Mechanical behavior and fracture of easily-decomposable dissimilar-materials-joint fabricated by friction stir forming

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Abstract
In this paper, the authors discuss dissimilar materials joining structures fabricated by friction-stir forming (FSF) and easily decomposable. Dissimilar-materials-joining has been successfully studied as a key for new producing light-weight parts; however, it can be a barrier to recycling in the future. The authors suggested the concept of easily separable joining of dissimilar materials employing friction-stir forming (FSF). A joined plate having a keyhole was prepared and put into a mold having a hook cavity. An aluminum alloy plate was put on and friction stirring was conducted on its back surface. Due to the massive heat and compression force generated by the friction stirring, a hook-like joint was successfully generated, and the substrate and joined member are sheared to disconnect them by hitting with a plastic hammer; however no room was observed between the hook and joined material after forming. Opposite hooks generated by the above approach join dissimilar materials tightly, but the materials can be separated smoothly after cutting them between the hooks.

In the experiment, a pair of a 0.8mm-thick JIS SPCC steel sheets and a 3mm-thick JIS A5083P-O aluminum alloy plate was joined. The authors evaluated the joints by tensile and shear tests and discuss their mechanical behavior and failure. The tensile strength of the joint was 652N (average). In the tensile tests, the deformation of the keyhole of 0.8mm-thick SPCC steel sheet caused the failure of the joint. The shear strength was affected by the shear direction, i.e. 1010N at 0deg, 705N at 45deg, and 1320N at 90deg (average) for the connecting line between hooks. It was thought that the hook-like joints had enough strength for the cross-sectional area of their stems (i.e. 4.16mm²).

Keywords : Friction-stir forming, Dissimilar materials joining, Recycling, Separable/decomposable joint, Shear test, Tensile test

1. Introduction

Recently, joining dissimilar materials, including steel, CFRP, and aluminum alloy, has been successfully studied due to multiple materials used in the structure of automobiles. However, such multiple-material products will be a problem for recycling. Joining the materials more tightly and wholly makes it more difficult to separate them in the recycling procedure. Therefore, it is worthwhile to discuss methods for easily decomposable joined dissimilar materials.

Figure 1 depicts the schema of friction-stir forming (Nishihara et.al., 2002, 2003). In the process, material is put on the die, and friction stirring is conducted on its back surface to transfer the shape of the die to it. Friction-stir processing was originally invented by TWI in the UK (Thomas 2001). Friction stirring has begun to be applied for material forming as well as the friction-stir forming, i.e., for incremental forming, by Otsu et al. (2014) and Matsumoto et al. (2015) and for boss generation on a plate by Yukutake et.al.(2012).

The authors studied fastenerless riveting, in which process a rivet-like structure is generated by the friction-stir forming with utilizing a die to join steel and aluminum alloy plate, and CFRP and aluminum alloy plate (Fig. 2)(Ohashi et.al, 2016, 2017a). In this paper, the authors propose a concept to easily separate joined dissimilar materials employing...
friction-stir forming (FSF) and report its demonstration, mechanical behavior, and failure.

Fig. 1 Schematic Drawing of FSF. (Nishihara et.al., 2003). A material plate is put on the die, and friction stirring is conducted on its back surface. The material deforms and precisely fills the cavity of the die due to high pressure and heat caused by friction stirring. This process is utilized for metal forming (i.e. die-forming), not for metallurgical welding.

Fig. 2 Fastenerless riveting utilizing friction-stir forming. (Ohashi et.al, 2016). First, a substrate which is capable for friction stirring, e.g. an aluminum alloy plate, was put on a dissimilar material plate having prepared holes. These members were put on a die having the cavity to fabricate the head of the rivet-like structure. Next, FSF is conducted to generate the rivet-like structure joining dissimilar materials.

2. Concept of easily-decomposable joined dissimilar materials

Figure 3 depicts the concept of easily separating joined dissimilar materials. First, a keyhole was prepared on the sheet to be joined. The sheet is then put on a mold having a hook cavity. In addition, the mold occupies a part of the keyhole to save space after processing. The substrate, i.e., aluminum alloy plate, is put on them and friction stirring is conducted on its back surface. Due to massive heat and compression force generated by friction stirring, a hook-like joint is generated to join them. The materials can be disassembled after processing by sliding them. By generating location pins or opposite hooks together to prevent materials from sliding, the materials can be hold tightly. In
recycling, the materials are able to be separated smoothly after destroying the location pins or cutting the materials between the hooks.

(1) Structure of the die and keyhole for generating a hook-like joint by FSF.

**Fastening methodology:**
Additional location pin(s) or screw(s)

After loosening or destroying a pin/screw(s), the materials become separable.

Hook-like joint(s)  Location pin or screw(s)

(Location pins can be generated by FSF as well.)

Fastening methodology:
Multiple joints interfering sliding each other.

After cutting the materials between the hooks, the materials become separable.

Cut line

Hook-like joint  Hook-like joint

(Joints can share one key hole.)

