Effect of Lack of Penetration on the Fatigue Strength of High Strength Steel Butt Weld

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Fatigue tests are performed to evaluate the fatigue strength of high strength steel containing partial penetration butt weld and full penetration butt weld. The influence of the unwelded ligament(Lack of Penetration) in the partial penetration welds on the fatigue life is analyzed for various LOP sizes. For full penetration welds, the fatigue crack initiated at the weld toe and propagated to the HAZ. For partial penetration welds, however, the fatigue cracks initiated at the LOP section and propagated to the weld metal(or weld toe) for the considered LOP sizes(from 2 mm to 4 mm) reducing the fatigue strength. Consequently, the increament of the LOP size yieled in the fatigue life degradation by some extent.

Key Words: Lack of Peneration, Butt Weld, Fatigue Strength

1. Introduction

The complete penetration weld joint has been widely used for many weld structures where the high weld strength is required. The complete penetration weld involves a back gouging process and large weld path resulting in the excessive weld material and labors. Even for such complete weld joint, however, the fatigue life degradations are often observed due to the stress concentration at the toe of the weld reinforcement. When the working stress level is critical as in the pressure vessel or as in the nuclear reactor, removal of the weld reinforcement toe is necessary to reduce the stress concentration. Such removal is not necessary when the working stress level is much below the fatigue limit of the weld. Furthermore, in those cases, partial penetration weld might be applicable if the fatigue characteristics of the partial penetration welds were carefully analyzed.

Lawrence and Munse(1973) considered the fatigue crack propagation in ASTM A36 steel butt welds containing joint penetration defects and found that a crack initiation period is about the half of the total fatigue life and the crack propagation life is severely reduced by joint penetration defects. Lawrence(1973) suggested the analytical model for the influence of joint geometry, weld reinforcement and other factors relative to the propagation of fatigue cracks. Zachary and Burger(1976) studied the fatigue behavior of the partial penetration butt weld under tension-compression fatigue loading. Their experiments show that the fatigue strength of the partial penetration welds are lower than the complete penetration weld depending on the size of the unwelded ligament. They also observed that the crack initiates mostly at the LOP and propagates to the weld metal when the unwelded portion exceeds 20% of the plate thickness. In the other hand, the crack initiates at the weld toe and propagates to the weld metal(or Heat Affected Zone) when the unwelded portion is smaller than 20%. Tobe and Lawrence(1977) studied the effect of inadequate joint penetration on fatigue resistance of high strength steel welds for both the complete penetration and partial penetration welds. They observed that the fatigue crack always initiates at the weld toe and propagates to the weld metal(or HAZ)

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when the complete weld with an intact toe of weld reinforcement is applied. For the partial penetration weld with intact reinforcement, however, locations of the crack initiation and propagation depend on the size of unwelded portion. For LOP larger than 1.5mm, the crack initates at the LOP(or weld toe) and propagates to the weld metal(or LOP). Later, Bowman and Munse(1983) studied the fatigue behavior of welded steel butt joints containing artificial discontinuities and the effects of various notch types, sizes and positions are anlayzed.

In this current analysis, the fatigue crack initiation/propagation behaviors of the partial penetration butt weld for high strength steel is examined and the fatigue strength are experimentally evaluated for artificially induced LOP size, and comparison with the complete penetration weld is quantitatively made to establish the partial penetration weld joint design data for high strength steel.

