 rpm and a feed rate of 0.1 in/min on 2-mm AZ31 magnesium alloy sheets. This joint has a reasonable sized mixed zone, and the sheet interfaces end not far from the extension of their original locations. There is a solid bonding at the interfaces next to the mixed zone, which would disappear if the specimen is etched, as seen in Fig. 4. The color image in Figure 6 clearly shows the material flow in the mixed zone as it has a different color from the base metal. This color change stems from oxidation of the heated Mg during riveting, oxidation during specimen preparation, and mixing with the steel debris chopped off from the rivet, as evidenced by an EDS (Energy-dispersive X-ray spectroscopy) analysis of the element distributions in the joint. The large gap at the sheet faying interface is the result of improper clamping of the sheets during riveting. In addition to the color change in the mixed zone near the rivet trunk, there is also a region with different color in the bottom sheet immediately in front of the rivet head. This appears to be created by the heat generated by the spinning action of the rivet, and an EDS analysis didn't reveal any changes in the chemical composition in this region.

Using the same process parameters as for the Mg-Mg joint in Fig. 6, a piece of Mg (top sheet) was joined to an Al (bottom sheet, Fig. 7). In the mixed zone there is a clear boundary between the Mg and Al, with the Mg portion darkened by oxidation and mixing with Fe particles, as revealed by an element mapping of the joint. Contrary to Mg, Al is not affected by oxidation and is not mixed with Fe scales from the rivet. The mixed zone also shows a clear distinction between the Al and Mg in material flow behavior. Mg appears to be more compliant and flows easier than Al, and it gives in when pushed by the Al squeezed by the rivet head. A closer look at the interface between Al and Mg shows a reasonable bonding between these two metals in the mixed zone.

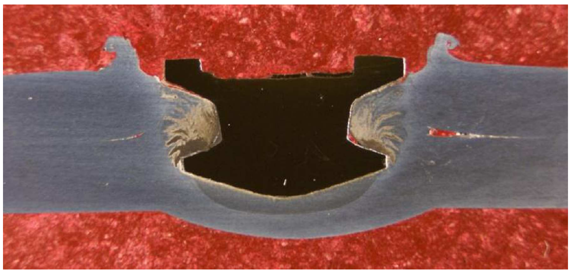

Fig. 6. A Mg-Mg riveted joint.

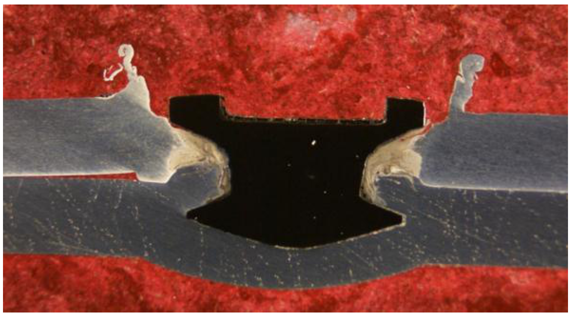

Fig. 7. A friction-stir riveted joint between an Mg sheet (top) and an Al sheet (bottom).

An interesting comparison can be made between this joint and a joint formed also on Al and Mg sheets, but in a reversed stack-up, that is, Al on the top and Mg at the bottom (Fig. 8). The cross section of this joint reveals that Al takes a larger proportion of the mixed zone than Mg does in Fig. 7, both as the top sheet. The stirred Mg is pushed away from the mixed zone by Al, as evidenced by the thickening of the Mg sheet near the mixed zone. Similar to the joint in Fig. 7 there is little mixing between the Al and Mg. There is also a layer of Al attached to the rivet tip in the bottom portion of the joint. It is carried over by the advancing rivet head from the top (Al) sheet. This is not observed in Fig. 7 when Mg is placed on the top of Al. In general, Al is not as easy as Mg to be softened during friction-stir riveting.

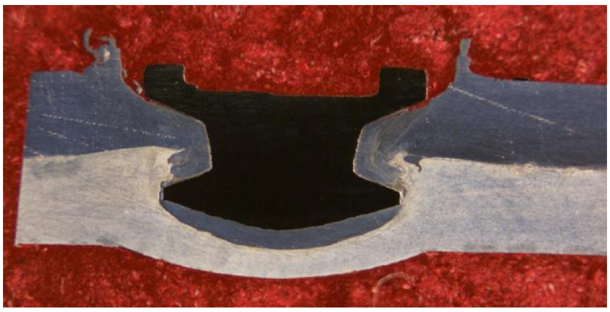

Fig. 8. A friction-stir riveted joint between an Al sheet (top) and an Mg sheet (bottom).

Tensile-shear testing of the friction-stir riveted joints shows similar strength level of such joints to that of self-piercing riveted joints on Al-Al stack-ups. A test on a riveted Mg-Mg joint shows slightly lower strength than its counterpart of Al-Al joints, and no direct comparison was made with self-piercing riveting process as it cannot be applied to Mg without heating the Mg sheets by an external heat source.

Three distinct failure modes were observed during tensile-shear testing friction-stir riveted joints. Figure 9a shows the first failure mode; it is the result of insufficient rivet penetration, and the resulting joint suffers from a weak tensile strength as well as fracture toughness. Figure 9b shows another type of failure mode in which the rivet penetrates deeply into the sheets, resulting in a desirable tensile strength and fracture toughness. The final failure mode can be seen in Figure 9c, where the depth of rivet insertion appears to be ideal; this joint has similar tensile strength compared with the joint in Fig. 9b but has a higher fracture toughness, with a large sheet deformation before separation of the pieces. These characteristic fracture modes may serve as a guidance for visual inspection of joint quality.

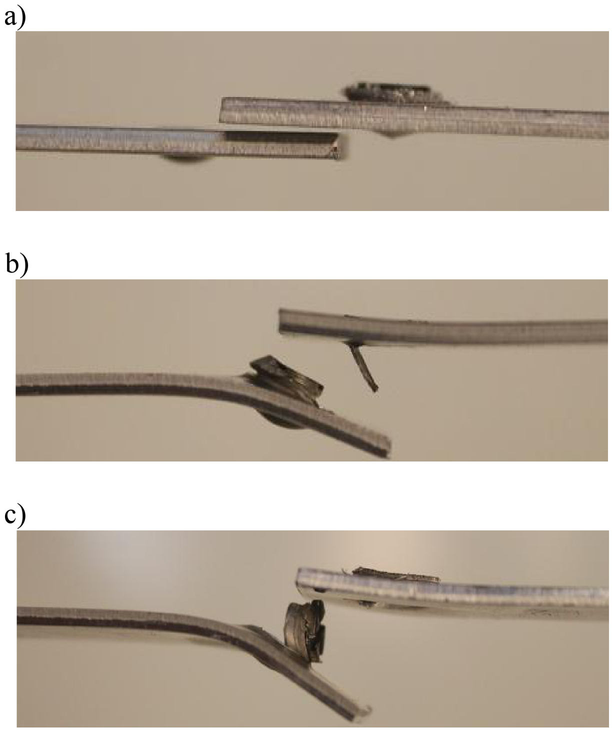

Fig. 9. Failure modes of riveted joints.

The friction-stir riveting technique appears to overcome the difficulties encountered in other joining techniques for light metals and dissimilar metals. The simplicity in equipment, operation and the robustness of this process make friction-stir riveting an ideal alternative to the more traditional joining techniques such as resistance spot welding. This technique can also be applied to other difficult-to-weld metals such as Cu and others for applications such as packaging of power battery packs.

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