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Mechanism of superiority of fatigue strength for aluminium alloy sheets joined by mechanical clinching and self-pierce riveting

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ABSTRACT

The static and fatigue strengths of mechanically clinched and self-pierce riveted joints in aluminium alloy sheets were compared with those of a resistance spot welded joint. Both static and fatigue strengths of the joint for the self-pierce riveting were the highest. Although the static strength for the mechanical clinching was about half for the resistance spot welding, the fatigue strength was almost similar. The mechanism of superiority of fatigue strength for the mechanical clinching and self-pierce riveting and was examined from finite element simulation of elastic loading of the joints. In the resistance spot welding, the stress concentrates at the edge of the weld nugget due to the complete bonding, whereas the concentration of stress is relaxed by the slight slip at the interface between the sheets for the mechanical clinching and self-pierce riveting. In addition, the yield stresses for the mechanical clinching and self-pierce riveting are increased by the work-hardening undergone during the joining processes, whereas the yield stress for the resistance spot welding is reversely decreased by the annealing in the welding. It was found that the mechanical clinching and self-pierce riveting have superior fatigue strength.

1. Introduction

To reduce the weight of automobiles, aluminium alloy sheets are attractive because of high specific strength. Kleiner et al. (2003) reviewed metal forming processes of lightweight components for the reduction. For the production of aluminium alloy parts, not only low formability and large springback but also joining is a problem. Although the resistance spot welding is usually used to join steel sheets for automobile body panels, it is not easy to weld aluminium alloy sheets because of the high thermal conductivity, low melting point, natural surface oxide layer, etc.

Joining processes by plastic deformation such as the self-pierce riveting and mechanical clinching are attractive for joining aluminium alloy sheets, because the sheets are not melted. Lennon et al. (1999) compared the joining processes by plastic deformation for steel sheets. The self-pierce riveting is a cold process for joining two or more sheets by driving a rivet through the upper sheet and flaring the skirt of the rivet in the lower sheet without fracture of the lower sheet. Since this riveting does not require a pre-drilled hole unlike the conventional riveting, the joining speed is the same level with that of the spot welding, and the equipment is also similar. Although Barnes and Pashby (2000) explained that the self-pierce riveting is mainly employed for joining of aluminium alloy sheets in automobiles, this riveting can be applied to dissimilar sheet metals because of cold joining. Abe et al. (2006) categorised defects for the self-pierce riveting of aluminium alloy and steel sheets to obtain optimum joining conditions. In addition, Mori et al. (2006) and Abe et al. (2009) optimised shapes of the dies for joining of aluminium alloy and high strength steel sheets.

The mechanical clinching is a cold joining process of sheets by local hemming with a punch and die without a rivet, and is widely used for electrical appliances, automobiles, etc. Abe et al. (2007) joined aluminium alloy and steel sheets by the mechanical clinching. Varis (2003) and Abe et al. (2010) used the mechanical clinching for the joining of high strength steel sheets. Abe et al. (2012) joined high strength steel and aluminium alloy sheets by mechanical clinching. Varis (2006) compared the production cost of the mechanical clinching with that of the self-pierce riveting. The mechanical joining is useful for joining the aluminium alloy sheets for automobile body panels because of low running costs.

Since the self-pierce riveting and mechanical clinching are mechanical joining and not metallurgical one, the strength characteristics of the mechanical joining processes are different from those of the welding processes. Particularly, the fatigue strength is crucial for joining of automobile body panels. Fu and Mallick (2003) examined the fatigue behaviour of self-pierce riveted joints in aluminium alloy sheets. Li and Fatemi (2006) compared static

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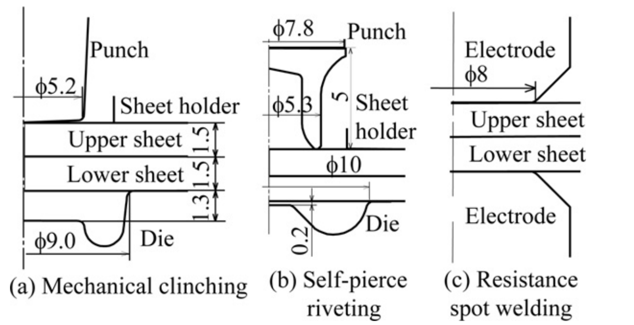

Fig. 1. Joining conditions of aluminium alloy sheets.

and fatigue strengths of self-pierce riveted joints in aluminium alloy sheets. Chen et al. (2003) and Han et al. (2006a,b) investigated the fretting fatigue of self-pierce riveted joints in aluminium alloy sheets. Sun et al. (2007) exhibited that the fatigue strength of the self-pierce riveted joints is considerably higher than that of the resistance spot welded joints. Carboni et al. (2006) found that the location of crack formation in the fatigue test of steel sheets joined by the mechanical clinching corresponds to that at concentration of stress calculated from finite element simulation. The fatigue strength is strongly dependent on a stress distribution during the repeated loading of the joint.

