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Parametric study on mechanical clinching process for joining aluminum alloy and high-strength steel sheets †

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Abstract

The purpose of this study is to investigate the effects of process parameters on the joint characteristics of advanced high-strength steel DP780 and Al5052 alloy sheet in mechanical clinching process. The defects in the clinching joint, such as necking of the upper sheet, cracks in the lower sheet, and no interlocking, occur because of the different ductility between advanced high-strength steel and aluminum alloy. In this study, the effect of the process parameters of the clinching process on the joinability of advanced high-strength steel with Al5052 alloy was investigated using finite element (FE) analysis. From the result, the die radius, die depth, and die groove shape were mainly affected by the joinability of advanced high-strength steel with Al5052 alloy. H-type tension test was performed under the same condition as the FE analysis. In addition, the joint strength was determined by interlocking length as well as neck thickness.

Keywords: Mechanical clinching process; Neck thickness; Interlocking length; Joinability; Joint strength

1. Introduction

In the automotive industry, lightweight materials like aluminum alloy and high-strength steel are used in modern automotive production for multi-material body design. These materials are not welded by the resistance spot welding process commonly used to join steel sheet for the automotive body because of the different melting points and thermal conductivity. Hence, an alternative method is required to achieve the successful multi-material body. The mechanical clinching process is an alternative joint method conducted by the plastic deformation of joined materials in clinching the die [1, 2].

J. Varis [3] compared the joining cost of the clinching process and the mechanical joining process with an additional joining element like rivet. If tool service life is guaranteed, the cost of a clinched joint will be cheaper than the other joint with additional joining element. Although mechanical clinching has a low running cost, its joining range of aluminum alloy with high-strength steel is small because of the low ductility of high-strength steel. The process condition should be optimized to join dissimilar sheet metals without defects in the mechanical clinching process.

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In the mechanical clinching process, the local plastic deformation of two sheets is created by the clinching tools. As shown in Fig. 1, the deformation mode of the upper sheet is similar to the ironing or shearing process. Necking is usually initiated at the upper sheet, and the lower sheet is filled in the die groove with tensile stress in the tangential direction. Tensile crack is usually initiated at the lower sheet. Joint strength is determined by the interlocking between the upper and lower sheets.

The clinching process should be designed to avoid defects in the mechanical clinching process, such as necking, cracks, and no interlocking. Specifically in the clinching process of high-strength steel, defects occur in high-strength steel due to its low ductility. According to K. Mori [4], the joining range and joint strength of the upper high-strength steel sheet is smaller to that of the lower high-strength steel sheet. Therefore, only the joining process for the lower high-strength steel was considered in this study.

In this study, finite element (FE) analysis for the mechanical clinching process with aluminum alloy Al5052 and advanced high-strength steel DP780 was performed to investigate the effects of the mechanical process parameters on the interlocking between two sheet metals. Based on the result of the FE analysis, the process condition was modified to improve the joinability of mechanical clinching. Joinability was evaluated by measuring the interlocking length at the maximum forming

Table 1. FE analysis conditions and material properties.

Parameter	Value
Punch radius, R_p	4.8, 5.0, 5.2, 6.0, 7.0 [mm]
Die radius, R_d	8.0, 9.0, 10.0 [mm]
Die depth, H	1.0, 1.2, 1.4, 1.6, 1.8 [mm]
Al5052	t=2.0[mm], $\bar{\sigma} = 358.9\bar{\varepsilon}^{0.162}$ [MPa]
DP780	t=1.6[mm], $\bar{\sigma} = 1177\bar{\varepsilon}^{0.133}$ [MPa]

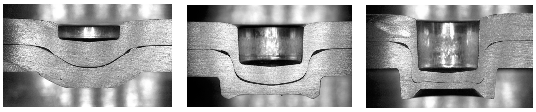
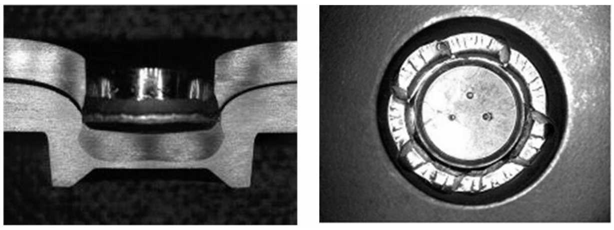


Fig. 1. Plastic deformation of the upper and lower sheet in the mechanical clinching process.



