

Fracture Mechanics Analysis of The Fatigue Strength of Various Spot Welded Joints

破壊力学による各種スポット溶接継手の疲労強度の解析

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1. Introduction

It is seriously required to establish the method to predict quantitatively the fatigue strength and life of spot welded thin structures in an automobile body. Many studies on the fatigue strength of spot welded joint specimens such as a tensile shear and a cross tension specimen have been reported. But no reliable or universal method has not been established yet to predict the fatigue strength of spot welded joint specimens as well as the spot welded structures, because the fatigue strength is significantly affected by the type of specimens, plate thickness, nugget diameter and others.

It seems that fracture mechanics is the most possible approach to this problem^{(1),(2)}, because the spot welded joint can be regarded as a crack like defect. Pook^{(3),(4)} and Davidson^{(5),(6)} tried to apply fracture mechanics to the prediction of the fatigue strength of a spot welded joint specimen. However their studies are limited to a tensile shear spot welded specimen and the fracture mechanics parameter used by them seems to be doubtful. A crack in the spot welded joint is a three-dimensional and a mixed mode crack in general. It is important to evaluate exactly the stress intensity factors for a spot welded joint.

In this study, the stress intensity factors for various spot welded joint specimens are analyzed by three-dimensional elastostatic finite element analyses. The stress intensity factors for a tensile shear, a cross tension, a T-type tension or bending, a double shear and an out-of-plane bending

specimen are presented. The fatigue strengths of these specimens are characterized by the stress intensity analyzed with use of a mixed mode fracture criterion and the usefulness of fracture mechanics is discussed.

2. Analyses of the Stress Intensity Factors

It is necessary for fracture mechanics analyses to evaluate the stress intensity factors for a spot welded joint. Three dimensional elastic analyses are carried out on six kinds of spot welded joint specimens as shown in Fig.1 by means of a finite element method. An example of the division of elements is shown in Fig.2, where quadratic isoparametric solid elements with 20 nodes are used. As shown in Fig. 3, the symmetric section is zoomed up near a crack tip where the fatigue crack is expected to grow and reanalyzed under plane strain condition by two-dimensional elastic finite element method. The stress intensity factors at a crack tip is determined by the displacement extrapolation method^{(1),(2)}.

Table 1 show the stress intensity factors K_I and K_{II} obtained for standard tensile shear (TS) and cross tension (CT) specimens with a nugget diameter of 5 mm and equi-thickness plates. The stress intensity factors are normalized by $P/a^{3/2}$, where P is an applied load and $2a$ is a nugget diameter. It is found that the ratio of K_I/K_{II} is quite different between TS and CT specimens. It is noteworthy that our results are quite different from the approximate equation for TS specimen proposed by Pook^{(1),(2)}.

Table 2 shows the stress intensity factors for TS,

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Table 3 Stress intensity factors for a T-type bending specimen ($2a=6$ mm)

Arm length l_1 (mm)	TB specimen		
	$K_{Ia}^{3/2}/(P/l_1)$	$K_{IIa}^{3/2}/(P/l_1)$	K_{II}/K_I
15	0.695	0.291	0.419
60	0.731	0.324	0.443
80	0.714	0.327	0.458

Table 4 Stress intensity factors for a double shear specimen ($2a=5$ mm)

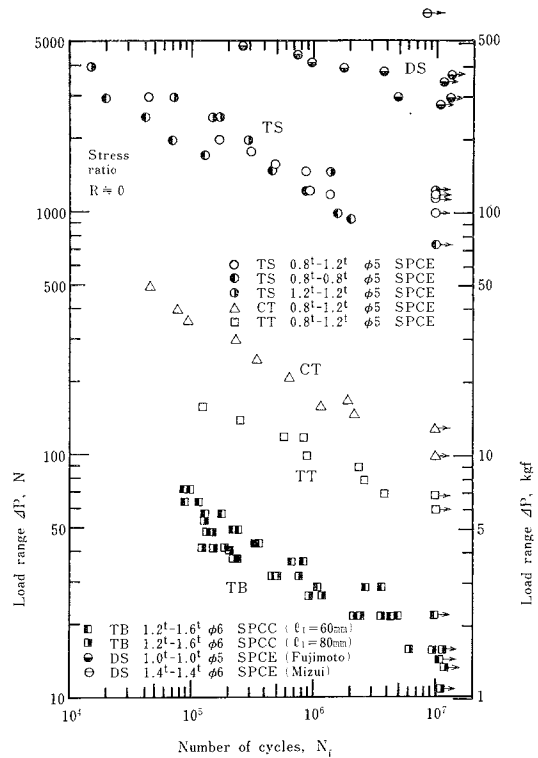
Plate Thickness t_1-t_2 (mm)	Double Shear Specimen			
	K at A		K at A'	
	$K_{Ia}^{3/2}/P$	$K_{IIa}^{3/2}/P$	$K_{Ia}^{3/2}/P$	$K_{IIa}^{3/2}/P$
1.0-1.0	0.0158	-0.1553	-0.0115	-0.1320
1.2-1.2	0.0245	-0.1478	-0.0190	-0.1265
1.4-1.4	0.0328	-0.1415	-0.0269	-0.1217
1.6-1.6	0.0427	-0.1368	-0.0364	-0.1186
1.2-0.8	0.0293	-0.1273	-0.0233	-0.1107

Table 5 Stress intensity factors for a Out-of-plane bending specimen ($2a=5$ mm)