In the present study, the strength characteristics of the mechanical clinching, self-pierce riveting and resistance spot welding were investigated. The static and fatigue behaviours of aluminium alloy sheets joined by the mechanical clinching and self-pierce riveting were compared with that by the resistance spot welding. The effect of the slight slip at the interface between the sheets on the static and fatigue behaviours for the mechanical joining was examined.

2. Procedure of experiment

The aluminium alloy sheets A5052-H34 conventionally used for automobile body panels were joined by the mechanical clinching, self-pierce riveting and resistance spot welding, and then the static and fatigue tests of the joints were performed. The mechanical properties of the aluminium alloy sheet and boron steel self-pierce rivet are given in Table 1. The properties except for the Vickers hardness for the sheet and rivet were measured from the static uniaxial tensile and compression tests, respectively.

The procedures of the mechanical clinching, self-pierce riveting and resistance spot welding are shown in Fig. 1. In the mechanical clinching, the diameter of the punch was 5.2 mm, and the thickness in the bottom of the joint was adjusted to 35% of the sum of the thicknesses of the upper and lower sheets by controlling the stroke of the punch. In the self-pierce riveting, the sheets were pierced with the boron steel rivet having a skirt until the flat upper surface of the joint. The sheets were lubricated with a press oil for the mechanical clinching and self-pierce riveting, because the stamped body panels are generally lubricated and the unlubrication brings about the increase in cost. In the resistance spot welding, the unlubricated sheets are joined with electrodes having a diameter of 8 mm under a force of 2.5 kN and a current of 22 kA.

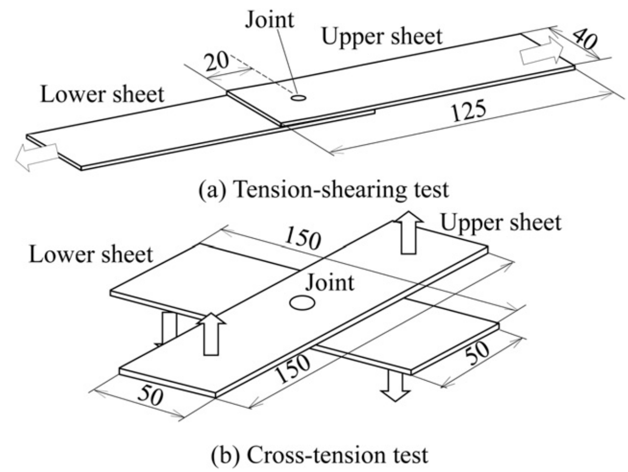

Fig. 2. Joined sheets used for tension-shearing and cross-tension tests of static and fatigue strengths.

The joined sheets used for the tension-shearing and cross-tension tests of the static and fatigue strengths are illustrated in Fig. 2. In the static test, the loading speed was 10 mm/min. On the other hand, in the fatigue test, the repeated load cycle between tension and unloading was employed under a frequency between 5 and 30 Hz.

3. Results for static and fatigue tests of joints

3.1. Joined sheets

The cross-sectional shapes of the joints obtained by the three joining processes are illustrated in Fig. 3. For the mechanical clinching and self-pierce riveting, the sheets are joined by being hooked on the interlocks generated by plastic deformation, i.e. the joined sheets are separated by cutting the joint in half. When the sheets joined by the mechanical clinching and self-pierce riveting are loaded, slight slip is caused at the interface between the sheets because of no bonding. As shown in Fig. 4, the non-bonded sheets for the mechanical clinching and self-pierce riveting are rotated. On the other hand, the sheets joined by the resistance spot welding do not slip at the interface by the appearance of the weld nugget. The strength of the joints is influenced by the slip.

