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Fatigue Fracture Mechanism on Friction Stir Spot Welded Joints Using 300 MPa-Class Automobile Steel Sheets under Constant and Variable Force Amplitude

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Abstract

The authors have shown an approach to evaluate the fatigue fracture mechanism of cross-tension specimen welded using low carbon steel by friction stir spot welding (FSSW) with the focus on fatigue crack behaviour. Results show that, the fatigue limit of FSSW specimen was very low comparing to the tensile force of base metal and FSSW joint itself. The fatigue cracks initiated near the interface between two thin steel sheets under constant force amplitude conditions were observed in detail by the 3-dimensional observation method. The typical morphologies of 3-dimension were observed with constant low force amplitude level at 0.19 kN and high force amplitude level at 0.49 kN of each fatigue life. It is clear that a main crack initiated at the end of slit and fracture modes were independent on force amplitude level. And, FSSW joint used in this study requires the large and few number of cyclic loading to initiate the fatigue crack under low and high force amplitude level, respectively. Moreover, an evaluation method for the cumulative fatigue damage under variable force amplitude conditions was observed. The results show that, this method can be used to evaluate FSSW joint efficiency in automotive industry and other practical applications.

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1. Introduction

Friction Stir Welding (FSW) was developed and patented by The Welding Institute (TWI) of UK in 1991 (Mishra et al. 2005). This joining process is relatively new solid-state joining process, energy efficient and environment friendly. Its application by using FSW technique has been newly developed, which is called friction stir spot welding (FSSW) that provides a superior alternative to resistant spot welding and riveting. FSSW process was invented by Kawasaki Heavy Industries Ltd. in 2000 as a variant of linear friction stir welding method (Sun et al. 2012). Further in 2003, FSSW was first used in the Mazda RX-8 rear door panel (Wang et al. 2007). With the successful application of FSSW technology to carbon steels, it has received considerable attention on automotive industries. Previous study correlated microstructure analysis and its analysis of mechanical properties and the corresponding parameters used to make the joint that leads to find better parameter sets. The mechanical properties measured in most researches are restricted to static tensile tests and hardness tests (Park et al. 2004; Fujii et al. 2011), however, cross-tension tests have also been cited (Feng et al. 2005). Regarding fatigue tests, some authors have performed studies in alloys series, determining fatigue lives, failure modes and microstructure analysis (Lin et al. 2008; Tran et al. 2008). Several previous studies (Chung et al. 2010; Sato et al. 2007; Cui et al. 2007) have reported the FSSW of carbon steels. Beside these studies, there are few reports about fatigue fracture mechanism of FSSW joint carbon steel, especially on cross tension FSSW specimen (Uematsu et al. 2010) and variable force amplitude.

In the previous work (Joy-A-Ka et al. 2013), the low temperature friction stir welding process should be the first example of welding general steels without any transformation. It has been observed that the relationship between the peak temperature and the A_1 point on the Fe-Fe_3C phase diagram. When the FSSW is performed in the α-γ two-phase region, the microstructure is refined and the highest hardness is then achieved. The specimen used for this study had a fatigue limit of 0.1 kN. This value is very low comparing to the maximum tensile force of the base metal and FSSW joint itself. Therefore, this paper investigates the fatigue fracture mechanism of friction stir spot welded 300 MPa-class low carbon steel sheets used as a general automobile steels. Fatigue crack initiation and fatigue crack propagation were observed at constant low and high force amplitude level by using the 3-dimensional observation method. Furthermore, an evaluation method for the cumulative fatigue damage under variable force amplitude conditions was observed.

2. Experimental Procedure

AISI 1012 sheet low carbon steels, 0.8 mm in thickness is used in this study. AISI 1012 is used in general applications, particularly in the automobile parts manufacturing. Chemical composition and mechanical properties of this steel were given in Table 1 and Table 2, respectively.

Table 1. Chemical composition (%weight) of AISI 1012.

C	Mn	P	S	Fe
0.12	0.50	0.40	0.045	Bal.

Table 2. Mechanical properties of AISI 1012.