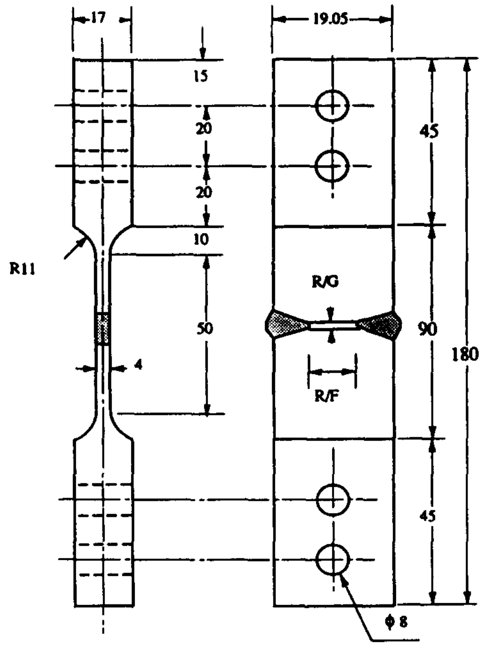


Fig. 1 Weld specimen geometry

2. Experiments

2.1 Specimen

The weld specimens are fabricated from 19.05 mm thick, 50 mm long and 4 mm wide high strength steel plate as shown in Fig. 1. The welding electrode is Mil-E-23765/2 Type 100S-1 with 1.2 mm diameter base. The mechanical and chemical properties for base metal and electrode are listed in Table 1 and 2, respectively. The specimens are prepared with a full penetration weld and partial penetration weld, respectively, using GMAW(Gas Metal Arc Welding) with a 95% Argon and 5% O_2 shielding gas. The welding conditions are listed in Table 3 and the welding procedure is followed by ASTM E647-88. For full penetration weld joints, the nominal root gap is 3.0 mm with the nominal root face 3.8mm. To ensure the complete penetration of weld, furthermore, back gouging process is applied after the first welding path. For partial penetration weld joint, the nominal root faces are selected as 1.9mm, 3.8 mm and 5.7mm, while the nominal root gap and groove angle are maintained as 0 mm and 54 degree, respectively to induce the

Table 1 Chemical composition for base metal and electrode

(a) Base metal

C	S	Al	P	Mn	B	Sb	Si	Ti	Mo	As	Zr	Cu
0.25	less 0.01	0.02	less 0.01	1.30	less 0.01	less 0.01	0.26	0.03	0.52	less 0.01	less 0.01	0.13

(b) Unwelded electrode

C	S	Al	P	Mn	Cr	Ni	Si	Ti	Mo	V	Zr	Cu
0.06	0.06	0.01	less 0.01	1.61	0.12	1.75	0.30	0.01	0.32	0.01	0.01	0.03

Table 2 Mechanical properties for base metal and electrode

(a) Base metal

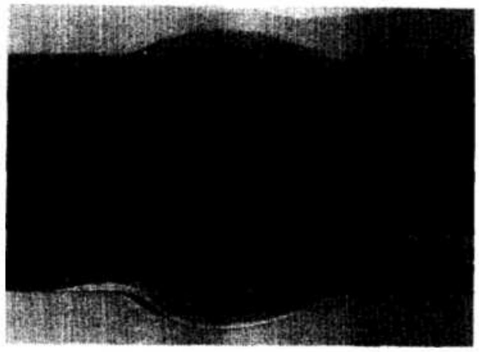
Yield strength (MPa)	Ultimate strength (MPa)	Endurance limit (MPa)
965	1,034	517

(b) Electrode(as welded)

Yield strength (MPa)	Ultimate strength (MPa)	Charpy impact strength (Ft Lbs)
650	710	133

Table 3 Welding conditions

Arc voltage (V)	Arc current (Amp)	Feeding rate (Inch/min)
25~29	250~320	6~14



(a) Full penetration weld

(b) Partial penetration weld (R/F=3.8 mm)

Photo 1 Macrostructure of weld specimen

intentionally unwelded ligament near the root section of the first weld path. Generally, the weld material penetrated to the root face section by 1-2 mm in the process of weld fusion for the first weld path and therefore, the actual LOP size is smaller than the root face size. In these experiments, the weld toe reinforcements and residual stresses are maintained to derive the weld joint design data for actual applications. To examine the soundness of the weld, the radiographic inspections are carried out. For full penetration weld inspection, MIL-STD-1264 is utilized and gloval NDT levels are determined as Grade II. For partial penetration weld inspection, MIL-STD-1894 is utilized and the gloval NDT levels are determined as Level II. The specimens are polished using 10% HNO_3+90% Alcohol to identify the weld material, HAZ and base material as shown in Photo. 1.

