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Mechanical Behavior of Clinched Sheet Material Joints and Strength Design Procedure

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Clinching is an effective joining technique for lightweight sheet materials that are difficult or impossible to weld. A theoretical model for clinched joints in metal sheets was established and a design method for improving joint strength by selecting different clinching tools was proposed. The analytic model is defined as a function of the neck-thickness and the undercut, which are the key parameters of joint geometry. Based on the analytic model, the design method of clinched joint strength that can satisfy required strength was proposed. Clinching experiments were conducted with 2.00 mm thick aluminium alloy 5052 sheets. Various conditions were used during the clinching process to validate the joint strength model. Tensile-shear strength of clinched joints was measured by a servo-hydraulic testing machine. The calculated joint strength was in good agreement with the experimental results.

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1. Introduction

In car manufacturing the reduction of moving masses without the decrease of safety parameters is a key factor for future economic success. This results in an increasing need to design lightweight structures and use lightweight materials in the manufacturing of vehicle bodies. Some of these lightweight materials are difficult or impossible to weld with conventional spot welding and so considerable effort has gone into developing new joining processes suitable for use with lightweight materials [1–3]. Clinching has also been developed rapidly in recent years for joining lightweight materials such as aluminum alloys [4–6]. The mechanical clinching process is a method of joining sheet metal or extrusions by localized cold forming of materials. The result is an interlocking friction joint between two or more layers of material formed by a punch into a special die. Depending on the tooling sets used, clinched joints can be made with or without the need for cutting. By using a round tool type, materials are only deformed. If a square tool is used, however, both deformation and cutting of materials are required.

Over the last 30 years clinching has been applied in industry and some studies on the qualitative relationship between tool parameters and joint strength have been conducted. An investigation on clinching mechanism has been conducted by Gao and Budde [7]. Some elementary terms were used to establish a basic theory for analyzing the clinching mechanism. The influence of the clinching process parameters on the join-ability of high-strength steel was studied by Mucha [8] using finite element (FE) method. The results showed that some parameters, such as die radius, die depth and die groove shape were mainly affecting the join-ability. De Paula et al. [9] researched the effect of various punch and die geometries on the joint neck-thickness and undercut using a finite element analysis. Varis [10] concluded that clinching tools should be chosen based on the characteristics of the sheet metals to be joined and proposed a procedure for tool selection.

In this paper, a theoretical model was established based on the main failure modes of clinched joints under tensile-shear condition, and a method for designing clinched joint strength was proposed. Various conditions were used during the clinching process to validate the joint strength model. The strength and failure modes of the joints under tensile-shear loading were studied to validate the theoretical model.

2. Theoretical model for joint strength

In practical applications, the joints bear mainly tensile-shear loads, so only tensile-shear stress is considered in this study. Typical joint failure modes are neck fractures and button separation mode as shown in Fig. 1 [11]. These are associated with joint section shape. Small neck-thickness t_N may result in the upper sheet fracturing at the neck where material is thinnest. Small undercut t_U may result in the separation of the upper and lower sheets because the interlocking between them is weaker.

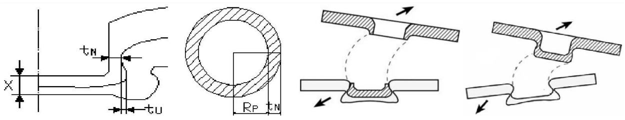

Fig. 1. Typical failure modes of clinched joint. (a) Key parameters of clinched joint, (b) projection area, (c) neck fracture mode, (d) button separation mode.

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2.1. Neck fracture mode

Under tensile-shear loading, a main shear load is applied to the neck of the upper sheet by geometrical interlocking and is increased gradually. The neck fractures when the shear stress reaches the fracture stress value, σ_τ, which is the ultimate shear stress of the upper sheet. The fracture load of clinched joints, F_N, can be calculated as follows:

$$F_N = \sigma_\tau A = \pi \left(2R_p t_N + t_N^2\right) \sigma_\tau, \tag{1}$$

where A is the projection area of the neck, R_p is the clinching punch radius, F_N is proportional to t_N and R_P and the shear stress of the upper sheet. However the punch radius is mainly determined by the forming load and the total thickness of the sheets in combination. Therefore, the clinching process condition should be such that it gives sufficient neck-thickness to result in the desired joint strength.

2.2. Button separation mode

Button separation is the separation of the upper sheet and lower sheet caused by insufficient geometrical interlocking in joint. The upper sheet undergoes plastic deformation during the button separation process. This deformation is similar to that, which occurs under the tube drawing process without a mandrel [12]. Thus the slab method is employed to evaluate the load required for the plastic deformation of upper sheet in button separation mode.

In the button separation, the plastic deformation is not axisymmetric. In this case, only part of the joint material in the upper sheet undergoes plastic deformation. Therefore, a correction factor k_1 should be included, with value of 0.9 for tensile-shear joint [12]. Then analytical model for the button separation mode can be defined by Eq. (2). Figure 2 can be used for calculation of the tensile force of the button separation.

$$F_p = k_1 \frac{\sigma_b}{\sigma_s} \sigma_s \pi R_p^2, \tag{2}$$

where

$$\frac{\sigma_b}{\sigma_s} = 1 - \frac{1 - \frac{\sigma_x}{\sigma_s}}{\mathrm{e}^c}.$$

F_P can be calculated using the following procedure.