0.2YS (MPa)	UTS (MPa)	Elong. (%)	Hardness (HV)
172	314	48	115

From Figure 1(a), one can see the shape and dimensions of the specimen after being machined into the rectangular shape. Steel plates were prepared with dimensions of 150 mm in length and 50 mm in width. Two test plates were conducted the cross-tension specimens by FSSW process at Joining and Welding Research Institute (JWRI), Osaka University as shown in Fig. 1(b). FSSW tool were manufactured from tungsten carbide (WC) with a shoulder diameter of 12 mm, probe length and diameter of 1 mm and 4 mm, respectively. The peak temperature of welded joint of approximate 973 K can be obtained by the welding conducted with force apply of 15.0 kN, rotational speed of 550 rpm and dwell time of 2 second.

Fatigue test were carried out at room temperature by using the servo-hydraulic testing machine operating at frequency of a sinusoidal wave of 5-10 Hz and force ratio *R* of 0.01. The precaution taken was that the specimen does not take any bending or tension stress mode when it is attached to the testing machine.

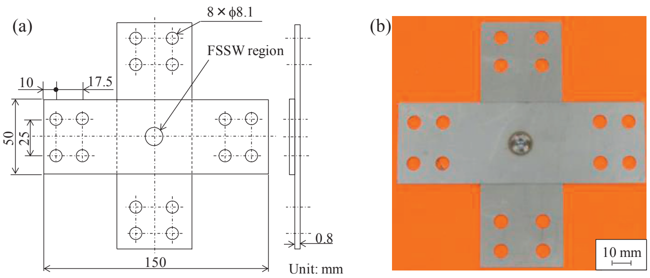

Fig. 1. (a) Schematic illustration of shape and dimensions of specimen; (b) FSSW cross-tension specimen.

3. Results and Discussion

3.1. Fatigue fracture mechanism under constant force amplitude conditions

This research mainly investigated about the fatigue crack propagation conducting in the macro and microscopic observation of the fracture surface. Throughout the analysis, the fatigue crack initiation and propagation should be observed 3-dimensionally for the detailed consideration because their behaviour appeared at the interface between two thin steels sheet. Therefore, we carried out the observation of the small fatigue crack initiation by using about 30-100 observation images taken at the cross section a specimen up to the $\%N/N_f$, the 3-dimensional fatigue crack propagation was produced by the 3-dimensional graphics software.

3.1.1. Low force amplitude level

3-dimensional observation of the fatigue crack propagation was conducted under the constant low force amplitude level of 0.19 kN in the mixed mode fracture. We used the 94,700 cycles which is the longest fracture life in the stress level as it is above the cyclic number to failure. Figure 2(a) shows the schematic illustration of the FSSW specimen along with *x*-*y*-*z* direction incorporated with loading direction. Figure 2(b) shows the macroscopic observation results of fractured specimen near the welded area at $100\%N/N_f$. The fatigue crack morphology of upper sheet propagated across *x*-direction around the spot welded or the diameter of shoulder of FSSW tool, and further propagates to the base metal until the specimen was broken as same as the lower sheet. That is the intermingled fracture type of welded joint and base metal fracture morphologies which referred to this fracture morphology as the mixed mode fracture.

In order to specify the fatigue crack initiation site, cross sectional observation of specimen was carried out. Figure 2(c) shows the micrograph of cross section at the centre of the welded area. It was observed that the crack initiated at the boundary between the welding interface zone and non-interface zone that located in the HAZ. The fatigue crack was found on the upper sheet at the distal slit through to the surface of sheet up to the concave zone.