(2) Fastening and separating methodologies

Fig.3 Schematic drawing of easily-decomposable dissimilar materials joined by FSF. First, a keyhole was prepared on the sheet to be joined. The sheet (i.e. joined member) is then put on a mold having a hook cavity. In addition, the mold occupies a part of the keyhole to save space after processing (i.e. mask). The host member is put on them and friction stirring is conducted on its back surface to generate a hook-like structure to join the members. The materials can be disassembled after processing by sliding them. By generating location pins or opposite hooks together to prevent materials from sliding, the materials can be hold tightly. In recycling, the materials are able to be separated smoothly after destroying the location pins or cutting the materials between the hooks.

3. Experiment for proof of concept and forming conditions

Figure 4 presents the dimensions of the die cavity and the keyhole on the joined member for the proof of concept experiment. We prepared the keyhole as two overlapped circles 4mm and 6mm in diameter. A 4mm wide, 2mm deep groove was the die cavity for the head of the hook-like joint. A 3mm-thick JIS A5083P-O aluminum alloy plate was the host member, and a 0.8mm-thick JIS SPCC steel sheet was the joined member. A5083 is one of the strongest non-heat-treated aluminum alloys, of which softening due to the heat affect in friction stirring was expected to be
suppressed comparatively with other aluminum alloys (Ohashi et al. 2017b). We inserted a 6mm diameter pin into the
die to hide the larger diameter as the mask. The level of the top of the pin met the bottom surface of the joined member.
In this case, the area of the aperture of the die was calculated as 4.16mm$^2$, which is equivalent to the area of the
2.3mm-diameter cavity, and the volume of the hook-like joint was 19.5mm$^3$.

A friction stirring tool having a 5mm-diameter and 2.5mm-height cylindrical probe with 20mm-diameter shoulder
was employed for the experiments.

Figure 5 plots the volume of cylindrical extrusions generated by FSF on the same substrate with the same tool as in
the previous study (Ohashi et al. 2016). For a 2.3mm-diameter cavity, the volume of an extrusion generated by spot FSF
(i.e., $V_t=0$mm/min) was expected to be 20.2mm$^3$ from the figure. Hence, we applied the spot FSF without tool travel.
The tool spindle speed was 1240rpm, and the plunge depth was 2.7mm.

Figure 6 depicts an example of a single hook-like joint generated by the FSF. A small underfill-part was observed
at the upper side of the tip of the hook joint. The cause of the underfill may be the folded shape of the die-cavity that
increased friction resistance and heat removal. However, the underfill location was not thought to have a significant
effect on the strength of the joint, because it was unrelated to the cross-sectional areas associated with the strength.

The substrate and joined member are sheared and separated by hitting them with a plastic hammer with only
human power. However, no room was observed between the hook and joined material after formation. Figures 7 and 8
depict the separated hook and the joined member. No deformation of the joined member and no metallurgical bonding
were observed around the keyhole, though there were burn marks. Hence, the hook was able to slide to the keyhole, i.e.
for unlock direction, without resistance.

Thus, the authors confirmed the concept of fabricating easily separable dissimilar material.

![Fig.4 Dimensions of the die and the keyhole of the joined member for generating a single hook-like joint. The authors prepared the keyhole as two overlapped circles 4mm and 6mm in diameter. A 4mm wide, 2mm deep groove was the die cavity for the head of the hook-like joint. A 6mm diameter pin was inserted into the die as a part of the die to hide the larger diameter of the keyhole to spare the space after FSF.]

![Fig.5 Volume of cylindrical extrusions on A5083 plate generated by FSF. (Tool spindle speed $n =1240$rpm, tool plunge](image)
depth $z_p = 2.7\text{mm}$ (Ohashi et al., 2017). For narrow cavities with diameters less than 6-mm, the extrusions generated by the spot FSF were taller than those generated by FSF with tool travel. However, the opposite result was seen for wide cavities with diameters exceeding 5mm. The authors expect that there are two key factors for estimating the forming limit in FSF. The one for narrow die cavities is compression force inside the material and softening of the material; the one for wide die cavities is the amount of deformable material volume generated by friction stirring. In spot FSF, tool plunge force increases the compression force inside the material, hence it applies more to the former condition.

![Image](image1.png)

**Fig. 6** Fabricated hook-like joint and the joined member after the process. A small underfill-part was observed at the upper side of the tip of the hook joint. However, the underfill location was not thought to have a significant effect on the strength of the joint, because it was unrelated to the cross-sectional areas associated with the strength.

![Image](image2.png)

**Fig. 7** Fabricated hook-like joint after separation. A hook-like structure was successfully generated and separated easily with only human power.

![Image](image3.png)

**Fig. 8** Joined member (SPCC sheet) after separation (host material side). No deformation of the joined member and no metallurgical bonding were observed around the keyhole, though there were burn marks. Hence, the hook was able to slide to the keyhole, i.e. for unlock direction, without resistance.

