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Fatigue strength and fatigue fracture mechanism of three-sheet spot weld-bonded joints under tensile–shear loading

Tomoyuki Fujii *, Keiichiro Tohgo, Yukinori Suzuki, Takahiro Yamamoto, Yoshinobu Shimamura

Department of Mechanical Engineering, Shizuoka University, 3-5-1, Johoku, Naka-ku, Hamamatsu 432-8561, Japan

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ABSTRACT

This paper deals with fatigue behavior of three-sheet spot weld-bonded (SWB) joints to investigate the influence of adhesive bonding on fatigue strength and fracture mechanism. From the results of tensile–shear fatigue tests, the fatigue strength of the SWB joint was higher than that of the spot welded (SW) joint. For fatigue behavior in the SWB joint, debonding between a steel sheet and adhesive propagated from an edge of bonded area to a nugget edge, and a fatigue crack initiated at the nugget edge. It was concluded that the delayed fatigue crack initiation at the nugget edge in the SWB joint resulted in the fatigue strength improvement of SW joint.

1. Introduction

Resistance spot welding technique has been widely used for assembling processes in the automotive industries, and a vehicle body is generally assembled by thousands of spot welds. It is necessary to evaluate fatigue life and strength of spot-welded (SW) joints to guarantee long-term use of vehicles. To evaluate the fatigue strength of SW joints under cyclic tensile–shear loading and peel loading, many studies on their fatigue behavior have been conducted [1–6], and some different methods to predict their fatigue lives have been proposed [7–20]; the fatigue lives were evaluated on the basis of local stress around a nugget of resistance spot weld [7], local strain in the vicinity of a nugget [8–10], and fracture mechanics approach by regarding a nugget edge as a crack tip [11–20].

Since 1990 s, ultra-high strength steels, of which the tensile strength is beyond 780 MPa, started to be applied for vehicles to improve their safety in case of crash impact and weight saving for high fuel efficiency. Many researchers, however, pointed out that the fatigue strength of SW joints made of ultra-high strength steels were not improved [1,11–13,19,20]. To investigate this problem, their fatigue strength was evaluated from viewpoints of the change in microstructure by welding [1], residual stress [12], notch sensitivity of base steels [19,20] and so on. Tohgo et al. [20] conducted the fatigue tests using smooth, notched and SW tensile–shear specimens made of mild and ultra-high strength steels to investigate the influence of strength level of base steels on fatigue strength. As a result, for the smooth specimens, the fatigue strength was higher in the ultra-high strength steel than in the mild steel in low to high cycle fatigue regime. For the notched specimens, however, although the fatigue strength was also higher in the ultra-high strength steel than in the mild steel in low cycle fatigue regime, the difference in their fatigue strengths became small in high cycle fatigue regime; the differences in applied tensile stress range between both steels were about 200 MPa and 30 MPa for fatigue life of 10^4 and 10^7 cycles, respectively. For the SW tensile–shear specimens, the difference in their fatigue strengths also decreased with increasing fatigue life, and this trend was similar to that for the notched specimens. They concluded that the fatigue strength was affected by notch-sensitivity to fatigue strength of the base steels by comparing the S–N curves obtained with these specimens. From this reason, the fatigue strength of SW joints of ultra-high strength steels could be improved by reducing stress concentration near a nugget edge.

Spot-weld bonding technique by combining spot welding and adhesive bonding has been expected to improve fatigue strength of SW joints. Many experimental and numerical studies on static and fatigue strengths of spot-weld bonded (SWB) joints have been carried out [21–29], and they showed that the static and fatigue strengths were higher in SWB joints than in SW joints. The authors conducted the fatigue tests of the SW and SWB joints made of mild steel (270 MPa class) and ultra-high strength steel (980 MPa class) using thermoset epoxy adhesive, and their fatigue processes and

* Corresponding author. Tel./fax: +81 53 478 1029.
E-mail address: fujii.tomoyuki@shizuoka.ac.jp (T. Fujii).

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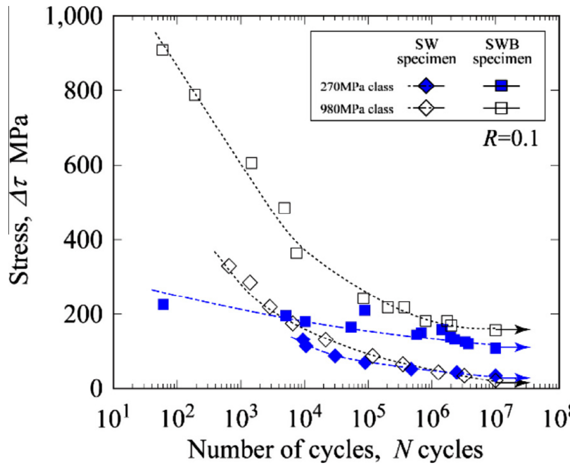

Fig. 1. S–N curves of single-lap joints by spot-welding and spot weld-bonding [30].