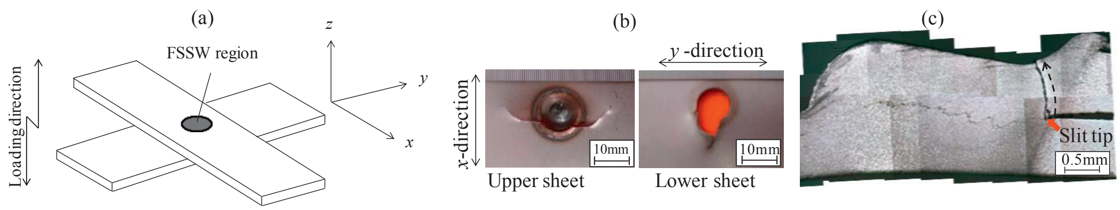

Fig. 2. (a) Schematic illustration of the FSSW specimen; (b) Fracture morphologies of FSSW under constant low force amplitude ; (c) Micrograph of cross section of FSSW

Using same axis system and loading direction in Fig. 2(a). Figure 3(a) shows the fatigue crack propagated on 61.5%N/N_f with 0.2 and 0.4 mm toward thickness direction of upper and lower sheet, respectively. Moreover, there was no fatigue crack near the welded spot on 55.9%N/N_f. This fact implies that specimen used in this study requires many cyclic loading to initiate the fatigue crack in the low force amplitude level. Figure 3(b) and (c) show that the fatigue cracks grow to the full thickness of upper and lower sheet, and that the fatigue cracks tend to grow around the welded joint as equal to the diameter of shoulder of FSSW tool. In Figure 3(d), the fatigue crack propagation of upper sheet grows to the both side of base metal, and two sides of fatigue crack propagation of lower sheet come across nearly circular and propagated to base metal. After the initiation, as the cyclic loading is increasing, the fatigue crack grew gradually the thickness direction. It is likely for the fatigue crack propagate at the centre of spot welded in the loading direction.

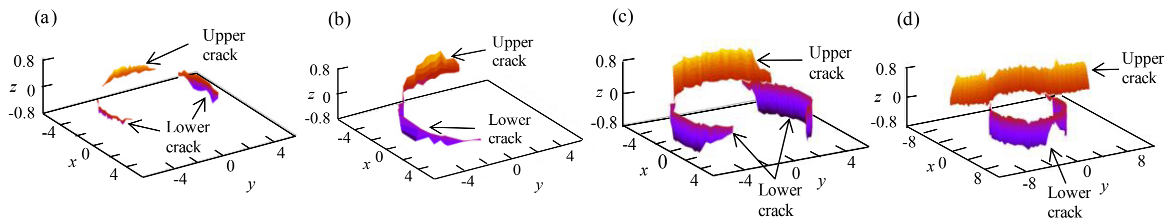

Fig. 3. 3-dimensional crack propagation of FSSW at low force amplitude level. (a) 61.5%N/N_f; (b) 67.1%N/N_f; (c) 78.3%N/N_f; (d) 83.3%N/N_f.

3.1.2. High force amplitude level

3-dimensional observation of the fatigue crack propagation was conducted under the constant high force amplitude level of 0.49 kN in the mixed mode fracture with the longest fracture life in the stress level with respect to the number of cyclic to failure of 9,760 cycles. The fatigue crack morphology of upper sheet propagated around the welded spot or the diameter of shoulder of FSSW tool about 25% of the diameter, and further propagated to the base metal until the specimen was broken. The fatigue crack morphology of lower sheet propagated around the diameter of shoulder of FSSW tool and propagated to base metal. That is the intermingled fracture type of welded joint and base metal fracture morphologies which referred to this fracture morphology as the mixed mode fracture. This means that the fracture mode of high force amplitude level is similar to low force amplitude level.

In order to specify the fatigue crack initiation site, it is observed that the crack initiated at the boundary between the welding interface zone and non-interface zone. The fatigue crack was found on the upper sheet at the distal slit through the surface of sheet up to the concave zone same as the results of low force amplitude level.

