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Fatigue analyses of self-piercing rivets and clinch joints in lap-shear specimens of aluminum sheets

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ABSTRACT

Fatigue behavior of self-piercing rivets (SPRs) and clinch joints in lap-shear specimens of 6111-T4 aluminum sheets with different thicknesses was investigated. Lap-shear specimens with SRPs and clinch joints were tested under quasi-static and cyclic loading conditions. Micrographs showed different failure modes of SPRs and clinch joints under different loading conditions. Dominant fatigue cracks were identified. The structural stress model from Tran and Pan's recent works was adopted. The structural stress solutions at the crack initiation locations and the stress-life data of aluminum 6111-T4 were adopted to estimate fatigue lives. The fatigue life estimations show good agreement with the experimental results.

1. Introduction

Resistance spot welding is widely used for joining body-in-white parts made of sheets. However, resistance spot welding of aluminum sheets is likely to produce poor welds due to voids and defects inside the nugget [1,2]. Recently, many joining processes, such as spot friction welding, self-piercing riveting, clinching, and ultrasonic spot welding, have been considered to make joints for aluminum sheets in the automotive industry. In contrast to the conventional welding processes, these joining processes make joints without melting the base metals.

Both self-piercing rivet and clinch joints are mechanical fastening joints since they fasten metal sheets mainly by mechanical interlock. As shown in Fig. 1, a semi-tubular rivet is punched by a tool into two metal sheets supported by a die. The rivet pierces through the upper sheet and then the tubular tail flares into the bottom sheet. A mechanical interlock is made between the rivet and the two sheets. Unlike the "traditional" riveting process, no pre-process, such as hole drilling and hole alignment, is needed here. Sun and Khaleel [3] showed that the failure load of self-piercing rivets strongly depends on the material properties of rivets and sheets, the thickness of sheets, and the mechanical interlock between the rivets and sheets. A failure criterion for self-piercing rivets with the rivet pullout failure mode was then developed based on the aforementioned factors and the lower bound limit approach to predict the failure load of rivets. Han et al. [4] studied the failure loads and failure modes of self-piercing rivets between multi-layer similar and dissimilar sheets in various types of specimens. They observed two types of failure modes of rivet pullout and sheet separation. Hoang et al. [5] studied the possibility of using aluminum rivets instead of steel rivets for the self-piercing riveting process by experiments and two-dimensional axisymmetric finite element analyses. Their results showed that the rivet material has significant effects on the interlock distance and failure load of self-piercing rivets. Li et al. [6] further indicated that the failure load of self-piercing rivets has strong dependence on the edge distance, pitch distance, and specimen width.

Fu and Mallick [7] studied the fatigue performance of self-piercing rivets in lap-shear specimens of aluminum 6111-T4 sheets by two-level cumulative fatigue tests. Their results showed that the loading path with a high load level following by a low load level appears to strongly improve the fatigue lives of rivets. The failure mode and fatigue crack growth behavior of self-piercing rivets were also identified. Sun and Khaleel [8] and Sun et al. [9] further studied the fatigue performance of self-piercing rivets between similar and dissimilar sheets in lap-shear and cross-tension specimens. Their research works showed that the fatigue lives of rivets in lap-shear specimens are higher than those in cross-tension specimens. In addition, the piercing direction has noticeable effects on the fatigue lives of rivets between dissimilar sheets. Li and Fatemi [10] studied the fatigue performance of

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self-piercing rivets and pop rivets in coach-peel specimens of aluminum sheets with different thicknesses under different load ratios. Their results showed that both sheet thickness and load ratio have significant effects on the fatigue behavior of both types of rivets. In addition, the overall fatigue performance of self-piercing rivets is better than that of pop rivets. Han et al. [11] further indicated that the pre-strains in the sheets caused by the pressing and stamping process in the automotive industry can increase the fatigue lives of rivets.

For the clinching process as shown in Fig. 2, two metal sheets are directly punched by a tool into a die. The upper and lower sheets are severely deformed to two button-shaped structures, which provide a mechanical interlock between the two sheets. Compared to the riveting process, no additional joining item is required in this process. Varis [12] studied the effects of the tool shape and sheet thickness on the failure load of clinch joints in lap-shear specimens of high-strength structural steel sheets by experiments. The results showed that the round-shaped clinch joint in general has higher failure loads compared to other types of clinch joints. Zhou et al. [13] and Lee et al. [14] conducted a series of parametric studies on the dimensions of the tool and die for clinch joints between aluminum and steel sheets based on experiments and finite element analyses. They discussed two types of failure modes of button neck fracture and button separation. They indicated that the die radius, die depth, and die groove shape have significant effects on the neck thickness and undercut distance of the button-shaped structures, which correlate to the joinability of clinch joints. Mucha [15] further indicated that among the aforementioned parameters, the die groove width is the most important one which strongly affects the material flow and energy consumption of the clinching process.

