Numerical evaluation of mechanical performance for self-piercing riveted fiber-reinforced plastic and metal sheets

W Noh¹, K Y Park¹, C Kim², M G Lee², C Y Jung³ and J H Song¹*

¹Research Institute of Advanced Manufacturing Technology, Korea Institute of Industrial Technology, Gaetbul-ro 156, Incheon 21999, Republic of Korea
²Department of Materials Science and Engineering, Seoul National University, Gwanak-ro 1, Seoul 08826, Republic of Korea
³Daewoo Industrial R&D Center, Simindae-ro 109-35, Gyounggi 14042, Republic of Korea

* jhsong@kitech.re.kr

Abstract. Finite element analysis is presented to evaluate the mechanical performance of self-piercing riveted fiber-reinforced plastic and metal sheets. The mechanical properties of the rivet and the sheets subjected to joining are considered for reliable simulation. Yielding and hardening behaviour of the rivet was inversely characterized by a coupled experimental-numerical analysis of a compression test, while those of the sheets were deduced by directional tensile test as usual. Fracture criterion was characterized and considered only in the sheets. The geometric features of the die and the rivet were also quantitatively measured and applied to the simulation as the boundary conditions. Consecutive simulations of riveting process and tensile shear test were carried out, which leads to determining sensitivity of peak load to characteristic rivet-joining features such as interlock and bottom thickness.

1. Introduction

It is one of main concerns in automotive industry that emission of exhaust gas should be reduced without loss of structural robustness in order to comply to environmental regulation getting more severe globally. Not only is structural design being changed for improving crashworthiness without gain of car body weight, but use of lightweight materials is extensively increasing in chassis and hang-on parts for dramatic reduction of weight [1].

Many kinds of ferrous alloy sheets have been developed and applied for accomplishment of large strength with minimization of formability reduction. Specific strength, ratio of strength to mass, of high strength steel is higher than conventional steel so that parts formed from high strength steel can contribute to weight reduction [2]. Non-ferrous alloys such as aluminum and magnesium alloys having low density are also put into sheet metal forming process of parts. Due to their lower formability than ferrous alloys, in general, pre- or post-processes are required for application of press-forming to them [3, 4]. In the latest, there are efforts to apply fiber-reinforced plastics into massive car production in that they possess most superior specific strength, in spite of most inferior ductility among the materials mentioned [5].

Efficient loss of car body weight needs to select a kind of light weigh materials according to specific use of a part. Assembly of parts require joining of dissimilar materials essentially for manufacturing a multiple material car body. There are large differences of thermal and electrical
properties between ferrous, non-ferrous, and composite materials so that fusion welding methods, e.g., spot, laser, and arc welding, is almost not applicable. As alternatives, mechanical joining methods are increasingly used for assembly of multi-material parts [6]. When using mechanical joining methods, selection of materials to be formed is comparatively free from consideration of chemical composition influencing their thermo electrical properties. Among various mechanical joining methods, in recent, self-piercing riveting (SPR) process is receiving much attention and increasing in application to manufacturing process because of its fast operation time per cycle as well as strong ability to fastening target sheets.

Experimental and numerical study on evaluation of the mechanical performance of self-piercing riveted (SPRed) fiber-reinforced plastic and metal sheets is presented in this paper. The mechanical properties of the rivet and the sheets subjected to joining are considered for reliable simulation. Yielding and hardening behavior of the rivet was inversely characterized by a coupled experimental-numerical analysis of a compression test, while those of the sheets were deduced by directional tensile test as usual. Fracture criterion was characterized and considered only in the sheets. The geometric features of the die and the rivet were also quantitatively measured and applied to the simulation as the boundary and initial conditions, respectively. Consecutive simulations of riveting process and tensile shear test were carried out, which leads to determining sensitivity of peak load to characteristic rivet-joining features such as interlock and bottom thickness.

2. Experimental procedure

2.1. Tensile test of sheet materials

A dual phase steel, GA590, and a strain-hardened Al-Mg alloy, Al5052-H32, are selected as target metal sheets to be joined. Two kinds of GA590 are 0.8 and 1.0 mm thick, while Al5052-H32 is in four different thicknesses: 1.2, 1.5, 2.0, and 2.5 mm. Hardening behavior of the metal sheets were evaluated through uniaxial tensile test by following the standard of ASTM E 8. Anisotropy of the metal sheets was ignored for simplification of analysis so that along only the rolling direction was tensile test carried out.

Tensile test was also used to induce rupture of the metal sheets. Under tensile loading, respective specially-designed specimens [7], depicted in Figure 1, lead loading path close to uniaxial tension and pure shear modes in the region where major deformation is concentrated.

