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Experimental Study on Optimal Design of High-Strength Rivet for Hot Press Forming Steel With Aluminum

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Abstract

Recently, the automotive industry has seen a global increase in demands for reducing automotive exhaust emissions and carbon dioxide emissions, as well as improving fuel efficiency. There has been continuous research and development focused on vehicle lightweighting. This involves implementing multi-material structures and increasing the proportion of lightweight materials. Additionally, there's a growing trend towards strengthening materials to enhance passenger safety and comply with collision regulations. With the ongoing transition from internal combustion engines to electric vehicles, there is an anticipated increase in the demand for hot press forming steel materials to protect large-capacity batteries in response to the growing eco-friendly automotive market.

In this study, we utilized Self-Piercing Riveting (SPR) technology for joining hot press forming steel materials (1.5GPa & 1.8GPa) with aluminum dissimilar materials. We analyzed the existing quality issues in conventional high strength rivet joints and identified areas requiring improvement. By developing high-strength rivets suitable for joining hot press forming steel materials and aluminum, we successfully ensured the quality of the joint sections through material and shape modifications.

1 Introduction

Hot stamping steel undergoes hot forming at temperatures above 900°C, resulting in a strength of around 400-700MPa during shaping. However, by combining rapid cooling within the mold, a final product with a strength of 1,500MPa can be achieved. Thus, different material properties are required for automotive components depending on the application area. High-strength steel, with tensile strength more than double that of regular steel, allows for reducing plate thickness. Consequently, it is increasingly being applied in structural components such as panels for improved torsional and bending stiffness, as well as passenger protection during collisions. Self-Piercing Riveting (SPR) is a joining method where rivets are pressed using strong pressure from a punch, enabling joining without the need for separate hole processing. It is widely used internationally in dissimilar material joining for lightweighting automotive bodies. When joining ultra-high-strength steel plates with SPR rivets, issues such as rivet softening deformation and cracking due to the strength of the material, as well as buckling under concentrated stress. Therefore, our research focuses on securing rivet strength and improving cracking by analytically approaching geometric design shapes based on applicable materials and heat treatment conditions, followed by prototype production to ensure joint quality.

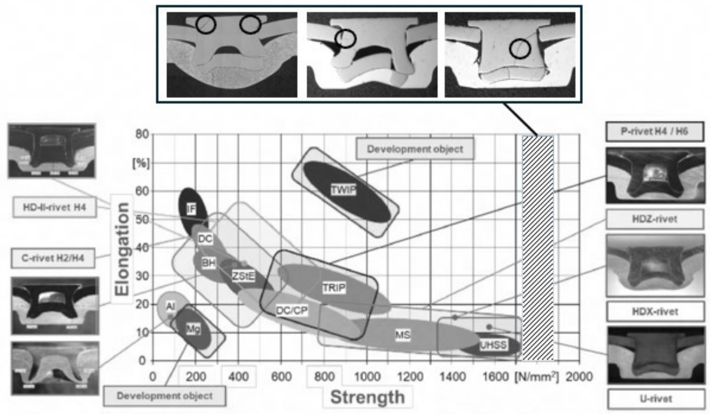

Figure 1: The application range of mechanical joining SPR rivets depends on the material strength and elongation.

2 Material

There was a total of four types of steel wires reviewed in this study. Table 1 shows the components of each wire rod. As a result of analysis of the components of each commercialized high-strength rivet types, the carbon content was generally found to be 0.36% to 0.47%, and the silicon content was found to be 0.05% to 0.08%.

Accordingly, selected a Steel wire rod with a high carbon content with the goal of increasing the material strength and hardness. Due to the nature of rivet plastic deformation, it is believed that toughness should also be considered when selecting a material.

Table 1: Chemical components of applied materials in this experiment

Rivet Material Type	C, wt.%	Mn, wt.%	Si, wt.%
Cr-Mo Steel Wire Type	0.40-0.45	0.70-0.80	0.10-0.20
Bearing Steel Wire Type#1	0.55-0.60	0.75-0.80	0.20-0.30
Bearing Steel Wire Type#2	0.90-1.00	0.30-0.40	0.20-0.30
Spring Steel Wire Typ	0.50-0.60	0.70-0.80	0.20-0.30

The materials used for joining dissimilar materials were 1.2mm of 1.5GPa and 1.8GPa hot press forming material and 2.0mm of aluminum 6000 series material.

