PRECISION JOINING OF STEEL-ALUMINUM HYBRID STRUCTURE BY CLINCHING PROCESS

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ABSTRACT: An innovative technology of clinching joining can reduce the production costs, cycle times, and also offer prospective product design and manufacturing. In this study, the overlap joining of low carbon steel and aluminum alloy in clinching process was experimentally and numerically investigated. The tensile-shear strength of overlap-clinched joints was evaluated through tensile-shear test. This test was also used to study the deformation and failure of clinched joints under tensile-shear loading. The results showed that the higher press load had a great influence for achieving better interlocking between steel-aluminum hybrid structures. Insufficient interlocking and thin neck thickness led to the failure of clinched joints. Moreover, the most critical region of the clinching tool was located at the radius corner of punch and die.

KEYWORDS: *Clinching; Undercut; Necking; FEM; Dissimilar Material*

1.0 INTRODUCTION

Recently, the demands on the clinching joining have increased in automotive industry, as it is proven successful in complementing or even replacing the conventional spot welding [1-3]. Clinching process is a mechanical joining method that allows materials to be assembled without the requirement of additive elements such as rivets and bolts, and surface preparation in comparison to welding process. It also has significant advantage where it can join the multi-materials with different individual thickness.

Hybrid structure is a modern approach for fabricating lightweight component. It involves multi-materials that can provide various properties and it has become attractive material in the automotive industry. However, it is difficult to join the heat sensitive materials using thermal joining. The uncontrolled heat input generates an overshoot, resulting in undesirable welded joints [4-6]. The lower joint strength makes adhesive bonding not suitable for automotive body [7-9]. In order to manufacture practical components from dissimilar materials, a promising technique is strongly required.

Clinching joining provides a better alternative for joining lightweight hybrid structure [10-12]. In addition, it has been proven that clinching joining can improve the fatigue properties of the assembled structure [13]. This technique is based on the local plastic deformation of joined sheets. The forming and drawing are two principal actions that cause the generation of the interlock between the layers of thin metal sheets. The tooling parts consist of punch and die which should be perfectly aligned and the specimen is to be correctly presented to the tooling. During the process, the die is fixed and the punch moved with the required press load depending on the thickness and the strength of the materials to be joined, resulting in the plastic deformation on the metal sheets. Practically, this process is performed at one stroke at a short time.

The influence of process parameters on the final clinched joints has been systematically investigated by Lee et al. [14] and Lambiase and Di Illo [15]. In order to widen the availability of the clinching process, Abe et al. [16-17] proposed a new tool configuration to avoid fracture. The recent development of finite element method (FEM) in clinching process has been extensively reviewed by He [18]. FEM has proven to be an effective tool in predicting the strength of clinched joints, modifications on die assembly geometry and material properties. Therefore, prediction of clinched joints is very significant at the early stage of product design and process development in terms of extending industrial applications of clinching process.

In this study, the overlap joining of dissimilar materials of low carbon steel and aluminum alloy in clinching process was experimentally and numerically investigated. The clinched joints were sectioned and the main geometrical dimensions, for example, undercut, neck thickness and bottom thickness were determined. A numerical analysis was conducted to analyze the material flow and the stress distribution during the clinching joining by FEM. Tensile-shear tests were also performed to evaluate the effect of press load and cross-head speed on mechanical behaviors of the clinched joint.

2.0 EXPERIMENTAL WORK

In this study, low carbon steel ASTM A36 and aluminum alloy AA5052 were used as specimens. The dimension was 110 mm x 20 mm with nominal thickness of 1 mm for both specimens. The punch and die were fabricated from tool steel AISI D2. The punch had a diameter, D_P = 4 mm and a corner radius, R_P = 0.2 mm. The die which constituted a fixed die anvil with diameter D_d = 5 mm and a corner radius R_d = 0.4 mm was employed in the experiments as shown in Figure 1. The chemical composition of the specimens, and punch-die are shown in Table 1.