A certain joining combination involves a carbon fiber reinforced thermoset plastic (CFRP) sheet with the thickness of 0.8 mm. With thermoset epoxy utilized, eight plies of unidirectional fibers are laminated as cross-ply of [0/90]4, and the laminated sheets were applied to SPR process. For mechanical property characterization of CFRP, a unidirectional sample, whose constituent plies are parallel to one another, was also fabricated and subjected to tensile test. The standard of ASTM D3039, whose specimen shape is drawn in Figure 2, was followed to measure the nominal stress-strain curves along 0, 45, and 90° with respect to the embedded fiber direction. Moreover, critical stress to rupture was analysed from the tensile test results because rupture of CFRP shows brittleness, in general.
2.2. Compression test of rivet
Rivet piercing and its skirt spreading play major role in formation of joint such that mechanical property of rivet should be considered in analysis of SPR process. Compression test was applied to measure the load-displacement curve of the machined-rivet whose head and tail was removed, as shown in Figure 3. Looking like hollow cylinder shape, the machined-rivet was subject to compression in either axial direction or radial direction, complementarily. Rivet employed in this study is made from boron steel with post for heat-treatment for ensuring high strength.

![Figure 2. Schematic of specimen for uniaxial tensile test of CFRP sheet.](image)

![Figure 3. Compression test of rivet: (a) machined rivet and (b) schematic of compression test.](image)

2.3. Self-piercing riveting and tensile shear test
SPR process was used to join dissimilar combination of the sheets presented above. Various dissimilar riveted joints of GA590 and Al5052 was fabricated with thickness variation of Al5052, where top layer was GA590 with the constant thickness of 1.0 mm. Process parameters were optimized, as listed in Table 1, to meet the guideline for enough interlock. Especially for rivet, characteristic shape is same, but different length was applied to SPR as different thickness of Al5052. Cross-sections of SPRed joints were observed to identify joint characteristic such as interlock and bottom thickness, as shown in Figure 4. Strength of SPRed joint was measured by tensile shear test. Misalignment was prevented by attaching spacer to specimen. Tensile load was increasingly imposed to the specimen until fracture appeared at the peak load and load then decreased. Peak load and fractured specimen are shown in Figure 5 and 6, respectively. Meanwhile, there was struggle to join a triple layer involving CFRP sheet by SPR, in which CFRP, GA590, and Al5052 are upper, middle, and lower sheets, respectively. Successful case, however, could not be found out even though numerous combinations of experimental process parameters valid in circumstances offered. It is numerical analysis that enabled to achieve SPR joint of triple layer with formation of interlock by suggesting a new design of die, as illustrated later.

3. Results and discussions

3.1. Characterization of material properties
Mechanical properties of materials constituting SPRed joint were obtained by analysis of experimental test results. As for sheet materials, their mechanical properties were examined based on tension test
results. Due to showing ductile response to external loading, as usual, metal sheets are described as a material model showing elasto-plastic response and ductile fracture. From the standard tensile test results, Young’s modulus and parameters of a Swift-type hardening model was determined, as listed in Table 2. A modified Mohr-Coulomb fracture criterion, newly proposed in this study, was used to specify fracture criterion and was inversely calibrated by numerical simulation of test results of the specimens shown in Figure 1, in which details of the numerical inverse method for calibrating fracture criteria can be referred to a previous study [8]. Meanwhile, anisotropy of metal sheets and property difference as thickness varies was ignored for simplification of analysis so that influence of metal sheet thickness on joint characteristics is revealed clearly as presented in the below section.

| Material combination (upper to lower) | Thickness combination [mm] | Rivet length [mm] | Rivet diameter [mm] | Rivet type | Die | Pre-clamping force [kN] | Setting force [kN] |
|--------------------------------------|---------------------------|------------------|-------------------|-----------|----|------------------------|-------------------|
| GA590/Al5052                         | 1.0/(1.2, 1.5, 2.0, 2.5)  | 4.0, 4.5, 5.0, 5.5 | 5.3               | C typeFM | 030 2 | 4                      | 45                |
| CFRP/Al5052                          | 0.8/1.2                  | 5.5              | 5.3               | C typeNew design | 4 | 40                     |

CFRP sheet is confirmed to show brittle mechanical behavior by tensile test. Linear elasticity and stress-based brittle fracture criterion were applied for characterization of its mechanical properties. Since its directional behavior was observed to be very different, CFRP is described as an orthogonal elastic material. With use of Hooke’s law, components of stiffness tensor were characterized, and their values are listed in Table 3. As for fracture criterion of CFRP, critical value of von Mises equivalent stress was defined.

![Figure 4](image1.png)  
**Figure 4.** Joint characteristics for GA590-Al5052.

![Figure 5](image2.png)  
**Figure 5.** Peak load during tensile shear test.