From the schematic illustration of the FSSW specimen in Fig. 2(a), 3-dimensional morphologies of the fatigue crack obtained in each observational results at the cross sectional area. On 23.4%N/N_f, Fig. 4(a) shows the fatigue crack propagated with 0.7 mm towards thickness direction of upper sheet. This indicate that the fatigue crack grow to the full thickness of the steel. Furthermore, there was no fatigue crack near the welded spot on 15.6%N/N_f. This fact implies that cross tension specimen used in this study requires few cyclic loading to initiate the fatigue crack in the high force amplitude level. On 45.2%N/N_f, Fig. 4(b) shows two fatigue cracks on upper sheet and the fatigue cracks tend to grows around the welded joint as equal to the diameter of shoulder of FSSW tool and further it grows to the one side on base metal. Figure 4(c) and (d) shows two fatigue cracks on upper sheet those fatigue cracks grows to the full thickness of sheet and tend to grow around the welded joint. Further, first fatigue crack grows to the one side on base metal and another fatigue crack was occurred opposite side of the first fatigue crack around the welded joint. As cracks on lower sheet, two cracks were occurred and grow around the welded joint.

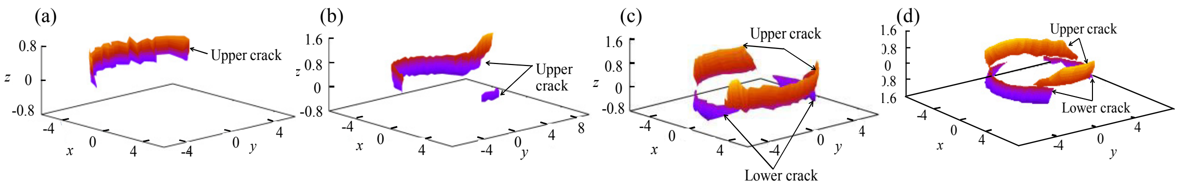

Fig. 4. 3-dimensional crack propagation of FSSW at high force amplitude level. (a) 23.4.%N/N_f; (b) 45.2%N/N_f; (c) 58.5%N/N_f; (d) 70.2%N/N_f.

3.2. Fatigue fracture mechanism under repeated two-step force amplitude conditions

Fatigue tests were carried out under repeated two-step force amplitude condition consisting of force amplitude above and below the fatigue limit, to investigate the effect of a variable force on the fatigue characteristic of FSSW joint. Figure 5(a) illustrates the repeated two-step force amplitude wave form, which has high force amplitude P_H and low force amplitude P_L. The fatigue tests were conducted using number of cyclic load with P_L before the specimen was loaded with a P_H 200 and 500 cycles, as shown in Fig. 5(a). The force ratio R was 0.01 in both load amplitudes, since the FSSW joints used in this study had a large proportion of fatigue crack initiation life in the whole fatigue life, as mentioned above. The fatigue life was estimated with the linear cumulative damage rule. In this study, the fatigue life estimation was conducted with two approaches. One is based on Miner's rule (D_M), which considers only the damage caused by the force above the fatigue limit. The other approach is based on the modified Miner's rule (D_{MM}), which considers the damage caused by the force both below and above the fatigue limit (Tanegashima et al. 2013). From the fatigue test results for each approach, the validity of the evaluation based on the cumulative damage rule was considered.

The results of the strain behaviour, the local strains were measured near the spot welded of both constant and repeated two-step force conditions of FSSW joint. From Figure 5(b), it is found that the strain range is reduced from the local strain response near the spot welded of the constant force amplitude conditions. In addition, from the results of strain behaviour of repeated two-step force amplitude fatigue test is that the specimen has pre-strain from excessive force as shown in Fig. 5(c). It was observed that the pre-strain has an effect of prolonging the fatigue life of the FSSW joint.

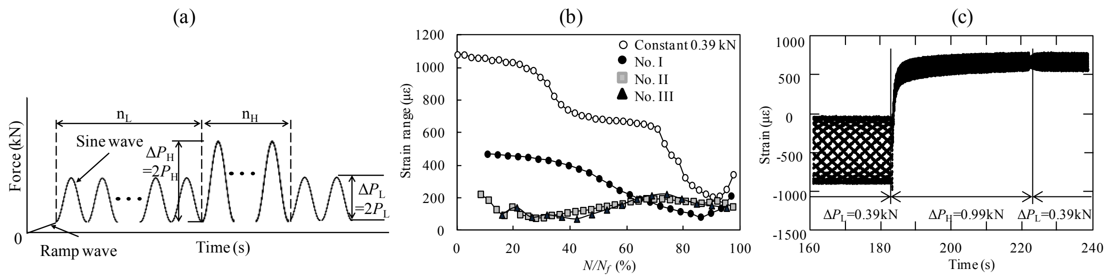

Fig. 5. (a) Illustration of the repeated two-step force amplitude wave form; (b) Strain range behaviour under constant and two-step force amplitude in each condition; (c) Local strain behaviour of the test specimen above fatigue limit No. II.