Plate Thickness t_1-t_2 (mm)	Out-of-plane Bending Specimen		
	K at A		
	$K_{Ia}^{3/2}/M$	$K_{IIa}^{3/2}/M$	K_{II}/K_I
0.8-0.8	2.52	-0.89	-0.35
1.0-1.0	1.81	-0.62	-0.34
1.2-1.2	1.42	-0.45	-0.32
1.5-1.5	1.13	-0.33	-0.29
2.0-2.0	0.82	-0.21	-0.26
0.8-1.2	2.37	-1.20	-0.51

bending (TB) specimens with different arm lengths, which is specially developed for this study. In this specimen, the nugget diameter is 6 mm and the plate thicknesses are 1.2 and 1.6 mm respectively. Table 4 and 5 show the stress intensity factor for a double shear (DS) specimen and an out-of-plane bending (PB) specimen with various plate thicknesses and a nugget diameter of 5 mm.

It is found that all specimens analyzed in this study have a mode I and a mode II mixed mode stress intensity factors at a crack tip in the symmetric section and however the ratio K_{II}/K_I varies at every specimen.

Fig.4 The $\Delta P-N_f$ curves for various spot welded joint specimens

3. Fracture Mechanics Analyses of the Fatigue Strength

Fig.4 shows the fatigue properties for five kinds of the spot welded joint specimens with different plate thicknesses, nugget diameters and materials against the applied load range ΔP . Here our experimental conditions and procedures are omitted for the sake of space^{1),2)} and the data of DS specimen are quoted from Fujimoto⁷⁾ and Mizui⁸⁾. In this figure, each specimen represents quite different property of the fatigue strength and life. But it is noted that the slopes of the time strength are nearly same with each other.

Next these fatigue properties are tried to be rearranged against the stress intensity factor analyzed by FEM. Since a crack is under a mixed mode condition, the following mixed mode fracture criterion after Erdogan and Sih⁹⁾ is employed. The fatigue crack will grow in the direction of $\theta=\theta_0$ where a tangential stress σ_θ at a cracks tip becomes

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a maximum.

$$\Delta K_I \sin \theta_0 + \Delta K_{II} (3 \cos \theta_0 - 1) = 0 \quad (1)$$

where ΔK_I is the mode I stress intensity range and ΔK_{II} is the mode II stress intensity range for a crack before the fatigue crack grows and the values of ΔK_I and ΔK_{II} can be calculated by the applied load range ΔP and the tables above. The mode I stress intensity range $\Delta K_{\theta_{\max}}$ at $\theta = \theta_0$ is defined as follows.

$$\Delta K_{\theta_{\max}} = \cos \frac{\theta_0}{2} \left(\Delta K_I \cos^2 \frac{\theta_0}{2} - \frac{3}{2} \Delta K_{II} \sin \theta_0 \right) \quad (2)$$

It can be considered that this parameter $\Delta K_{\theta_{\max}}$ should control the initiation and growth of the fatigue crack under mixed mode condition. Therefore $\Delta K_{\theta_{\max}}$ is employed in this study as the universal parameter for the fatigue strength of spot welded joints.

Fig.5 shows the $\Delta K_{\theta_{\max}} - N_f$ curves for various spot welded joint specimens. This figure contains all data shown in Fig.4 and also the data for PB specimen which can not be plotted in Fig.4. A part of the data for this PB specimen is due to Mabuchi⁽¹⁰⁾. Although the data for five kinds of specimens with different plate thicknesses, nugget diameters and materials are plotted in this figure, all data fall within a narrow scatter band and the fatigue limit on this curve seems to be nearly consistent with the threshold condition of the mode I fatigue crack growth ΔK_{Ith} . It is confirmed that the stress intensity factor with use of a mixed mode fracture criterion is very useful for the evaluation of the fatigue strength of spot welded joints. Moreover it is possible to predict the direction of the fatigue crack growing from the nugget by using the equation (1).

4. Conclusions

The fatigue strengths of various spot welded joint specimens have been studied in this paper based on fracture mechanics. The stress intensity factors for these specimens are obtained by a finite element method. It is found that the fracture mechanics parameter $\Delta K_{\theta_{\max}}$ for a mixed mode crack can characterize well the fatigue properties of the spot welded joint specimens with different loading types, plate thicknesses and nugget diameters. It is

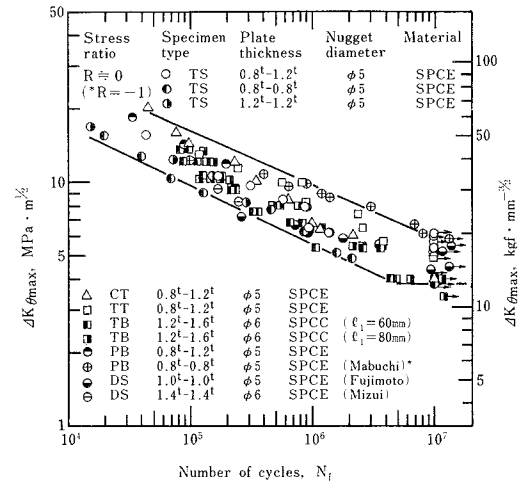


Fig.5 The $\Delta K_{\theta_{\max}} - N_f$ curves for various spot welded joint specimens

confirmed that fracture mechanics approach is very useful for the prediction of the fatigue strength and life of the spot welded joints specimens. This method can be also applied to the fatigue life prediction of a spot welded structure if the stress intensity factor for a spot in the structure can be calculated.

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