(a) Necking in the upper sheet (b) Cracks in the lower sheet

Fig. 2. Defects in high-strength steel sheet in the mechanical clinching process with a different position.

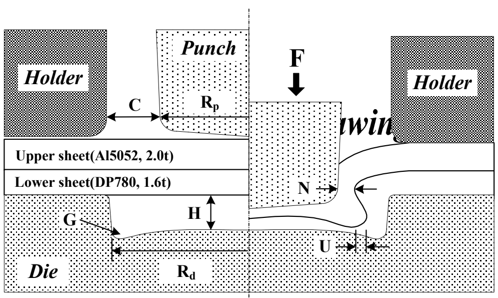


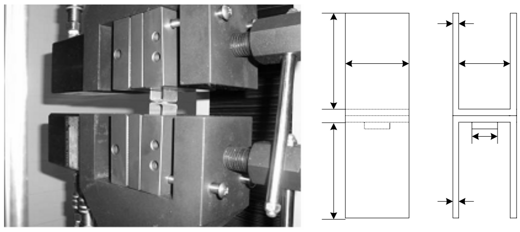
Fig. 3. Schematic illustration of the geometry of the mechanical clinching process.

load, while joint strength for the modified process condition was evaluated by the H-type tensile test.

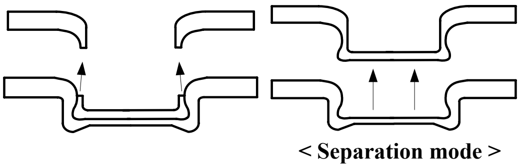
2. Experimental procedure

2.1 FE analysis for the clinching process

FE analysis was performed to evaluate the effects of process parameters on the joinability of DP780 with Al5052 by using commercial FE analysis s/w DEFORM 2D. As shown in Fig. 3, radii of punch (R_p) and die (R_d), die depth (H), clearance (C), and groove shape (G) are considered as the process parameters in this study. The FE analysis condition and mechanical properties of the sheets are listed in Table 1. Frictional factors of tools and the interface of two sheets are assumed to be 0.2 and 0.35, respectively.



(a) H-type test tools and dimensions of specimen



(b) Typical failure mode of mechanical clinched joint

Fig. 4. Dimensions of H-type tension test specimen its failure mode in tension test.

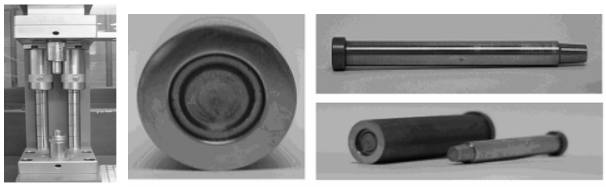


Fig. 5. Mechanical clinching tools for the experiment.

In general, the failure modes of a mechanical clinched joint are classified as interface-failure and button-failure. Interface-failure is the fracture of the upper sheet at the interlocking part caused by thinning of neck thickness of upper sheet, and button-failure is separation of interlocking by yield of upper sheet. Joinability was evaluated by the interlocking length (U) and neck-thickness (N) of the upper sheet at a maximum punch stroke. To prevent punch failure, the punch stroke is limited by allowable punch stress. The average punch stress (σ_p) is calculated as the following:

$$\sigma_p = P / A , \tag{1}$$

where P and A denote the forming load and punch area, respectively. In this study, the allowable punch stress is 3 GPa. The small radius of the punch has a large range of stroke because its coining force at the upsetting step is smaller than the large radius of the punch.

2.2 Clinching experiment and H-type tensile test

The mechanical clinching experiment was conducted to verify the result of the FE analysis. DP780 was used for the lower sheet, while Al5052 was used for the upper sheet. All clinching experiments were conducted within the allowable punch stress and load capacity of 100 kN of the clinching machine, as shown in Fig. 5. The cross-section shape of the clinching experiment was compared with the FE analysis. The fracture test was performed to verify the reliability of the clinched joint

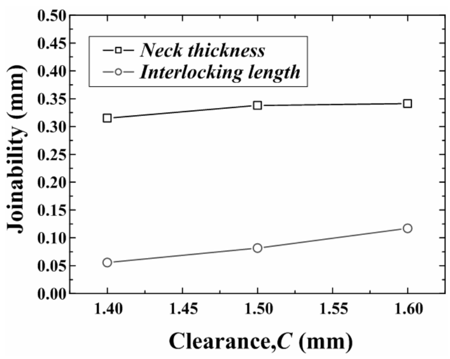


Fig. 6. Variation of the neck thickness and interlocking length with the increase in clearance (C).