In the equation of D_M and D_{MM}, N_H is the estimated fatigue life corresponding to the high force amplitude P_H, obtained by a power regression curve from fatigue test results under constant force amplitude conditions, and N_L is the estimated fatigue life corresponding to the low force amplitude P_L, obtained by the power regression curve which was extended below the fatigue limit. The regression curve was obtained in the log-log scale as $\log P_a = -0.288\log N + 3.785$. n_H and n_L indicates the actual fatigue life on the force amplitude P_H and P_L respectively. In this study, D_M and D_{MM} are the cumulative damage values based on Miner's rule and modified Miner's rule, respectively.

Table 3 shows the cumulative damage results from the repeated two-step force amplitude fatigue tests. The result above fatigue limit show that the cumulative damage more than 1. This is due to pre-strain from excessive force that has effect of prolonging the fatigue life and increased cumulative damage. The result of D_M, which does not consider the fatigue damage caused by the force amplitude below the fatigue limit, was compared with D_{MM} which does consider the damage both above and below the fatigue limit. D_M tends to show a comparatively large difference against 1, which is assumed as fatigue fracture on the linear cumulative rule. The fatigue limit of FSSW joints disappears under variable force conditions in the case of cumulative damage value indicated 0.49. Furthermore, the results suggest that it is important to consider the effect of force below the fatigue limit when evaluating the fatigue characteristics of FSSW joints under variable loading conditions in practical applications.

Table 3. Results of cumulative fatigue damage of two step variable force amplitude

Testing condition	Specimen No.	n_H/n_L (cycle)	ΔP_H (kN)	ΔP_L (kN)	$\sum n_H$ (cycle)	$\sum n_L$ (cycle)	D_M	D_{MM}
Above fatigue limit	I	500/1500	0.69	0.39	1.38×10^4	4.20×10^4	0.94	-
	II	200/1800	0.99	0.39	7.07×10^3	6.48×10^4	1.45	-
	III	500/4500	0.99	0.39	9.03×10^3	8.55×10^4	1.91	-
Below fatigue limit	IV	200/6000	0.39	0.15	9.14×10^4	2.75×10^6	0.61	1.24
	V	200/24000	0.39	0.10	7.38×10^4	8.83×10^6	0.49	0.99

4. Conclusions

The crack initiation occurred as a boundary between the welding interface zone and non-interface zone or slit tip regardless of amplitude level which located in the HAZ. The fatigue initiation was found on the upper sheet at the distal slit through to the surface of sheet up to the concave zone. The fatigue fracture modes were independent on force amplitude level. 3-dimensional observation clarified the fatigue fracture mechanism in FSSW joints. Furthermore, the results of the 3-dimensional observation near the welded joint showed that the fatigue crack initiation of low force amplitude level was approximately 56%N/N_f of the whole fatigue life. Consequently, the FSSW joints had a fatigue crack initiation life that accounted comparatively large- proportion of the whole fatigue life. In contrast with high force amplitude level was approximately 16%N/N_f of the whole fatigue life, which FSSW joints had a fatigue crack initiation life that accounted comparatively less proportion of the whole fatigue life.

Under repeated two-step force conditions above fatigue limit, pre-strain from excessive force has effect of prolonging the fatigue life and increased cumulative damage. And under repeated two-step force conditions below fatigue limit, it was found that the fatigue limit of spot welded joints disappeared. Therefore, it is important to consider the effect of force amplitude below the fatigue limit.

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