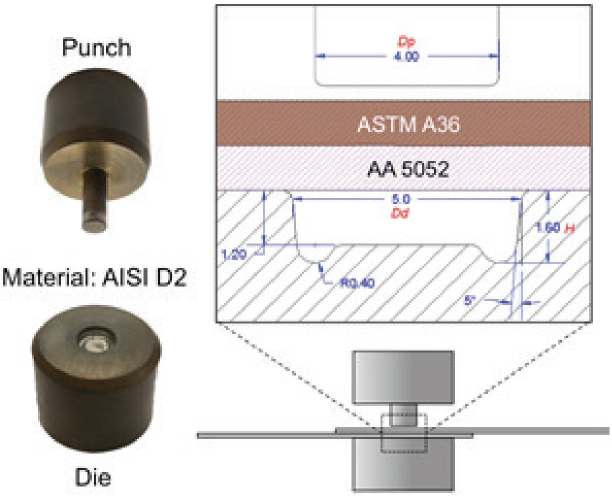

Figure 1: Schematic diagram of the experimental setup

Table 1: Chemical composition of specimens and punch-die (wt.%)

ASTM A36	C (0.25-0.29); Cu (0.2); Mn (1.03); P (0.04); Si (0.28); S (0.05); Fe (Bal.)
AA 5052	Al (95.8-97.7); Mg (2.2); Fe (0.4); Cr (0.15); Si (0.25); Cu (0.1); Mn (0.1); Zn (0.1)
AISI D2	C (1.4-1.6); Mn (0.6); Si (0.6); Co (1.0); Cr (11.0-13.0); Mo (0.7-1.2); V (1.1); P (0.03); Ni (0.3); Fe (Bal.)

Universal testing machine with load capacity up to 100 kN was used. In order to ensure that the machine can perform a clinching process, additional fixtures were fabricated to clamp the punch and die. The specimens were clinched in an overlap joint geometry where the low carbon steel overlapped on an aluminum alloy with an overlapping length of 50 mm. This arrangement was decided based on the materials with high strength or thicker need to be located at the top [19]. The main processing parameters were press load and cross-head speed. In this study, the press load and cross-head speed varied between 13-18 kN and 180-420 mm/min, respectively.

After the clinching process, the specimen was cut using the waterjet cutting machine. The sectioned surface of clinched specimen was ground and polished for the clinched joint observation through an optical microscope. The tensile-shear test was carried out according to the ASTM standard E8M to measure the tensile-shear strength of the overlap-clinched joints. Universal testing machine was utilized in this test. The cross-head speed was set to 1 mm/min. The specimen was gripped by the clampers which were placed in the fixture blocks. Then, a tensile-shear load was slowly increased at appropriate increments by the mechanical lever system until the clinched joint of specimen was fractured.

3.0 NUMERICAL ANALYSIS

Further analysis of the joining phenomenon was conducted by finite element method (FEM). A 2D axisymmetric model was developed using ANSYS FE software. The analysis model was based on the Cowper-Symbols model to consider the influence of strain rate. The constitutive equation representing the sheet material strain-hardening can be written as follows.

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}^t}{C}\right)^{\frac{1}{p}}\right]\left(\sigma_0 + f\left(\varepsilon^p_{eff}\right)\right) \tag{1}$$

where σ_0 is the yield stress in constant strain rate, $\dot{\varepsilon}^t$ is the effective strain rate, *C* and *P* are the parameters of strain rate and $f\left(\varepsilon^p_{eff}\right)$ is the hardening coefficient, which is based on an effective plastic strain.

Figure 2 shows the FE model of clinching process. An elasto-plastic behavior was assumed for the specimens whereas the punch, die and blank holder were modeled as rigid bodies. The mesh was graded the finest in the region of specimens and a coarse mesh was used for punch, die and blank holder. Different mesh sizes on the specimens had been tested and the maximum stress was evaluated in the sensitivity analysis of mesh size [20]. A meshing with 6170 elements and 17285 nodes was found to be accurate enough to predict the clinch profile. In addition, structural analysis element namely PLANE183 for 2D eight-node structural solid was used.

In this study, the friction coefficients were assumed uniform between the contact surfaces. The friction coefficients between different parts in the model were adapted from He et al. [21]. The values of the Coulomb friction coefficient between different interfaces in the model were assumed as follows: punch-upper sheet $f_1 = 0.25$, upper sheet-blank holder $f_2 = 0.15$, upper sheet-lower sheet $f_3 = 0.15$, lower sheet-die $f_4 = 0.25$. These values were kept constant for all simulations. Bilinear isotropic strain-hardening rule and the associated flow rule were adopted because the specimens were modeled as elasto-plastic model. The material properties of low carbon steel, aluminum alloy and tool steel are shown in Table 2. The clinching process was simulated by applying a specified downward velocity to every node within the punch.

