Form-fit joining behaviour between an aluminium tube and sheet using electromagnetic forming

Hyeonil Park¹,², Jinwoo Lee¹, Se-Jong Kim¹, Youngseon Lee¹ and Daeyong Kim¹*

¹Materials Deformation Department, Korea Institute of Materials Science, 797 Changwondae-ro, Changwon, Gyeongnam 515508, Republic of Korea
²Department of Mechanical Engineering, Pusan National University, 2 Busandaehak-ro 63beon-gil, Busan 609-735, Republic of Korea

*daeyong@kims.re.kr

Abstract. The electromagnetic forming (EMF) process is a typical high speed forming technique using Lorentz forces generated by interaction between the magnetic field and induced electric current. Recently, researchers have discussed form-fit joining using tube compression by EMF without additional connection elements for application in the industry. This paper provides analysis into the form-fit joining behaviour achieved by tube expansion using EMF. The aluminium 6063 tube was inserted into an aluminium 7075 sheet with hole of the same size as the diameter of the tube, and they were fixed on the coil. The flanging and bulging of the tube were simultaneously conducted by the magnetic force with given charging voltage, and then the form-fit joining was achieved between the tube and sheet. To investigate the effect of the input voltages, the experiments were performed with various charging voltages from 5.7 kV up to 11.1 kV. In addition, the connection strength of the joined specimen was measured by the pull-out test between the tube and sheet. As a result, the connection strength was stronger than the yield strength and lower than the tensile strength of the aluminium 6063 tube.

1. Introduction

As the problem of air pollution caused by industrialization have begun to be serious in the latter half of the 20th century, the stricter emission standards were implemented [1], and the fuel consumption of vehicles in the automobile industry is a topic of constant importance. Improving the automotive mileage can be achieved by enhancing the performance of the internal combustion engine or by reducing the weight of the automotive body. Nevertheless, as the average performance of the internal combustion engine of an automobile had early been optimized, there is not much room for improvement, so the weight reduction of the automotive body has become the most important issue. Several methods have been proposed for lighter automotive body weight, such as applying high strength steel sheet with a high strength per density [2,3], and applying lightweight materials such as an aluminum [4]. When lightweight materials such as aluminum are used to reduce the weight of the body, a space frame structure is often used to increase the rigidity that is lower than the conventional steel [5]. This concept is a method to increase the structural rigidity by a skeleton truss framing, and it was widely used in small-sized production vehicles such as a formula race car of the 1960s. At that time, the productivity of the method was low, so it was not used in the general automotive body, but currently the potential of that approach is re-examined as the reduction of the automotive weight.
becomes important. Directly affecting the productivity of this concept is the joining between the parts such as the extruded aluminum tube that makes up the frame. With regard to joining, it is already known how to use adhesive bonding [6], welding, and fastening by using additional connection elements and the conventional methods often are pushed to their technological and productivity limits.

An alternative method without heating and additional connection elements is joining by electromagnetic forming (EMF), which also has a positive effect on productivity with fast process speed. The EMF process is a typical high speed forming technique using Lorentz forces generated by interaction between the magnetic field and induced electric current [7]. The aluminum tubes, which are mainly applied to the space frame structure, are suitable for applying EMF because they have high electrical conductivity. Recently, a study has been carried out on joining between the aluminum tubes by the tube compression using EMF [8]. However, to apply the space frame structure to an automobile body, it is necessary not only to make joints between the tubes, but also to join tube and sheet such as a bumper and a crash box. In this study, after form-fit joining between the tube and sheet by the tube expansion using EMF, the connection strength was compared with the strength of the base material, and the potential of the process is examined based on the experimental results.

2. Experimental procedure

2.1. Materials

Al-Mg-Si alloys of 6xxx series have wide applications in automotive frame due to their better strength and corrosion resistance compared to other Al alloys (AA) along with good joining capabilities. In this study, experiments were conducted to join AA6063-O extruded tube to AA7075-T6 sheet. The detailed geometries of the specimens are shown in Figure 1. The outer diameter of the AA6063-O tube with a thickness of 3 mm was 100 mm, the length was 150 mm, and the size of the AA7075-T6 sheet with the thickness of 3 mm sheet was 180 mm by 180 mm. The AA7075-T6 sheet had a hole of 101 mm size, taking into consideration the tolerance of 1 mm for the tube diameter.