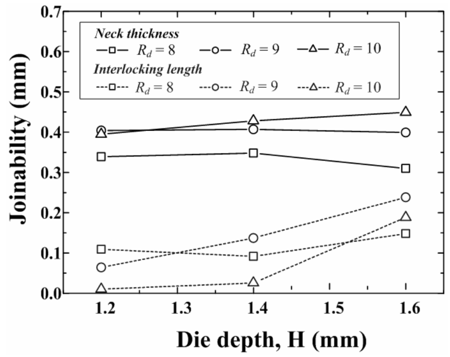
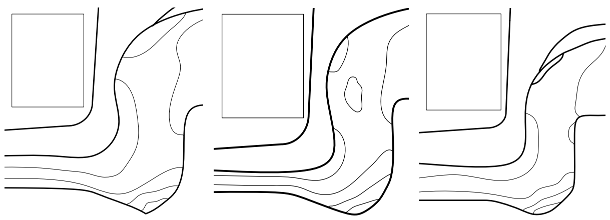


Fig. 7. Variation of the neck thickness and interlocking length with the increase in die depth (H) and die radius (R_d).



(a) R_d= 8.0, H =1.2 (b) R_d= 8.0, H =1.6 (c) R_d=10.0, H = 1.6

Fig. 8. Distribution of damage in the lower sheet under different conditions of die depth (H) and die radius (R_d).

through the experiment. In this study, the H-type tension test was employed to evaluate the strength of the clinched joint. Fig. 4 shows the dimension of the H-type tension test specimen and its failure mode in the test. The equipment with 50 kN was used for the tensile test. The test specimens were gripped hydraulically. The upper sheet was drawn to the axial direction, while the lower sheet was fixed downwards in the experiment.

3. Parametric study for the clinching process

3.1 Effects of clearance (C)

To evaluate the effect of the clearance between die and punch on the joinability, FE analysis was conducted by increasing the clearance from 1.4 to 1.6 mm. As shown in Fig. 6,

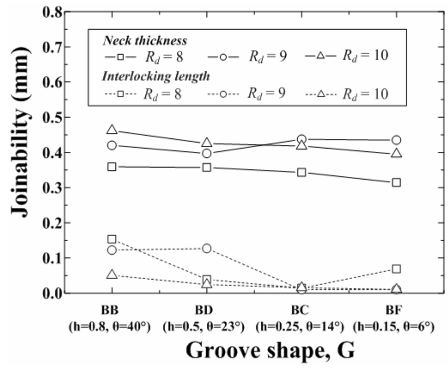


Fig. 9. Variation of the neck thickness and interlocking length with the increase in groove shape (G) and die radius (R_d).

the interlocking length and neck-thickness are increased, but at R_d =8.0, the neck thickness is decreased where the neck of the clinched joint is created at the clearance between punch and die. The increase in clearance means that there is enough space to draw the upper sheet into the die cavity. The lower sheet is also squeezed to the die side by the upper sheet.

3.2 Effects of die depth (H) and die radius (R_d)

Increasing the die depth from 1.2 to 1.6 mm and the die radius from 8.0 to 10.0 mm with same clearance of 1.5mm, FE analysis was conducted to investigate the variation of the neck thickness and interlocking length. As shown in Fig. 7, the neck thickness increases with the increasing die depth at R_d= 10, but at R_d= 8, it decreases. The increase in H means that the punch stroke is increased, and it induces a large thinning neck of the upper sheet. If R_d is increased, the die has more space to push out the lower sheet to the die wall.

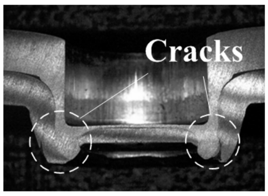
The interlocking length increases with the increasing in H. Although the interlocking length is increased, the damage in the lower sheet at the groove is accumulated by the increase in axial stress, causing cracks in the lower sheet, as shown in Fig. 2(b). The distribution of damage, calculated by Cockcroft and Latham's equation, is illustrated in Fig. 8. At R_d= 8 and H = 1.6, the damage is 0.795 but is decreased to 0.524 at R_d= 10. The circumferential stress is reduced by increasing R_d.