Nordgerg [16] reviewed the fatigue properties of commonly used lap joints, including spot welds, adhesive-bonded joints, weld-bonded joints, laser welds, and clinch joints, for steel sheets. The results indicated that the fatigue performances of spot welds, laser welds, and clinch joints for the sheet thickness of 1 mm appear to be similar. In addition, the round-shaped clinch joint shows better fatigue performance than the rectangular-shaped one. Carboni et al. [17] studied the fracture and fatigue behaviors of double clinch joints in lap-shear specimens. They discussed three types of failure modes of button separation, button neck fracture, and sheet separation. Mori et al. [18] compared the mechanical properties of self-piercing rivets, clinch joints, and resistance spot welds in lap-shear and cross-tension specimens of aluminum sheets under quasi-static and cyclic loading conditions. Their results showed that the fatigue performances of self-piercing rivets and clinch joints are better than that of resistance spot welds since the fatigue load limits of self-piercing rivets and clinch joints are both nearly 50% of their failure loads, while those of resistance spot welds are only 30–40% of the corresponding failure loads. A possible reason is that the crack/notch along the spot weld circumference naturally induces considerably high stress concentration, whereas the stress concentration from the structures of rivets and joints can be relaxed by slight slip motion between sheets.

Although the fracture and fatigue behaviors of self-piercing rivets and clinch joints have been investigated by many researchers, most of the literature only focuses on their fatigue performance. The fatigue life estimations for both types of joints have not been well studied. Unlike resistance spot welds and spot friction welds, there is no pre-existing crack along the circumference of both types of joints. Therefore, the kinked crack growth model of Lin et al. [19–21] based on the global and local stress intensity factor solutions at the critical locations of spot welds or spot friction welds is not applicable here. Kim [22] studied the fatigue crack growth behavior of clinch joints in lap-shear specimens of cold rolled steel sheets and adopted the fatigue crack growth model

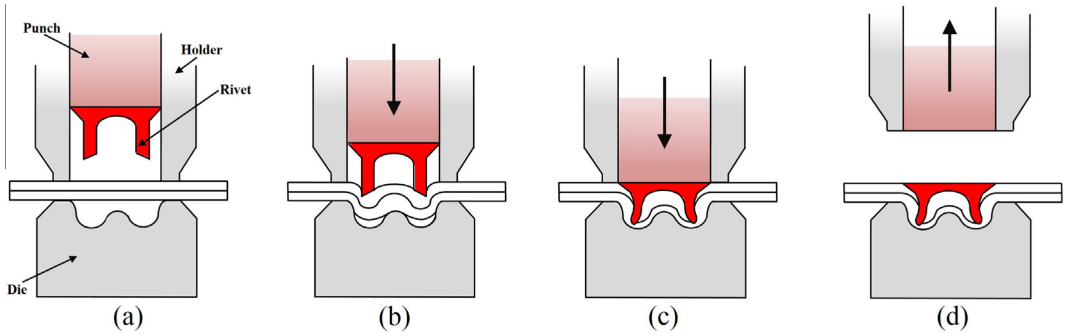

Fig. 1. Schematics of the self-piercing riveting process.

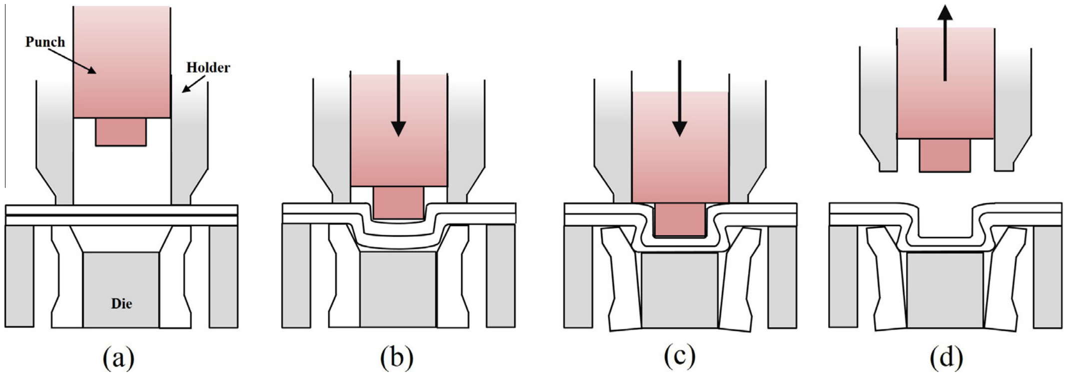

Fig. 2. Schematics of the clinching process.