3.2. Static test

The failures and the load–stroke curves for the static tension-shearing test of the joints obtained by the three joining processes are illustrated in Fig. 5. In the static tension-shearing test, failures occur under large plastic deformation. In the mechanical clinching, the upper sheet fractures at the neck having a minimum thickness in the joint, the rivet is pulled out of the lower sheet in the self-pierce riveting, and the weld nugget fractures in the resistance spot welding. The load for the self-pierce riveting is the highest, the resistance spot welding the next and the mechanical clinching the last. In the mechanical clinching, the neck shown in Fig. 3(a) is

Table 1
Mechanical properties of aluminium alloy A5052-H34 sheet and boron steel self-pierce rivet.

	Thickness (mm)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Flow stress (MPa)	Vickers hardness (HV)
A5052-H34 sheet	1.5	70	0.34	211	$\sigma = 366\varepsilon^{0.11}$	80
Boron steel self-pierce rivet		206	0.3	1850	$\sigma = 1955\varepsilon^{0.013}$	505

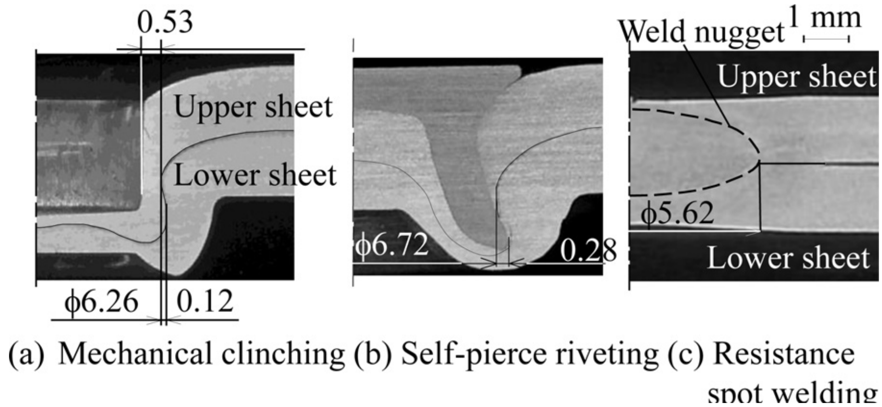

Fig. 3. Cross-sectional shapes of joints obtained by three joining processes.

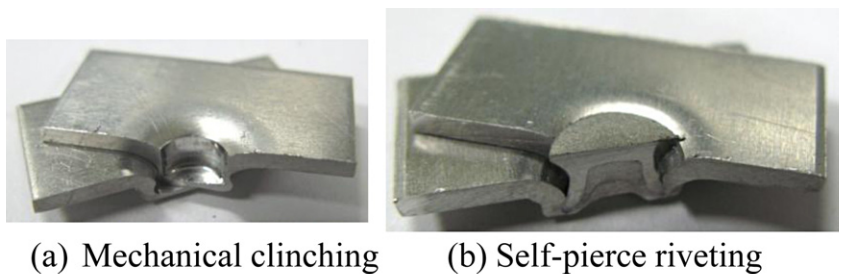

Fig. 4. Rotation of non-bonded sheets for mechanical clinching and self-pierce riveting.

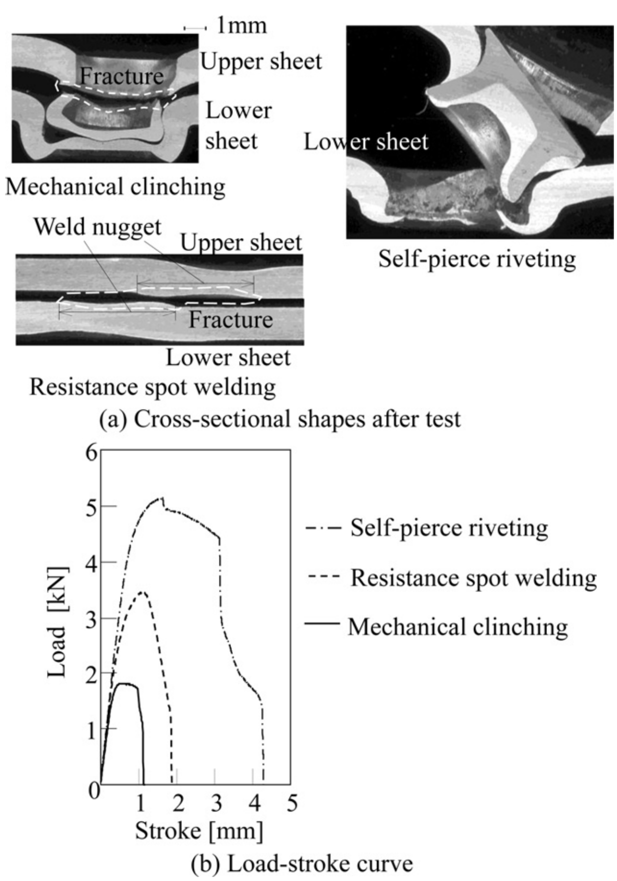

Fig. 5. Failures and load–stroke curves for static tension-shearing test of joints obtained by three joining processes.