3 Rivet Shape Design

To improve the design of rivet shapes, we categorized the failure modes based on areas requiring attention in the joint quality when using conventional high-strength rivets. During riveting, it was observed that the rivet foot often undergoes buckling or cracking after joint. primarily due to the influence of the strength of the top material. Additionally, most instances of crack formation occurred in the rivet head area in contact with the top material. This is predominantly attributed to the concentrated stress generated by the material strength during riveting and the subsequent rivet deformation caused by the equipment punch.

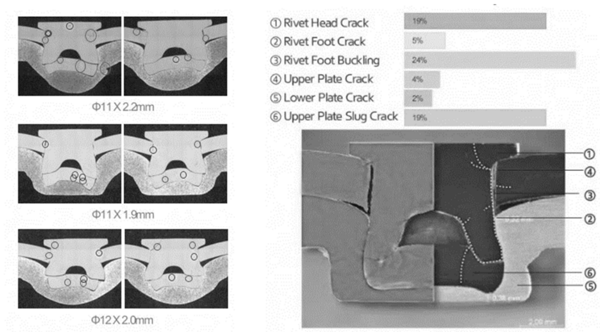

Figure 2: *Classification of Failure Modes in Riveting.*

The existing high-strength rivet joint process has been improved by enhancing the shape of the rivet head to better conform to the contact area with the top material. Additionally, to minimize stress concentration during penetration of the top material by the rivet, the inner arch structure of the rivet has been incorporated into the design.

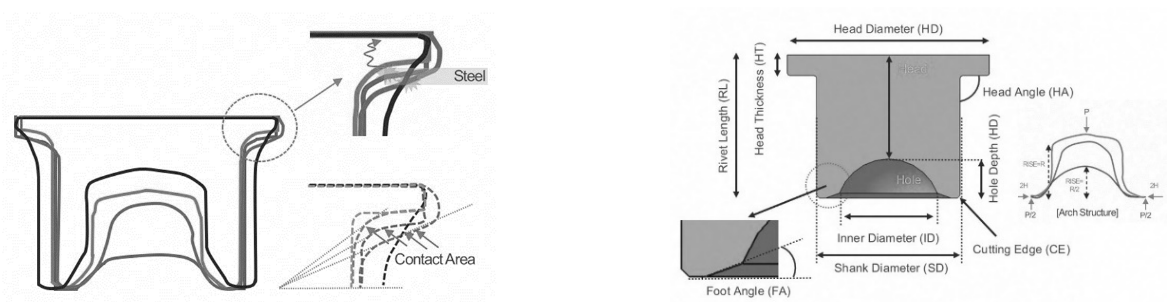

Figure 3: *The Optimization of shape design through analysis of commercial high-strength rivet shape.*

4 Experiments

The SPR(Self-Piercing Riveting) joining equipment used in this experiment has a maximum pressure capacity of 78 kN. The system consists of setting unit driven by an servo motor and a control unit with a quality check display. The controller enables the specific programming of the process variables and allows for limit setting. A C-frame setting device contains an electric brushless DC servomotor that drives a ball screw spindle against a die by use of a sprocket. The SPR machine has a built-in encoder to precisely control the spindle position, which enables an accurate measure of the joint stack-up thickness. An in-line force transducer is used to measure the force during the process from the moment the rivet touches the base material to the completion of the joining process. Riveting speed and pressure depth were set as fixed variables. The high-strength rivets utilized in the experiment had a length of 5.0mm. Anvil depth was varied into three conditions, and after joining, the pressure was measured. Figure 4 below shows the SPR joining process.