3.3 Effects of groove shape (G) and die radius (R_d)

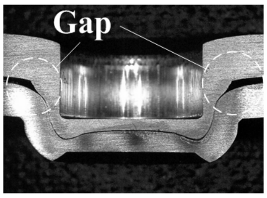
The groove shape is one of the main factors in the clinching process. The groove shape is defined by groove depth and tapered angle in this study. Fig. 9 shows that the variation in neck thickness and interlocking length with the change in groove shape. Neck thickness and interlocking length decrease with the flattening of the groove shape under the larger R_d. Although the flat groove shape can reduce the accumulation of damage at the groove, it induces the backward extrusion of the upper and lower sheet. The die groove is filled with the lower sheet because of the small volume of the die cavity, as shown in Fig. (c).

Damage *Damage* *Damage*

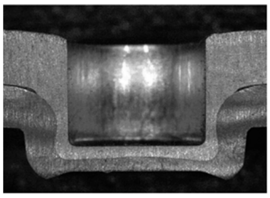
A = 0.555 A = 0.795 A = 0.524



(a) R_d=8.0, H=1.6



(b) R_d=9.0, H=1.4



(c) R_d=10.0, H=1.4

Fig. 10. Cross-section of the clinched joint by the experiment under different conditions of die depth (H) and die radius (R_d).

4. Results and discussion

4.1 Clinching experiment

The cross-section shape between FE analysis and the experiment is compared in Fig. 8. The cross-section of the clinched joint has a similar shape and deformation mode as with the FE analysis result. In the case of R_d= 8 and H = 1.6, as shown in Fig. 8(a), the cracks are initiated in the lower sheet, and the upper sheet penetrates the lower sheet. When R_d is increased, H is decreased to prevent the cracks in the lower sheet. At R_d= 9.0, 10.0, H = 1.4, cracks are not created in the lower sheet, as shown in Figs. 8(b) and (c). However, at R_d= 9.0, the lower sheet is extruded backward by the different stiffness of the sheet, and the interfaces of the lower and upper sheets are detached.

If the joint has a gap between the lower and upper sheets, it causes the corrosion of the clinched joint due to the penetration of water into the gap. As shown in the FE analysis result, the neck thickness and interlocking length are organized without defects in the clinching process at R_d= 9.0 and H = 1.4mm.

4.2 Result of the H-type tensile test

The fracture test was performed to verify the reliability of the clinched joint through the experiment. In this study, H-type tension test was employed to evaluate the strength of the clinched joint. Fig. 8 shows the dimension of the H-type tension test specimen and its failure mode in test. The joint strength and failure mode for the neck thickness and interlocking length of each experiment case are listed in Table 2.

In this study, R_d= 9.0 has a good joinability with high joint strength. R_d= 9.0 shows a higher joint strength even if it has a small interlocking length. In the case of R_d= 8.0, which has a thin neck thickness and a large interlocking length, the joint is fractured at the neck of the upper sheet and shows a lower joint strength. R_d = 10.0 shows the separation failure mode with the joint strength as 1,957 N. However, a gap occurred at the interface of the two sheets. Thus, this result shows that the joint strength is determined by the interlocking length as well as the neck thickness. Therefore, following the failure mode of the clinched joint, neck thickness should be considered in the design step of the clinching process. To prevent neck fracture in the clinched joint, neck thickness of the upper sheet should be increased. In the separation mode, interlocking length should be increased.

5. Conclusions

The effects of the process parameters on the joinability of the mechanical clinching process were evaluated using FE analysis and the H-type tension test. Die radius is the most important process parameter, and it should be determined by considering the forming volume. In this study, the case where R_d= 9.0 had the highest joint strength determined by the interlocking length and neck thickness. Interlocking length increased with the increase in die depth, but it caused cracks in the lower sheet. Neck thickness increased with the increase in die radius. The interlocking of the two sheets was difficult at a large die radius. To increase joint strength, the process parameters should be determined by following the failure mode of the clinched joint.

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