fatigue strengths were investigated [30]. Interfacial debonding between a steel sheet and adhesive occurred in the SWB joints, and then a crack initiated at a nugget edge. The fatigue strength became higher in the SWB joints than in the SW joints, irrespective of strength level of the base steels, as shown in Fig. 1. Moreover, the fatigue strength in the SWB joints made of the ultra-high strength steel became higher than that of the mild steel at low to high cycle fatigue regime because the debonding of the mild steel specimens occurred at a lower number of load cycles than in the ultra-high strength steel for the same load level. To clarify the mechanism of fatigue strength improvement, finite element analysis for the SW and SWB specimen subjected to tensile–shear loading was conducted, and the influence of bonded area and progress of debonding on stress distribution around the nugget edge was investigated on the basis of the fracture mechanics approach. It was revealed that the stress intensity of the nugget edge was very low due to the adhesive, and then was increased with progress of debonding. This result implied that the fatigue crack would initiate at the nugget edge at a higher number of load cycles in the SWB specimen than in the SW specimen. In this study [30], single-lap joints using two sheets by means of spot welding and spot weld-bonding were focused on. In the case of a single-lap joint under tensile–shear loading as in Fig. 2(a), a weld-bonded part rotates by bending deformation of the upper and lower steel sheets, and the tensile stress is created in the adhesive and nugget by the rotation. This tensile stress would affect the fatigue strength and fracture mechanism of the SW and SWB joints. To reduce the tensile stress in the adhesive and nugget under tensile–shear loading, double-lap joints are expected because the rotation of a weld-bonded part could be suppressed, as shown in Fig. 2(b). The double-lap joints made from a combination of more than two sheets are sometimes used in complicated structures, such as vehicle bodies [31,32]. Their fatigue strength, however, remains to be evaluated to guarantee their long-term use.

In this study, quasi-static and fatigue tests of double-lap joints made of mild steel and ultra-high strength steel by three-sheet spot welding and spot weld-bonding were conducted to investigate their fatigue strength and the influence of strength level of the base steels on fatigue behavior. Fatigue processes were investigated from viewpoints of debonding behavior at an interface between a steel sheet and adhesive and fatigue crack initiation at a nugget edge. Then, mechanism of the fatigue strength improvement of the SWB joint was investigated on the basis of stress distribution in the vicinity of a nugget by finite element analysis.

2. Experimental procedure

2.1. Materials and specimen

Mild steel sheet (JSC270D, 270 MPa class) and ultra-high strength steel sheet (JSC980Y, 980 MPa class) with thickness of 1.4 mm were used. Table 1 shows their chemical compositions and mechanical properties. Fig. 3 shows configurations of the SW and SWB specimens. In the SW specimen, spot welding was processed on three steel sheets. In the SWB specimen, spot weld-bonding was made by a combination of spot welding and adhesive bonding. Spot welding was processed on three steel sheets bonded by thermoset epoxy adhesive (OROTEX4901, Iida Industry CO., LTD), and then the adhesive was cured at 170 °C for 20 min. The gripping parts (right-hand area in Fig. 3(a) and (b)) were welded with another sheet to fill a gap. Fig. 4 shows the microstructure of cross section around a nugget of the SWB

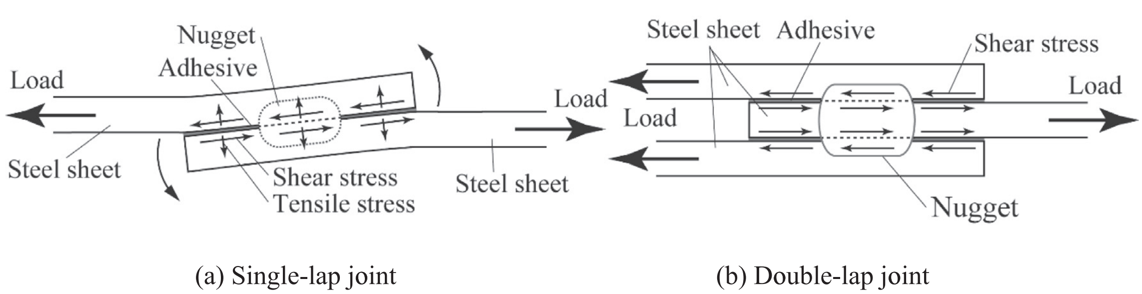

Fig. 2. Schematic illustration of deformation of a weld-bonded part.

Table 1
Chemical compositions and mechanical properties.

	C	Si	Mn	P	S	Fe	0.2% proof stress (MPa)	Tensile stress (MPa)	Elongation (%)
(a) For spot welded (SW) specimen									
JSC270D	0.001	0.01	0.09	0.004	0.008	Bal.	137	271	52
JSC980Y	0.13	0.04	2.57	0.009	0.003	Bal.	665	984	15
(b) For spot weld-bonded (SWB) specimen									
JSC270D	0.001	0.01	0.14	0.015	0.012	Bal.	158	310	49
JSC980Y	0.14	0.97	2.21	0.008	0.003	Bal.	774	1006	14