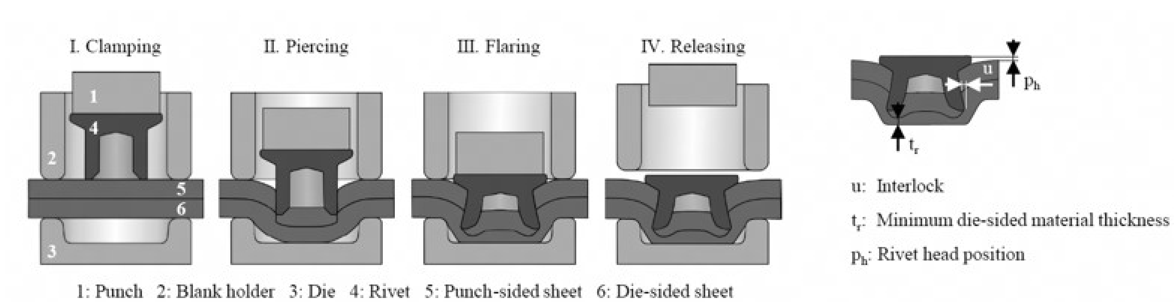

Figure 4: *The Self-Piercing Riveting joining process.*

The procedure for conducting the coupon tests is as follows (Fig. 5)

(1) Install an appropriate die into the die holder.
(2) Certify the axial alignment of the punch and the die.
(3) Place the two coupons on the top of the die top surface, and align the coupons with their edges.
(4) Clamp down the sheets gently using the punch holder.

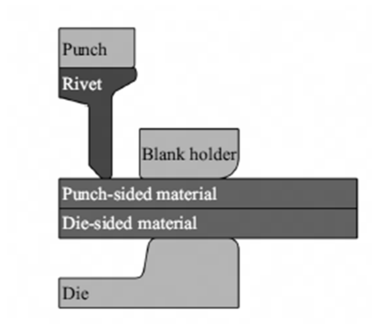

Figure 5: *The Procedure for conducting the coupon test.*

5 Evaluation and Results

The plastic deformation behavior of the joint during the SPR process was examined using the SORAPAS simulation software, which is which is highly reliable for measuring major SPR quality factors due to the inserted clamp and verified friction effect. The die, punch, and blank holder were rigid bodies. The speed control method was used for the vertical movement of the punch. The analysis results were presented in four stages as shown in Fig 6.

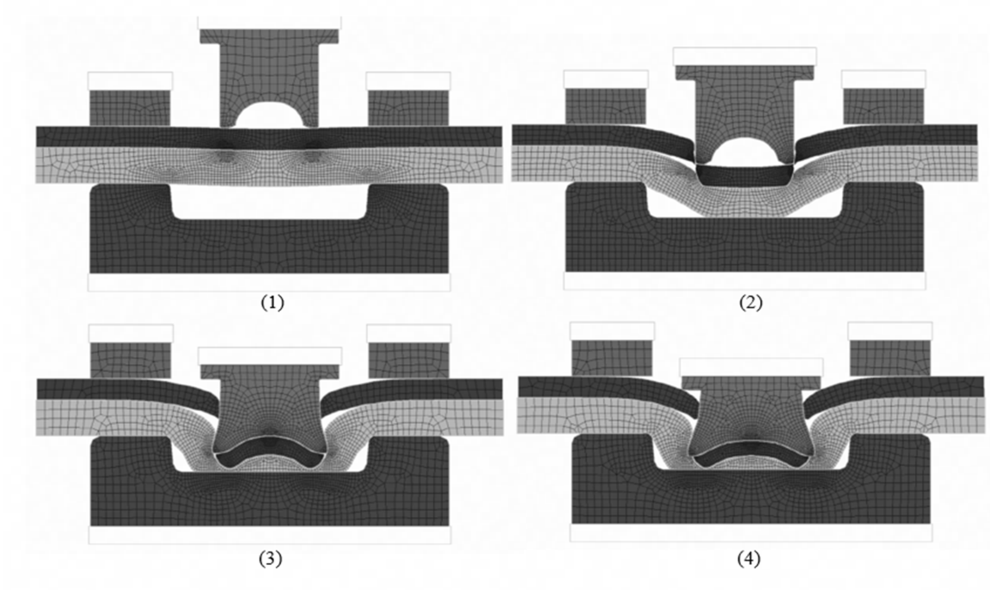

Figure 6: *Stage of SPR joining process (1) Rivet pressing the upper layer (2) Rivet into upper layer without deformation (3) piercing of the lower layer (4) Final deformation of the rivet with interlock.*