4. **Experiment for observing the mechanical behavior and failure**

A pair of opposite hook-like joints, of which the die is depicted in Fig. 9, was generated for examining their mechanical behavior and fracture. It is confirmed that the joint was separable by cutting the product between hooks. The shapes of the hooks were measured by non-contact 3D measurement system KEYENCE VR-3200. The volumes of generated hooks were $19.57\text{mm}^3$ and $18.03\text{mm}^3$, and were close to the designed value $19.5\text{mm}^3$ estimated with Fig.5.
Fig. 9 Design of the die and the keyhole of the joined member to generate a pair of opposite hook-like joints, and actual fabricated joints. (1) The volume of the one hook was designed as 19.5 mm³. (2) A pair of hook-like structures was successfully generated. (3) Volume of the structures were close to the design.

Tensile and shear tests were conducted as shown in Fig. 10. The test was performed with a universal testing machine, SHIMADU AUTOGRAPH AG-250kN with a ram speed of 1mm/min. There were four samples for each test. Tensile and shear strength of a pair of the opposite hook-like joints are plotted in Fig. 11. The tensile strength of the joint was 652N (average). The shear strength was affected by the shear direction, i.e. 1010N at 0deg, 705N at 45deg, and 1320N (average) at 90deg for the connecting line between hooks. Figures 12 and 13 depict typical failures in the tests. In the tensile tests, the deformation of the keyhole in 0.8mm-thick SPCC steel sheet caused the joint failure. In the shear tests, the deformation of the hooks caused the joint failure. Both of hooks was sheared at 90 deg, and either hooks was done at 45 deg. At 0 deg, either hooks was pulled down.

The strength of a rivet in a shear test is generally evaluated by both shear strength and bearing strength. Shear strength of a rivet is estimated by the area of shearing and the shear strength of the material, and it is isotropic. However, bearing strength of the assigned joints may display anisotropy, not only because of the disposition of hook-like joints, but also because of the noncircular cross-sectional stem of each joint. To achieve flexural rigidity in the bearing-force direction (i.e., the moment of inertia of the area), 90deg is the best, and 45deg is the next best. To achieve bearing stress, the bearing length is shortest at 90deg and next shortest at 45deg. Thus the order of magnitude of bearing stress is 90deg>45deg>0deg, provided that a hook-like joint bears the same load. From the observation of the fracture of the joints, two hook-like joints bear the load at 90deg, and one joint bears the load at 0deg and 45deg. The strength at 90deg was thus greatest because two hook-like joints supported the load, and 0deg was next. Shearing stress was calculated as 243Mpa for 0deg, 169MPa for 45deg, and 159MPa for 90deg (average). Since proof-stress $\sigma_y$
is 145Mpa and shear strength of A5083 is 170MPa, and since the limit of shear strength of a steel rivet is designed to be 0.7 to 0.9 times yield-stress $\sigma_y$ generally, it was thought that the hook-like joints were strong enough for the cross-sectional area of their stems (i.e., 4.16mm$^2$). Therefore, a larger cross-sectional stem and new keyhole design may be needed for stronger joining.

Fig.10 Schematic drawing of the tensile and shear tests. Bearing strength of the assigned joints may display anisotropy, not only because of the disposition of hook-like joints, but also because of the noncircular cross-sectional stem of each joint. Hence, shear tests were conducted for different three directions.

Fig.11 Tensile and shear strength of a pair of the opposite hook-like joints. (Four samples for each test.) In the shear tests, the strength at 90deg. was the greatest and at 0 deg. was next.
Fig.12 Typical failure in the tensile tests. In the tensile tests, the deformation of the keyhole in 0.8mm-thick SPCC steel sheet caused the joint failure.

Fig.13 Typical failure in the shear tests. In the shear tests, the deformation of the hook caused the joint failure. Both of hooks were sheared at 90 deg, and either hooks was done at 45 deg. At 0 deg, either hooks was pulled down.

5. Summary

In this paper, the authors propose the concept of easily separable joining of dissimilar materials employing friction-stir forming (FSF) and report its demonstration and its mechanical behavior and failure. A hook-like joint was generated successfully, and the substrate and joined member are sheared to disconnect them by hitting with a plastic hammer; however no room was observed between the hook and joined material after forming. The joined member around the keyhole was not deformed, though there were burn marks. Thus, the authors confirmed the concept of fabricating easily separable joined dissimilar-materials. The authors evaluated the joints by tensile and shear tests and discussed their mechanical behavior and failure. The tensile strength of the joint was 652N (average). In the tensile tests, the deformation of the keyhole of 0.8mm-thick SPCC steel sheet caused the failure of the joint. The shear strength was affected by the shear direction, i.e. 1010N at 0deg, 705N at 45deg, and 1320N at 90deg (average) for the connecting line between hooks. It was thought that the hook-like joints had enough strength for the cross-sectional area.
of their stems (i.e. 4.16mm$^2$). Hence, a larger cross-sectional stem and new keyhole design will be needed for stronger joining in the future.

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