2.2 Test procedure and results

2.2.1 Stress concentration measurement test

The resulting strains for partial penetration weld are measured to quantitatively evaluate the stress concentration near the tip of the unwelded ligament and weld toe. The 2 mm gage length strain gage(KYOWA Type KFC-2-D9-11) which has 5 strain measurement points and the YOKOKAWA strain amplifier/recorder are utilized for the experiment. Two strain gages are attached for each weld specimens ; one gage is installed parallel to the tip of the unwelded ligament and the other is installed parallel to the weld toe as shown in Photo 2. The uni-axial strains are measured when static loading of 66 kgf/mm^2 is applied. From the measured strains, the resultant stresses are evaluated and the resulting stresses vs. distance from notch tip is plotted as in Fig. 2. The stresses near the tip of the unwelded ligaments are more concentrated than near the weld toe. This is consistent with the fatigue test results for partial penetration weld that the fatigue crack initiated at the section of the unwelded ligament and propagated to the weld metal(or HAZ) which will be discussed next.

2.2.2 Fatigue test

The fatigue tests are performed under loading control at the ambient temperature. The Electro-

(a) Root face

(b) Weld toe

Photo 2 Optical micrographs showing the position of strain gage installation for stress concentration tests

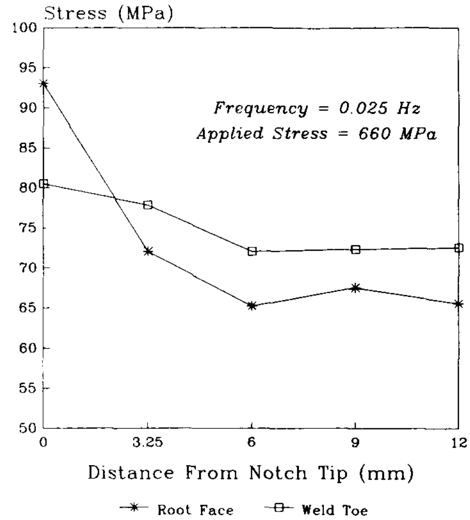


Fig. 2 Stress profiles for partial penetration weld near tip of LOP section and weld toe

servo hydraulic dynamic machine(INSTRON MODEL 1350) is utilized with 100,000Kgf maximum loading capacity. During the test, the loading rates maintain 1-2 Hz and the loading amplitudes are varied as 10, 20, 40, 60 kgf/mm^2. The fatigue tests are often interrupted to examine the location of crack inintiation. The fatigue life and crack propagation path are measured for each weld joint type and for each loading level. The fatigue test results for full penetration welds and partial penetration welds are summarized in Table 4 and 5. Typical fracture modes for partial penetration welds are shown in Photo. 3. For full penetration welds, the fatigue crack initiated at the weld toe and propagated to the HAZ for all specimen. For partial penetration welds, however, the fatigue crack initiates at the tip of the unweld-

Table 4 Fatigue test results for full penetration butt weld

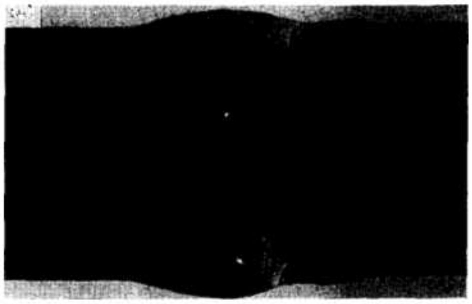
Specimen) type	Stress (MPa)	Cycles	Initiation location	Propagation path
CP102	400	56,944	TOE	TOE to HAZ
CP102	300	57,277	TOE	TOE to HAZ
CP102	250	154,140	TOE	TOE to HAZ
CP102	200	269,244	TOE	TOE to HAZ
CP102	200	486,326	TOE	TOE to HAZ
CP102	170	2,000,000	TOE	TOE to HAZ
CP102	150	2,000,000	TOE	TOE to HAZ