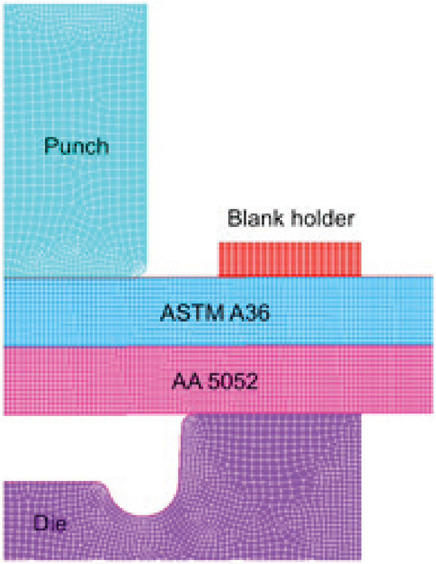

Figure 2: Finite element model of clinching process

Table 2: Material properties of specimens and punch-die

Material	Young's modlus, *E*	Poisson's ratio, *v*	Density, *ρ*
ASTM A36	200	0.26	7850
AA 5052	70	0.33	2680
AISI D2	210	0.30	7700

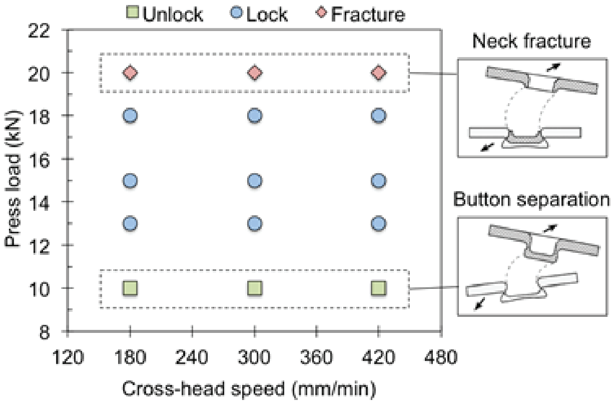

Figure 3: Condition of clinched joints with different process parameters

4.0 RESULTS AND DISCUSSION

Figure 3 shows the preliminary experiment to identify the range of processing parameters that can be used. Cross-head speed about 180-420 mm/min and the press load above 10 kN were selected based on previous studies [15, 22]. The 10 kN load with cross-head speed of 180-420 mm/min performed an abnormal failure mode of clinching process namely button separation. The insufficient interlocking was caused by insufficient press load, hence, small undercut was introduced, leading toward the separation of the upper and lower sheets. On the other hand, the 20 kN load with cross-head speed of 180-420 mm/min also produced the neck facture of abnormal failure mode. The thin neck was caused by excessive punch load, introducing fracture on the neck of upper sheet. Therefore, an abnormal failure mode is often caused by insufficient interlocking and thin neck thickness [23-24]. This type of failure mode should be avoided. Owing to the sufficient locking of clinched joints, the press load and cross-head speed were selected between 13-18 kN and 180-420 mm/min, respectively.

The cross-section of clinched joint is shown in Figure 4. The clinched joint had ‘S’ shape that was evaluated as locking parameters. The values of locking parameters were neck thickness, undercut and bottom thickness. This ‘S’ shape was created when pressing the material into the bottom of the die. Sufficient locking parameters were needed to keep the sheets together while the joint was subjected to tensile-shear loading to determine the joint strength.

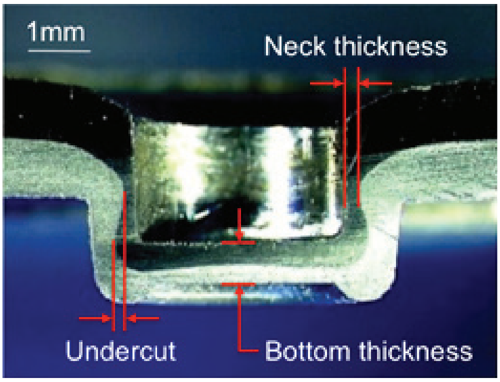

Figure 4: Cross-sectional view of clinched joint (15 kN, 420 mm/min)

Figure 5 illustrates the influence of press load and cross-head speed on the locking parameters. At constant cross-head speed, increasing press load significantly affected the undercut or interlocking between steel-aluminum sheets. Subsequently, increasing the press load also caused the bottom thickness to become thinner. In addition, the faster cross-head speed, the narrower neck thickness was generated. Moreover, the material flow and characteristic of locking parameters were highly influenced during the offsetting and subsequent upsetting phases of clinching process. This mechanism of clinched joint was determined when the punch pushed the steel-aluminum sheets with the desired maximum load resulting in the upper and lower sheets joined by being hooked on the interlock generated by the material flow between the corners of the punch and die, thus, reducing the thickness of the bottom sheet.