formed to generate the interlock, and becomes a weak portion in the static test.

The distributions of Vickers hardness around the mechanically clinched and resistance spot welded joints and the cross-sectional areas of the fractured portion in the tension-shearing test of the joints are shown in Fig. 6. In the mechanical clinching, the hardness of the joint is increased by the work-hardening for large plastic deformation, whereas the weld nugget is softened by annealing in the resistance spot welding. Since the cross-sectional area of the fractured portion for the mechanical clinching is considerably smaller than that for the resistance spot welding, the load for the mechanical clinching shown in Fig. 5 becomes small.

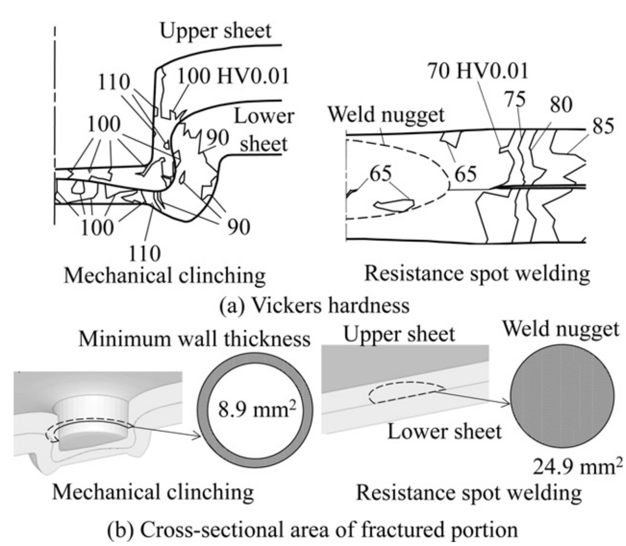

Fig. 6. Distribution of Vickers hardness around mechanically clinched and resistance spot welded joints and cross-sectional areas of fractured portion in tension-shearing test of joints.

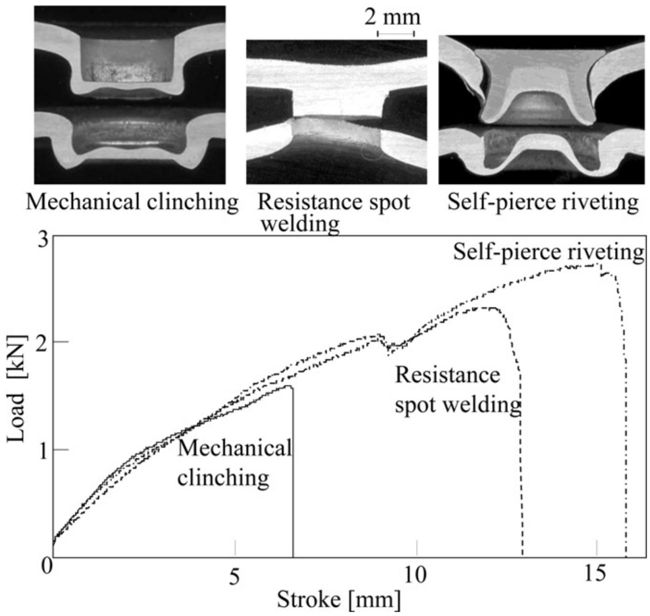

Fig. 7. Failures and load–stroke curves for static cross-tension test of joints obtained by three joining processes.

The failures and the load–stroke curves for the static cross-tension test of the joints obtained by the three joining processes are illustrated in Fig. 7. Although the load for the cross-tension test is smaller than that for the tension-shearing, the tendency of the maximum load for the three joining processes is similar to the tension-shearing test. In the mechanical clinching and self-pierce riveting, the upper sheet and the rivet are pulled out of the lower sheet, respectively, and the lower sheet fractures in the resistance spot welding.