(1) is the stage in which the punch is pressed. The top and bottom sheets sagged under the pressure of the punch, and the rivet has not penetrated the top sheet. (2) represents the stage where the rivet initiates penetration into the top sheet without deformation, while the bottom sheet undergoes plastic deformation according to the die's geometry. (3) the rivet penetrates the top sheet (1.5GPa & 1.8GPa) and the pierced top sheet does not fill the rivet cavity due to the high strength of hot press forming

steel, causing a flow with the rivet legs to the aluminum bottom sheet. In addition, as the bottom sheet completely fills the die, the stress by reaction force and the beginning of the rivet leg deformation are observed. (4) the leg deformation and flaring of the rivet are completed, thereby forming an interlock between the top and bottom sheets. Significantly high effective deformation is observed in the bottom sheet slug area joining the pierced top sheet at the end of the rivet legs, indicating a lack of the residual thickness of the bottom sheet and the possibility of penetration.

A high-strength rivet prototype was produced by applying four types of steel wire, and the joint cross-section results were confirmed as shown in Figure 7 below. Clearly, the fracture mode that occurs when cracks occur at the rivet head, which is in contact with the top plate material, is similar for each rivet material, but the rivet foot did not fracture due to the arch structure shape.

In the case of Bearing steel Type #1, it generally satisfied the SPR joint cross-sectional quality standards, and in the case of the remaining materials, it was confirmed that cracks in the rivet head still remained. In the case of existing commercialized high-strength rivets, the slug of the upper plate material was broken by the pressing of the rivet foot after joining, but in the case of the developed rivet shape, the slug was in contact with the entire slug, and it was confirmed that the slug breakage was also partially improved.

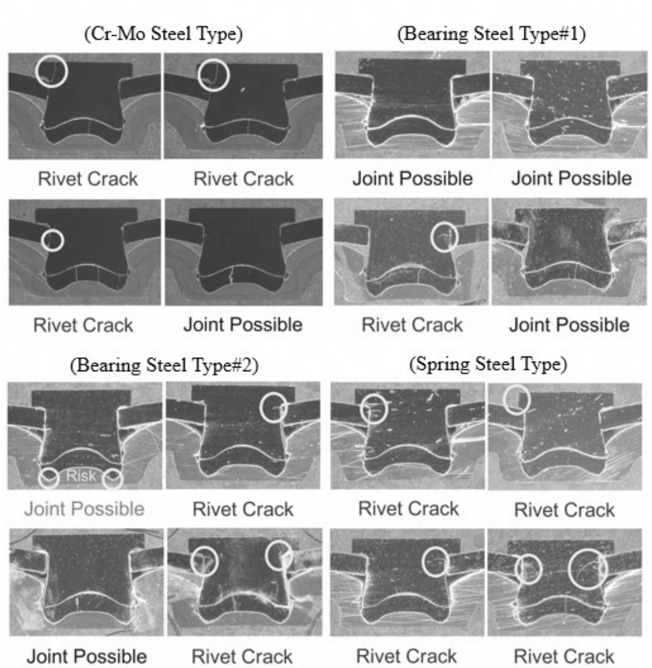

Figure 7: *Joint quality cross-sectional result*

6 Conclusion

We conducted an analysis of the issues encountered during the assembly of hot press forming steel and aluminum dissimilar materials using commercially available high-strength rivets and derived key factors requiring improvement. By incorporating an arch-shaped design into the rivet configuration to minimize softening deformation of the rivet foot during penetration of the top hot press forming steel material, we obtained the following results during the evaluation of joint characteristics.

1) Comparative computational analysis between the hollow rivet type and the arch-shaped structure revealed that the arch-shaped design effectively disperses stress concentrated.

2) After considering various materials such as chrom-molybdenum wire, spring wire, bearing wire, it was determined that bearing wire type could provide optimal hardness values without internal cracking within the rivet.

3) Evaluation of the self-piercing riveting joint cross-section quality criteria showed that both the rivet head gap and the amount of rivet foot inter-lockt, as well as the residual thickness of the lower aluminum material, met the joint cross-section quality standards.

Future plans, considering that the area where the rivet foot can deform due to the arch structure height may be limited, there could be insufficient interlocking of the lower aluminum material. Therefore, it is deemed necessary to design a configuration that ensures sufficient interlocking of the rivet foot with the aluminum material, even if changes are made to the anvil specifications to derive the optimal height condition.

References

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