![Figure 1. The geometry of the specimen for the test: (a) tube specimen, (b) sheet specimen](image)

The mechanical properties of the AA6063-O tube and AA7075-T6 sheet were measured from tensile tests along the extrusion direction and the rolling direction, respectively. The measured mechanical properties of the aluminums are listed in Table 1.

|        | E (GPa) | YS (MPa) | UTS (MPa) | g^UTS (%) | g^fract (%) |
|--------|---------|----------|-----------|-----------|-------------|
| AA6063-O | 68.3    | 58.9     | 107.2     | 23.9      | 35.8        |
| AA7075-T6 | 71.6    | 535.4    | 588.5     | 12.3      | 15.9        |

2.2. Test setup

The EMF apparatus used in this study consisted of a power supply, a capacitor bank and a coil mold. A capacitor bank with a total capacitance of up to 824 μF serves to charge the electric current supplied
by the power supply and the high density electric current charged in the capacitor bank is instantaneously applied to the coil mold to generate the Lorentz force. The maximum working voltage of the apparatus is 17 kV and it corresponds to the maximum stored energy of 119 kJ in the capacitor bank. The charged electric current profiles were measured using a Rogowski flexible coil probe and a storage oscilloscope. The coil is made of pure copper with high electrical conductivity and low yield strength. In this study beryllium copper, which has a 400 % higher yield strength compared to the pure copper, was adopted as a coil material to improve the strength of the coil. As shown in Figure 2, the coil was wound with 17 turns with cross sectional area 27 mm by 3 mm and the gap between the windings is 6 mm and the coil surface was covered by a thin epoxy layer with thickness of 0.5 mm to insulate between the coil and the tube specimen.

![Coil Mold Assembly](image)

**Figure 2.** The configuration of the coil mold for the tube expansion: (a) beryllium coil, (b) coil mold assembly

The die consisted of three parts which were the side, upper and lower part. The fastening shape and structure of each die are shown in Figure 3. The side part fixed the sheet specimen and the upper and lower parts fixed the tube specimen. They were fastened as shown in Figure 3(b), the tube specimen was expanded to the empty space inside the die by the Lorentz force generated using several charging voltages from 5.7 kV to 11.1 kV. The form-fit joining was achieved by the flanging and the bulging and the gap in the tooling for the bulging was 3.5 mm, as shown in Figure 3(c). The shape of the jig which consisted of the upper part, middle part and lower part for the pull out test to measure the connection strength between the sheet part and tube part that were joined with previous the form-fit joining is shown in the Figure 4. To hold the specimen to the jig, bolt holes were machined on each of the sheet specimen and tube specimen. The sheet specimen was placed between the upper and middle parts, and was tightened with bolts and nuts to fasten it strongly. Since the bolts restrained the sheet by passing through the bolt holes of the upper part, middle part and the sheet, it was possible to prevent the rotation under load during the pull-out test. The tube specimen was fixed to the lower part of the jig using the bolts and nuts and the pull out test was carried out by the universal tensile testing machine.
Figure 3. The configuration of die and specimens for the form-fit joining process: (a) assembly procedure, (b) assembly model, (c) joining section

Figure 4. The configuration of the jig for the pull out test: (a) assembly procedure, (b) assembly model

3. Experimental observation

3.1. Form-fit joining
In order to investigate the effect of the charging voltages on the joined shape between the tube specimen and the sheet specimen, the form-fit joining experiments were performed with four charging voltages, 5.7, 7.5, 9.2 and 11.1 kV. These voltages correspond to the energy stored in the capacitor, 6.7, 11.6, 17.5, 25.4 kJ, respectively. The electric current profiles measured from the experiments are shown in the Figure 5. As the charging voltage increases, the peak electric current directly affecting the form-fit joining process increased linearly.
Figure 5. Measured electric current profiles