The tensile-shear strength of clinched joint is shown in Figure 6. It was used to evaluate the quality of joint and its relationship with the locking parameters. The tensile-shear load of clinched joint increased with the increment of press load. Hence, there was a direct relationship between the tensile-shear strength of clinched joint and undercut size. Besides, the increasing size of the undercut greatly increased the tensile-shear load, resulting in the increase of the clinched joint strength. The strength of clinched joint was directly proportional to the undercut size and inversely proportional to the sizes of neck and bottom thickness. Hence, the optimal parameters for this particular clinched joint on medium cross-head speed with highest press load are 300 mm/min and 18 kN respectively.

In order to verify the FE simulation results, the clinched joint profiles in the cross-section obtained from the experiments were compared as illustrated in Figure 7. The simulation result showed a good estimation of the locking parameters where the maximum errors for neck thickness, undercut and bottom thickness were 1.4%, 8.0% and 0.8%, respectively. The good agreement indicated the validity of FE model. Figure 8 shows the FE simulation of clinching process. As the joining displacement progressed within the time increment, the punch forced the steel-aluminum sheets to deform plastically, reducing their initial thickness. The punch had been moved 2.75 mm (end of punch stroke, t = 0.39 s) downward with 420 mm/min speed until the bottom thickness reached 0.5 mm when the blank holder and die were fixed. With progressing deformation of clinched joint, both steel-aluminum sheets underwent a significant thinning deformation near the punch corner radius toward the die cavity until the desired shape of interlock or undercut was formed.

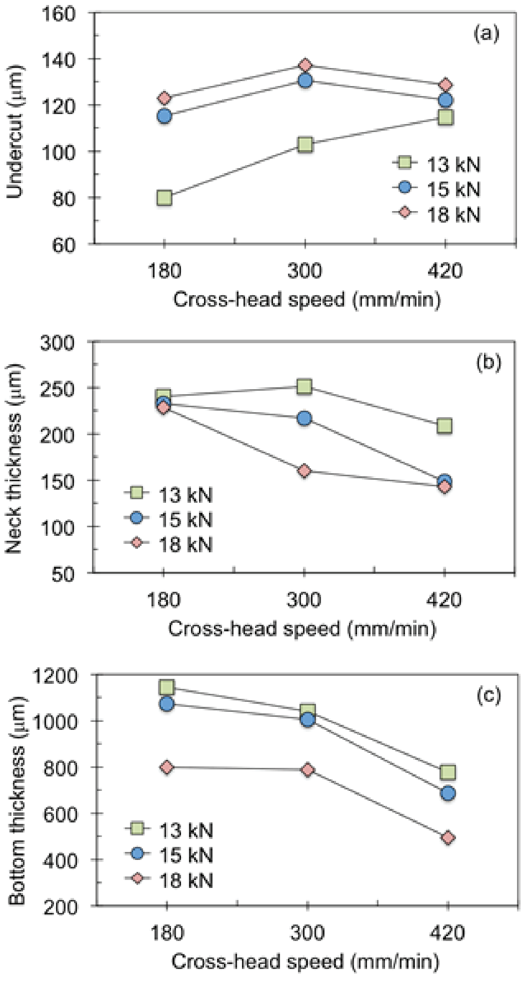

Figure 5: Locking parameters of (a) undercut, (b) neck thickness and (c) bottom thickness

With progressing deformation of both upper and lower sheet, the ability of their strain hardening increases, causing the increase of press load. The development of stress of clinched joint originated from contact interface between punch and steel sheet ,hence, distributed to the aluminum sheet toward the die cavity. The development of stress started to progress from the radius corner of punch to the steel sheet towards contact interface between the aluminum sheet and radius corner of die at punch stroke of 1.05 mm (t = 0.15 s). In addition, it was found that after the aluminum sheet touched the anvil of die, the stress distribution of both plates were homogeneous at punch stroke of 1.75 mm (t = 0.25 s). The maximum equivalent stress of 9304.5 MPa occurred at the radius corner of punch when the punch reached the desired stage of forming undercut or interlock. Based on the occurrence of maximum stress value, the most crucial region of the clinching tool was the radius corner of punch.