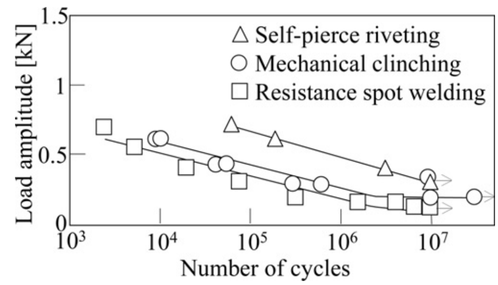

Fig. 9. Relationship between load amplitude and number of cycles in fatigue cross-tension test.

3.3. Fatigue test

The relationship between the load amplitude and the number of cycles in the fatigue tension-shearing test is shown in Fig. 8. Each test was ended when the displacement became excessive. In the mechanical clinching, self-pierce riveting and resistance spot welding, the upper sheet fractures at the neck in the joint, around the head of the rivet and around the weld nugget, respectively. As the number of cycles increases, the load amplitude decreases, and is finally kept constant. Although the static strengths of the self-pierce riveting and mechanical clinching are about 1.5 and 0.5 times as large as that of the resistance spot welding, respectively, as shown in Fig. 5, the fatigue strengths are increased to about 3 and 1 times, respectively.

The relationship between the load amplitude and the number of cycles in the fatigue cross-tension test is shown in Fig. 9. Although the load amplitude for the cross-tension test is smaller than that for the tension-shearing, the tendency of the load amplitude for the three joining processes is similar to the tension-shearing test. It was found that the self-pierce riveting and mechanical clinching have superior fatigue strengths.

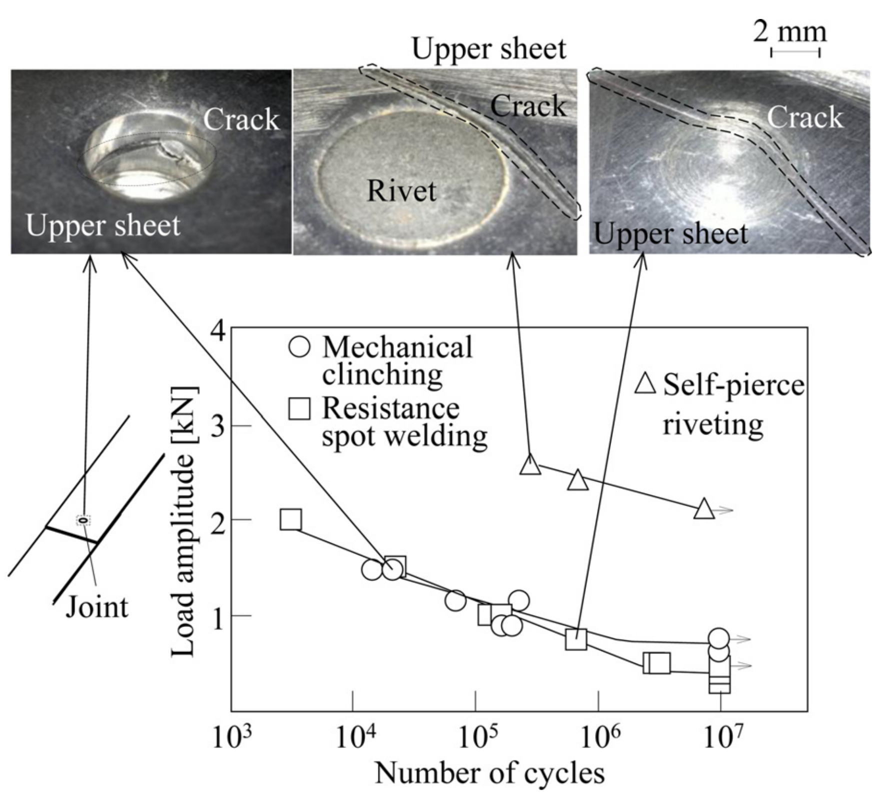

Fig. 8. Relationship between load amplitude and number of cycles in fatigue tension-shearing test.