1. Calculate the lengthening coefficient during the tensile-shear process

$$\lambda = \frac{2R_p + t_N + t_U}{2R_p - t_N - t_U}.$$

2. Calculate coefficient B for given friction factor μ and the angle α

$$B = \frac{\mu}{\tan\alpha} = \frac{\mu X}{t_U}.$$

3. Seek the value of σ_x/σ_s in Fig. 2 based on parameter λ and B. Specifically, find the position of λ in the abscissas, and draw a vertical line from it. A horizontal line is drawn through the intersection of the vertical line and the B line, which intersects with the vertical axis resulting in a crossover point with the value of σ_x/σ_s.

4. Calculate modulus C

$$C = \frac{2\mu X}{2.1R_p}.$$

5. Determine the mean hardening degree during the tensile-shear process

$$\bar{\varepsilon} = \frac{t_U}{X}.$$

6. Calculate the flow stress σ_s

$$\sigma_s = 350 \left(\bar{\varepsilon}\right)^{0.13}.$$

Thus, all parameters in Eq. (2) are determined, and the load required in button separation mode can be calculated. Equation (2) and the calculation show that the strength of the joint in button separation mode is depended on the friction factor μ, the bottom thickness of the clinched joint X, the neck-thickness t_N, undercut t_U, and average flow stress σ_s. Among these parameters, neck-thickness t_N, and undercut t_U are under control during the clinching process.

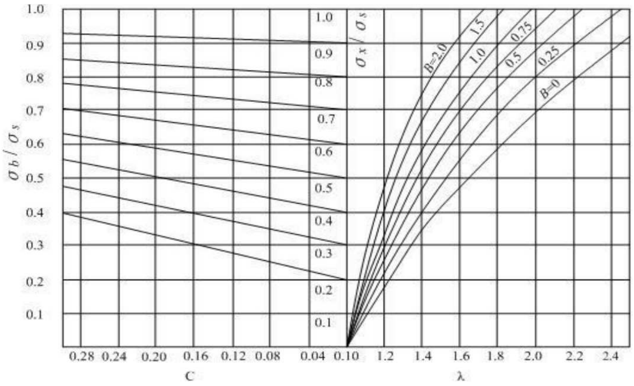

Fig. 2. Calculation curve of tensile force.

TABLE I

Clinched joints.

Type	Clinching parameter		Joint geometry		
	Punch radius [mm]	Punch corner radius [mm/10]	Die depth [mm/10]	Neck-thickness [mm]	Undercut [mm]
1	2.5	7	7	0.563	0.058
2	2.5	7	10	0.473	0.162
3	2.5	7	14	0.420	0.280
4	2.6	7	14	0.429	0.421
5	2.6	7	10	0.513	0.196
6	2.6	7	7	0.550	0.065
7	2.6	10	7	0.610	0.044
8	2.6	10	10	0.594	0.053
9	2.6	10	14	0.501	0.153
10	2.75	7	14	0.392	0.291
11	2.75	7	10	0.516	0.193
12	2.75	7	7	0.616	0.045
13	2.85	7	7	0.612	0.084
14	2.85	7	10	0.496	0.245
15	2.85	7	14	0.347	0.453

3. Experimental verification of the theoretical model

Clinching experiments were conducted with 2.00 mm thick aluminum alloy 5052 sheets. The 5052 alloy sheets were clinched together in the central part of lap section using a RIVCLINCH 1106 P50 clinching machine with the joining pressure set to 0.6 MPa. Various conditions were used during the clinching process to validate the joint strength model. Fifteen types of clinched joints were employed, as shown in Table I. Tensile-shear tests were conducted to evaluate the joint strength.

Using measurements of the neck-thickness and the undercut, the joint strength in both neck fracture and button separation modes was calculated using the theoretical model proposed here. Joint strength and failure mode were measured by means of a servo-hydraulic testing machine. The calculated joint strength was in good agreement with the experimental results, with an 8.9% error (see Table II). The prediction of the joint failure mode was exactly keeping with the experiment.

TABLE II

Comparison of analytical model and experiment.

	Analytical model result		Experiment	Error	Failure mode	Failure mode
Type	F_N (N)	F_P (N)	F_E [N]	[%]	(analytical model)	(experiment)
1	2360.2	2034.0	1982.7	2.6	Button separation	Button separation
2	1627.3	1727.0	1694.1	–3.9	Neck fracture	Neck fracture
3	1431.0	1649.3	1455.6	–1.7	Neck fracture	Neck fracture
4	1518.0	2135.5	1635.8	–7.2	Neck fracture	Neck fracture
5	1842.4	1979.2	1788.0	3.0	Neck fracture	Neck fracture
6	1988.0	2313.0	1893.2	5.0	Neck fracture	Neck fracture
7	2227.9	1533.4	1683.5	8.9	Button separation	Button separation
8	2163.5	2303.4	2152.6	0.5	Neck fracture	Neck fracture
9	1795.5	1825.9	1705.5	5.3	Neck fracture	Neck fracture
10	1451.9	2060.0	1546.4	6.1	Neck fracture	Neck fracture
11	1951.4	2094.4	1965.8	–0.7	Neck fracture	Neck fracture
12	2271.3	2040.7	1978.8	3.1	Button separation	Button separation
13	2428.4	2476.9	2530.6	4.0	Neck fracture	Neck fracture
14	1931.9	2163.2	2031.0	–4.9	Neck fracture	Neck fracture
15	1319.1	2281.9	1393.9	–5.4	Neck fracture	Neck fracture

4. Conclusions

A theoretical model was established based on the main failure modes of clinched joints under tensile-shear condition, and a method for designing clinched joint strength was proposed. Clinching experiments were conducted with 2.00 mm thick aluminium alloy 5052 sheets. Various conditions were used during the clinching process to validate the joint strength model. The calculated joint strength was in good agreement with the experimental results.

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