Compression test of the rivet body cannot induce uniform deformation in both radial and axial loading directions due to geometry of the tubular shape. Numerical analysis was employed to inversely characterize hardening behaviour from the compression test results and resulting hardening parameters are listed in Table 2.
3.2. Strength analysis of self-piercing riveted sheets

Joint geometry and strength of SPRed sheet metals were evaluated by finite element (FE) analysis of experimental test results. FE model was established by implementing continuum three dimensional elements for sheets and rigid body elements for tools. As characterized earlier, material properties were implemented into the FE model. Especially, ductile fracture model was also adopted to make reproduction of fracture on simulation because SPR process and tensile shear test accompany fracture of the sheet. Simulation of SPR process and tensile shear test was successfully carried out with axisymmetric and half-symmetric boundary conditions, respectively, as shown in Figure 8. As for joint characteristics, similar trend was observed between calculation and measurement, in which interlock and bottom thickness increase as lower sheet gets thicker, as shown in Figure 4. Furthermore, peak load as well as fracture pattern in tensile shear test was reproduced similarly by simulation, as shown in Figure 5 and 6, and capability of the FE model to predict mechanical performance was then confirmed. Though there are gap between measured and calculated values especially for joint geometry, overall joint geometry is quite similar so that gap does not make significant effect on prediction of mechanical performance.

![Figure 6. Comparison of fractured tensile shear specimens between experiment and simulation.](image)

![Figure 7. Modified M-C fracture criterion: (a) shape in principal stress space and (b) calibrated fracture strains as a function of stress triaxiality.](image)

| Material  | Young's modulus (GPa) | Poisson's ratio | Yield strength (MPa) | Swift model parameters |
|-----------|-----------------------|-----------------|----------------------|------------------------|
|           |                       |                 |                      |                        |
| Al5052    | 63.0                  | 0.33            | 238                  | 419                    |
| GA590     | 177                   | 0.30            | 373                  | 1060                   |
| Rivet     | 210                   | 0.30            | 1200                 | 1710                   |

Swift type hardening model, \(\sigma = K(e_0 + \varepsilon)^n\)

3.3. Tool design for self-piercing riveting of CFRP and metal sheets

Iterative virtual experiment of SPR process drew a new design of die for joining the triple layer involving the CFRP sheet. Since conventional dies led to deficient interlock, die shape was modified...
in the FE model implementing the material properties characterized already. FE simulation was executed with quarter-symmetric boundary conditions due to orthogonal anisotropy of the CFRP sheet, as shown in Figure 9. From FE simulation, the joint geometry could be calculated and was accounted for change of die shape in terms of slope and diameter. There was sufficient interlock calculated by simulation with an optimized die shape, as shown in Figure 10. In the process with a conventional die, rivet after piercing high strength CFRP sheet has lack of linear momentum and cannot, in turn, form interlock even with rivet buckling. By comparative examination with a conventional die, FM-type, inclined angle was introduced into the optimum die in order to make it easier for rivet shank to penetrate into the lower sheet.

![Figure 8. Boundary conditions imposed for FE analysis of (a) SPR process and (b) tensile shear test.](image)

| $C_{11}$ | $C_{22}$ | $C_{33}$ | $C_{23}$ | $C_{31}$ | $C_{12}$ | $C_{44}$ | $C_{55}$ | $C_{66}$ | Others |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|
| 121     | 8.8     | = $C_{22}$ | 3.17    | = $C_{31}$ | 4.02    | = $C_{35}$ | 2.82    | 3.53    | 0.0    |

*unit= GPa; 1=fiber, 2=transverse, 3=normal direction*

![Figure 9. Boundary conditions imposed for FE analysis of SPR process involving CFRP sheet.](image)
4. Conclusions
There is investigation of mechanical characteristics for SPR joints of dissimilar combinations of lightweight sheet materials: Al5052, GA590, and CFRP. Riveting process and tensile shear test were simulated by the FE model constructed in this study. Mechanical properties of constituent parts, especially for rivet, were characterized and implemented into the FE model. Joint characteristics predicted by FE simulation shows similar trend with experiment, in which both interlock and bottom thickness get larger as lower sheet get thicker. Furthermore, the FE model achieved reliable prediction of not only tensile shear strength but fracture pattern. For joining a triple-layer sheets including CFRP, besides, die design was newly devised by simulation of SPR process in which slope and diameter was adaptively changed based on analysis of failure cases.

![Simulated joint formation with use of (a) conventional FM-type die and (b) newly-designed die](image)

**Figure 10.** Simulated joint formation with use of (a) conventional FM-type die and (b) newly-designed die

References

[1] Song J H, Choi S, Kang M J, Kim D, Lee M G and Lim C Y 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **159** 012003
[2] Bouaziz O, Zurob H and Huang M 2013 *Steel Res. Int.* **84** 937-947
[3] Mahabunphachai S and Koç M 2010 *Mater. Design* **31** 2422-2434
[4] Toros S, Ozturk F and Kacar I 2008 *J. Mater. Process. Technol.* **207** 1-12
[5] Koronis G, Silva A and Fontul M 2013 *Compos. Part B: Eng.* **44** 120-127
[6] Han L, Thornton M and Shergold M 2010 *Mater. Design* **31** 1457-1467.
[7] Mohr D and Marcadet S J 2015 *Int. J. Solids Struct.* **67–68** 40-55
[8] Noh W, Kim W, Yang X, Kang M, Lee M G and Chung K 2017 *Int. J. Mech. Sci.* **121** 76-89