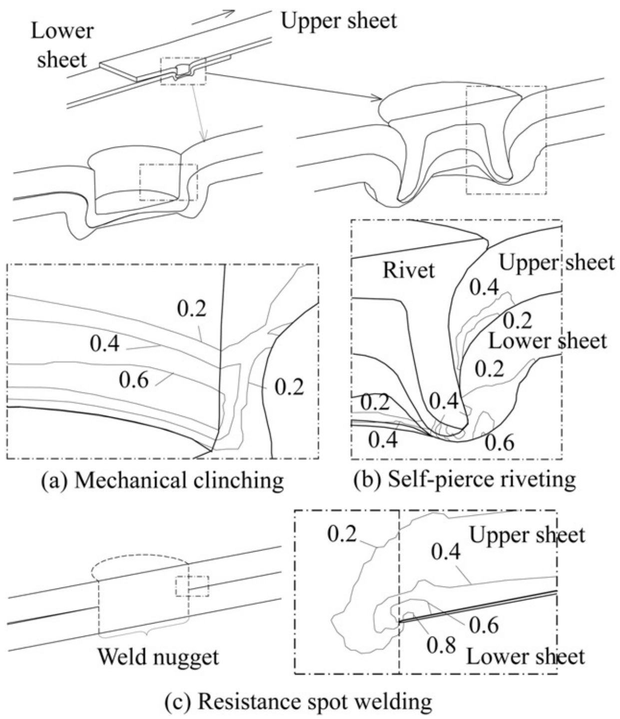

Fig. 10. Distribution of ratio of maximum principal stress to yield stress in tension-shearing test of joined sheets obtained from finite element simulation for $P = 0.5$ kN.

4. Discussion for strength

4.1. Conditions of calculation

The mechanism of superiority of fatigue strength for the self-pierce riveting and mechanical clinching was examined from the finite element simulation using the commercial software LS-DYNA. Since deformation for the repeated load of the fatigue test is elastic, the distribution of stress for elastic loading of the joints obtained by the three joining processes was calculated from the finite element simulation. Only half of the specimen was three-dimensionally divided into hexahedral elements because of symmetric deformation.

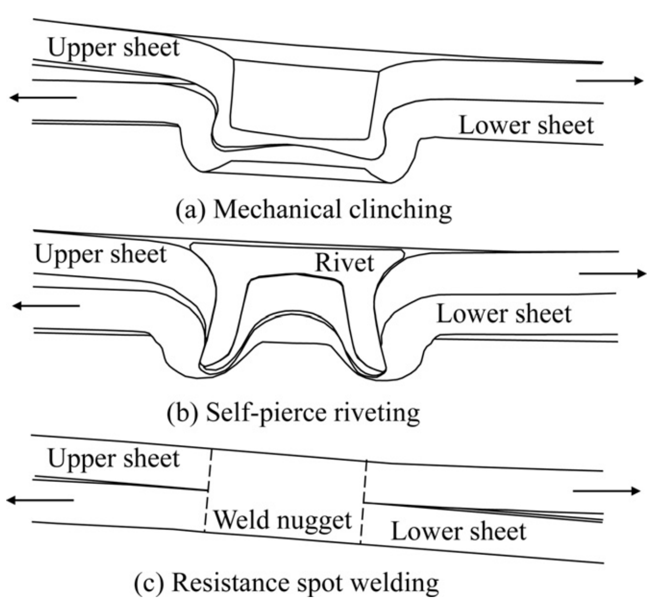

Fig. 11. Deforming shapes in tension-shearing test of joined sheets obtained from finite element simulation for $P = 0.5$ kN (displacement enlarged ten times as large as real one).

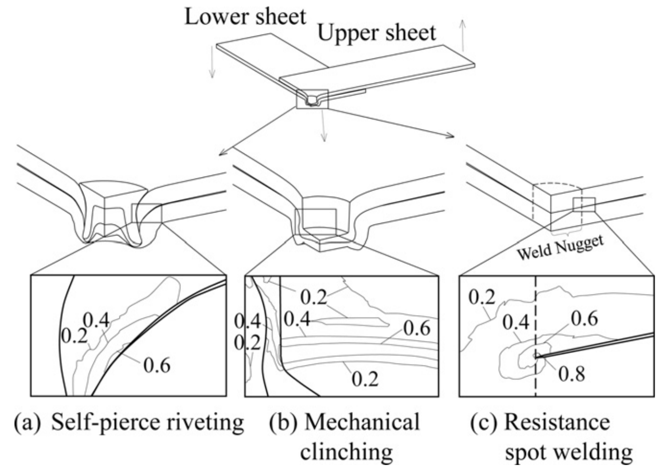

Fig. 12. Distributions of ratio of maximum principal stress to yield stress in cross-tension test of joined sheets obtained from finite element simulation for $P = 0.5$ kN.