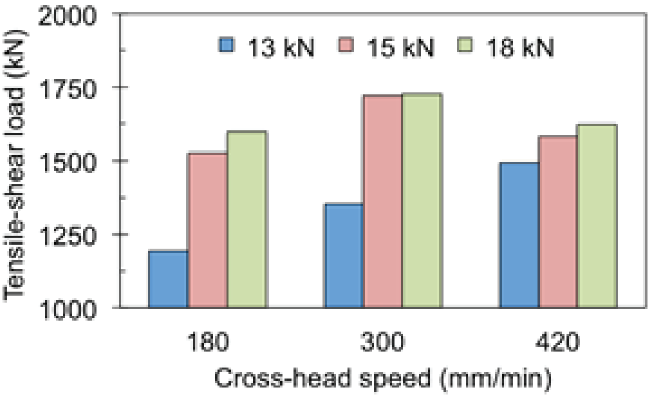

Figure 6: Tensile-shear load of clinched joint

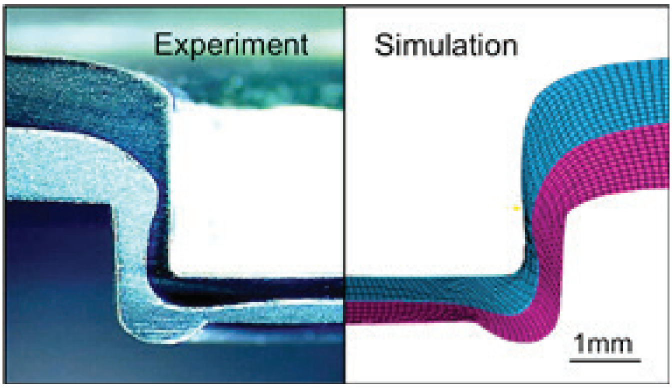

Figure 7: Comparison of experimental and simulated clinched joint

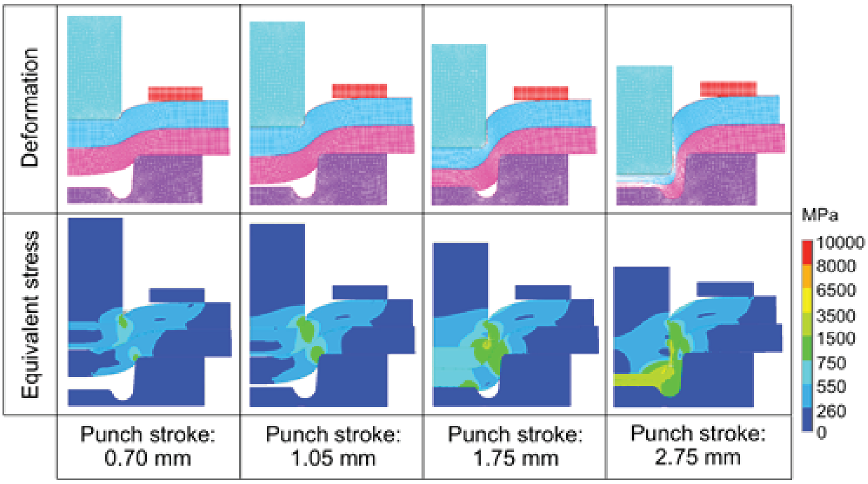

Figure 8: Deformation and equivalent stress distribution at different stroke (18 kN, 420 mm.min)

5.0 CONCLUSION

In conclusion, the overlap joining of dissimilar materials of low carbon steel and aluminum alloy using clinching process has been experimentally and numerically investigated. The result shows that the generation of locking system in clinching process depends on neck thickness, undercut and bottom thickness. The strength of clinched joint is directly proportional to the undercut value and inversely proportional to the values of neck and bottom thickness. The optimal parameters of clinched joint are 300 mm/min medium speed of punch with the highest press load of 18 kN. The radius corners of punch and die are the crucial regions in performing clinching process. After the bottom plate touches the anvil of die, the stress distributions of both plates are homogeneous. Two types of failure modes namely normal failure mode and abnormal failure mode are obtained. The former is obtained by tensile shear test and acquired to evaluate the clinched joint mechanical strength whereas the latter mode is attained due to insufficient interlocking and thin neck thickness.

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