Finite element analysis of self-piercing riveting of aluminum alloy and carbon fiber reinforced polymer composites

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Abstract. Self-piercing riveting (SPR) is a high-speed fastening process that can join similar and dissimilar sheet materials without the need for pre-processing such as drilling or punching. During SPR processes, two overlapping sheets are joined by a rivet. The upper sheet is punched first by the rivet and then the lower sheet is deformed between the rivet and the die, creating a mechanical interlock. In this study, self-piercing riveting of aluminum alloy and carbon fiber reinforced polymer composites (CFRP) sheets was analysed using finite element simulations. For the validation of the composite material model, the punching process of CFRP was performed and the results were compared with FE predictions. The SPR process of the aluminum alloy and CFRP was simulated numerically and the performance of the joint was evaluated.

1. Introduction

Currently, many researches are being conducted on utilizing various materials such as aluminum, magnesium, high strength steel, and composite materials for achieving light weight and high strength. In particular, for automobile body parts such as A-pillar, B-pillar, and side seal, carbon fiber reinforced polymer (CFRP), aluminum alloy, and advanced high strength steel sheets are attempted to be used to reduce weight. In order to use various materials together, not only forming technology but also technology for joining different materials must be developed.

Conventional joining techniques have been used to join similar materials mainly using heat sources. Spot welding, arc welding, laser welding, and friction stir welding are the typical welding methods using these heat sources. However, they are not suitable for joining materials with different thermal and mechanical properties. In addition, although there is a method of using an adhesive, this method generally does not satisfy the bonding strength.

One method of joining different types of materials is self-piercing riveting (SPR). Because of the mechanical bonding, it can be used with adhesive bonding, and materials with different thermal and mechanical properties can be easily bonded. SPR is widely used because the materials can be joined in a very short time so that it can easily be added to a part production line. Various studies related to SPR have been conducted. In addition to the study of SPR joining similar or different materials, the effect of plate thicknesses and combinations in the SPR process, the joining ability of rivet material to aluminum, and the effect of friction were studied [1-4]. Studies on the strength of SPR junctions and numerical analysis of SPR joint were conducted [5-12].

In this study, the SPR joint of CFRP plate and Al7XXX alloy plate is analysed numerically. There are many experimental papers on this topic, but not many numerical studies were conducted. Since the
physical properties of the composite material and the metal sheet are very different, it is challenging to analyse the joining process numerically.

2. Process of Self-Piercing Riveting
SPR consists of four processes. The first process is the clamping process, where the top and bottom materials are held in place by the holder to prevent movement between the rivet and the die, and the rivet is placed perpendicular to the top material. The next step is piercing, through which the rivet penetrates the top material by the force that goes into the punch. When the rivet that completely penetrates the top material meets the bottom material, the rivet tail opens and the rivet and the plates undergo deformation together. This is called the flaring process. Finally, a compression process ends where the rivet is compressed to the end with the specified stroke or force. The shape of the rivet used in this study was a semi-tube and a flat die was chosen for the Al7XXX alloy sheet to avoid the fracture.

3. Material Properties

3.1. Sheet material
The plates used in this study are CFRP composite plates and Al7XXX alloy plates. CFRP is a brittle material with no plastic deformation. The brittle material of the SPR process cannot be used for the bottom material. The CFRP composite plate used in this study is a uni-direction plate and has anisotropic mechanical properties. The physical properties of CFRP composites were assumed to be orthotropic and the strength and stiffness values for each direction were used (Figure 1). The direction of piercing is the direction of thickness, and the physical property in the thickness direction is difficult to measure or estimate. The stiffness values are calculated as follows.

\[ \nu_{21} = \nu_{12} \left( \frac{E_{22}}{E_{11}} \right) \]  
\[ \nu_{23} = \nu_{32} = \nu_{12} \left( \frac{1-\nu_{21}}{1-\nu_{12}} \right) \]  
\[ G_{23} = \frac{E_{22}}{2(1+\nu_{23})} \]

where the indices 1, 2, and 3 represent the fiber, transverse and thickness directions, respectively. \( E_{ii} \) is the stiffness in the i direction, \( \nu_{ii} \) is the Poisson ratio in the i direction, and \( G_{ii} \) is the shear stiffness in the i direction. The criterion for determining fracture is calculated by the strength and shear stiffness in each direction using the Hashin's damage model.

![Figure 1](image1.png)

**Figure 1.** Schematic description of CFRP composite and Al7XXX SPR setting.
Aluminum 7XXX alloy sheet was evaluated for mechanical properties by uniaxial tension test. The strain was measured using a digital image correlation system (Figure 2).

3.2. Rivet material
Rivets should be stronger than the base sheet used in the process because they must not break during the SPR process. In this study, high-strength steel with a strength higher than Al7XXX alloy plate or CFRP composite plate was used. The mechanical properties were evaluated by the uniaxial tension test (Figure 3).

Figure 2. Image of Al7XXX alloy sheet uniaxial tension test digital image correlation system.

Figure 3. Uniaxial tension test of cylindrical specimen made by rivet steel material.

4. Numerical Analysis
Numerical analysis was done using a commercial FE program, LS-DYNA explicit. The 3D model was used to implement the CFRP composite properties with significant deformation in the thickness direction. The die was assumed to be rigid, and a uniform force was applied to the rivet head (Figure 4). The measured properties of rivets and plates were used. The half model was used to reduce the computation time.

Figure 4. Schematic description of CFRP composite and Al7XXX SPR setting.

5. Conclusion
In this study the self-piercing riveting process of CFRP composite plate and Al7XXX alloy plate were simulated numerically. It can be seen that the composites on the top are easily punched and have little effect on the deformation of the semi-tube rivet. After that, when the rivet meets the bottom sheet, the rivet tail opens. The amount of opening was smaller than that of the metal-metal joint, interlock distance [13]. Figure 5 shows an experiment in which the SPR process was performed by changing only the top plate to a DP780 steel sheet with a thickness of 1.6 mm and a model that analyzed it numerically. When the top plate was CFRP composite, the interlock distance was 0.35 mm on average, whereas when the top plate was DP780, the experimental and numerical values were larger, 0.74 and
0.63 mm, respectively, despite the smaller thickness. It seems that the deformation of the top plate and rivet when the rivet penetrates the top plate affects the interlock distance.

![Figure 5](image)

**Figure 5.** Average interlock distance of cross-section (a) numerical model of CFRP composite 2.3 mm at top plate, (b) experiment of DP780 1.6 mm at top plate, (c) numerical model of DP780 1.6 mm at top plate SPR joint.

6. References

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