For the self-pierce riveting and mechanical clinching, the joining processes were simulated first, and then the elastic loading of the joints was calculated. For the resistance spot welding, only the elastic loading of the joint was calculated, and it was assumed that the sheets are completely joined in the weld nugget. The distribution of flow stress in the sheets for the resistance spot welding was obtained by measuring the hardness.

4.2. Distribution of stress in joint

The distribution of the ratio of the maximum principal stress to the yield stress in the tension-shearing test of the joined sheets obtained from the finite element simulation for the load $P = 0.5$ kN equivalent to the fatigue limit of the resistance spot welding is shown in Fig. 10, where the yield stresses for the mechanical clinching, self-pierce riveting and resistance spot welding are the values at the neck of the joint, the lower surface of the upper sheet in the head of the rivet and the edge of the weld nugget at which cracks were initiated in Fig. 8, respectively. For the resistance spot welding, the maximum stress ratio is the highest, the mechanical clinching the next and the self-pierce riveting the last.

The deforming shapes in the tension-shearing test of the joined sheets obtained from the finite element simulation for $P = 0.5$ kN are shown in Fig. 11, where the displacement is enlarged ten times as large as the real one. The displacements for the mechanical clinching and self-pierce riveting are considerably larger than that for the resistance spot welding. In the resistance spot welding, the stress concentrates at the edge of the nugget due to the complete bonding, whereas the concentration of stress is relaxed by the slight slip at the interface between the sheets for the mechanical clinching and self-pierce riveting as shown in Fig. 10. In addition, the yield stresses for the mechanical clinching and self-pierce riveting are increased by the work-hardening undergone during the joining processes, whereas the yield stress for the resistance spot welding is reversely decreased by the annealing in the welding as shown in Fig. 6.

The distribution of the ratio of the maximum principal stress to the yield stress in the cross-tension test of the joined sheets obtained from the finite element simulation for $P = 0.5$ kN is shown in Fig. 12. The tendency of the stress ratio for the three joining processes is similar to the tension-shearing test, i.e. the maximum stress ratio for the resistance spot welding is the highest. The slight slips for the mechanical clinching and self-pierce riveting are effective in relaxing the concentration of stress, and thus the fatigue strength is improved.

The difference between the tendencies of the static and fatigue strengths is due to deformation. The static strength is determined for a failure of single large plastic deformation, and the degree of joining becomes a main factor. Although the sheets are joined by the hooking on the small interlock for the mechanical clinching, the sheets are completely bonded by the weld nugget for the resistance spot welding as shown in Fig. 3. On the other hand, the fatigue strength is determined for a fracture under repeated small elastic deformation, and the concentration of stress within elastic deformation is influential. Small cracks are caused by the concentration of stress and grow for the repeated loading. The slight slip at the interface between the sheets for the mechanical joining has an effect on the relaxation of the concentration of stress.

The joining loads for the mechanical clinching, self-pierce riveting and resistance spot welding were 20.4, 57.4 and 2.5 kN, respectively. The price of one self-pierce rivet is about USD 0.03, and electricity and consumable electrodes are required for the resistance spot welding. The mechanical clinching having low running costs is useful for the joining of automobile body panels, because the fatigue strength is the same level with that of the resistance spot welding. In joining of automobile body panels, the fatigue strength is crucial.

5. Conclusions

The static and fatigue strengths of mechanically clinched, self-pierce riveted and resistance spot welded joints in aluminium alloy sheets were investigated. The static and fatigue behaviours between the mechanical joining and metallurgical welding processes were compared. The mechanism of superiority of fatigue strength for aluminium alloy sheets joined by the mechanical clinching and self-pierce riveting was clarified. The following results were obtained:

1. The static strength for the self-pierce riveting was the highest, the resistance spot welding the next and the mechanical clinching the last.
2. The small static strength for the mechanical clinching was due to the small cross-sectional area of the fractured portion.
3. The fatigue strength for the self-pierce riveting was considerably large, and the fatigue strength for the mechanical clinching was the same level with that for the resistance spot welding.
4. The fatigue strengths for the mechanical clinching and self-pierce riveting were heightened by the slight slip at the interface between the sheets.
5. The mechanical clinching having low running costs is useful for the joining of automobile body panels, because the fatigue strength is the same level with that of the resistance spot welding.

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