Figure 6 shows the joined shape of the specimen after the form-fit joining process. It can be seen that the joining was achieved by upper flanging and lower bulging. As the charging voltage was increased, the degree of the flanging and bulging increased. The diameters were measured after joining with respect to the charging voltages, as shown in Figure 7. In the case of the bulging, since the diameter of 105 mm which was the diameter of the die’s bulging portion was the maximum bulging diameter, the formed diameter of the bulging was gradually saturated until the diameter becomes close to 105 mm. When the voltage of 5.7 kV was applied, the formed diameter of bulging and flanging was too small, and the sheet specimen could be pulled out of the tube specimen by hand. When the voltage of 7.5 kV was applied, the formed diameter of the bulging was nearly close to the maximum bulging diameter of the die. However, since the variable small gap between the tube specimen and sheet specimen caused by the 30% less formed diameter of the flanging than the specimen with the charging voltage of 11.1 kV was existed, the connection status was not tight binding. Form-fit joined specimens with charging voltage of more than 9.2 kV were achieved tightly without any looseness. Therefore, measurement of connection strength was carried out for the specimens with relatively well form-fit joints using the 9.2 kV and 11.1 kV charging voltages.

Figure 6. Form-fit joined shape of the specimen with the several charging voltages
3.2. Pull-out test

The pull-out tests were performed to measure the connection strength of the form-fit joined specimen with the charging voltage of 9.2 kV and 11.1 kV, as shown in Figure 8. The pull-out test of form-fit joined specimen with the charging voltage of 9.2 kV was achieved successfully to measure the connection strength of the specimen, even though the bolt holes of the tube specimen was deformed as shown in Figure 9(a). The maximum connection strength of the specimen with 9.2 kV charging voltage is about 69.7 kN. On the other hand, in case of the specimen using 11.1 kV charging voltage, the bolt holes were fractured before the pull-out between the tube specimen and the sheet specimen as shown in Figure 9(b). So, its maximum connection strength could not be measured. Both connection strengths of the form-fit joined specimens were higher than the yield strength of the material and lower than the ultimate tensile strength of that as shown in Figure 8(b). Therefore, it could be seen that the form-fit joining using the tube expansion by EMF can be applied to the joining process between the tube and sheet. Additionally, to measure the connection strength of the 11.1 kV charging voltage specimen and in future, the pull-out test method should be improved.
4. Summary
The form-fit joining experiments using tube expansion by EMF were carried out with several charging voltages from 5.7 kV up to 11.1 kV. With charging voltage of more than 9.2 kV, a successful form-fit joining was achieved without any looseness. Hence, the pull-out tests were performed to measure the connection strength of the previous form-fit joined specimens with respect to the charging voltages of 9.2 kV and 11.1 kV. As a result, the connection strengths of the tightly joined specimen are higher than the yield strength of the original tube material.

Acknowledgments
This study was financially supported by the Fundamental Research Program of the Korea Institute of Materials Science (KIMS).

References
[1] 2009. Setting emission performance standards for new passenger cars as part of the Community’s integrated approach to reduce CO2 emissions from light-duty vehicles. Regulation (EC) 2009 Eur. Parliam. Counc. No.443
[2] Kim D, Park H, Lee J, Kim J H, Lee M and Lee Y 2016 Experimental study on forming behavior of high-strength steel sheets under electromagnetic pressure J. Eng. Manuf. 229 670–81
[3] Park H, Kim D, Lee J, Kim S-J, Lee Y and Moon Y H 2016 Effect of an aluminum driver sheet on the electromagnetic forming of DP780 steel sheet J. Mater. Process. Technol. 235 158–70
[4] Cole G S and Sherman A M 1995 Lightweight Materials for Automotive Applications Mater. Charact. 9 3–9
[5] Birch S 1994 Aluminum Space Frame Technology Automot. Eng. 102 70–3
[6] Corona E and Eisenhour T 2007 Wiping die bending of laminated steel J. Mech. Sci. 49 392–403
[7] Boulger F W and Wagner H J 1960 High velocity metal working processes based on the sudden release of electrical energy DMIC Memorandum (Columbus, Ohio: Defense Metals Information Center)
[8] Erlangung Z 2014 Electromagnetic Form-Fit Joining (Technical University of Dortmund)