ed ligament and propagates to the weld metal(or HAZ). From the fatigue test results, the S-N curves are plotted as in Fig. 3 using a linear least square fit assuming the linearity between the applied stress(S) and logarithmic of cycle number($\log N$). i.e.,

$$S = Ax + B \tag{1}$$

Table 5 Fatigue test results for partial penetration butt weld

Specimen type	LOP length (mm)	Stress (MPa)	Cycles	Initiation location	Propagation path
R/F=3.8 mm	2.68	600	1,240	LOP	LOP to WM
R/F=3.8 mm	2.27	600	3,189	LOP	LOP to WM
R/F=3.8 mm	2.10	400	18,260	LOP	LOP to WM
R/F=3.8 mm	2.08	400	14,563	LOP	LOP to WM
R/F=3.8 mm	1.96	200	113,864	LOP	LOP to WM
R/F=3.8 mm	1.98	200	106,016	LOP	LOP to WM
R/F=3.8 mm	2.10	150	366,644	LOP	LOP to WM
R/F=3.8 mm	2.30	150	414,528	LOP	LOP to WM
R/F=3.8 mm	2.49	100	2,000,000	-	NO FRACTURE
R/F=3.8 mm	2.19	100	2,000,000	-	NO FRACTURE
R/F=1.9 mm	1.31	150	2,000,000	-	NO FRACTURE
R/F=1.9 mm	0.88	150	2,000,000	-	NO FRACTURE
R/F=1.9 mm	0.98	200	259,744	LOP	LOP to WM
R/F=1.9 mm	0.82	200	217,269	LOP	LOP to WM
R/F=1.9 mm	0.78	400	58,803	LOP	LOP to HAZ
R/F=1.9 mm	1.15	400	87,324	LOP	FAST FRACTURE
R/F=1.9 mm	0.86	600	4,385	LOP	FAST FRACTURE
R/F=1.9 mm	1.24	600	4,020	LOP	FAST FRACTURE
R/F=1.9 mm	1.67	200	237,077	LOP	LOP to WM
R/F=1.9 mm	1.74	200	235,103	LOP	LOP to WM
R/F=5.7 mm	3.83	600	689	LOP	LOP to HAZ
R/F=5.7 mm	3.42	600	1,369	LOP	LOP to WM
R/F=5.7 mm	3.75.	400	9,349	LOP	LOP to HAZ
R/F=5.7 mm	3.25	400	11,014	LOP	LOP to WM
R/F=5.7 mm	3.55	200	125,375	LOP	LOP to WM
R/F=5.7 mm	3.40	200	181,053	LOP	LOP to WM
R/F=5.7 mm	3.80	150	125,375	LOP	LOP to WM
R/F=5.7 mm	3.15	100	841,059	LOP	LOP to WM
R/F=5.7 mm	3.26	70	2,000,000	-	NO FRACTURE



(a) $\Delta\sigma = 60$ kgf/mm^2

(b) $\Delta\sigma = 40$ kgf/mm^2

(c) $\Delta\sigma = 20$ kgf/mm^2

Photo 3 Typical mode of fatigue fractured specimen

where,

$$x = \log N \qquad (2)$$

From the fatigue data in Table 4 and 5, coefficient A and B are determined for each weld joint types as follows ;

(1) Full penetration weld joint

$$S = -118.7\log N + 890.2 \qquad (3)$$

(2) Partial penetration weld joint

i) $S = -182.9\log N + 1243.7$
for R/F = 1.9 mm (4)

ii) $S = -141.7\log N + 961.6$
for $R/F = 3.8$ mm (5)

iii) $S = -149.9\log N + 990.8$

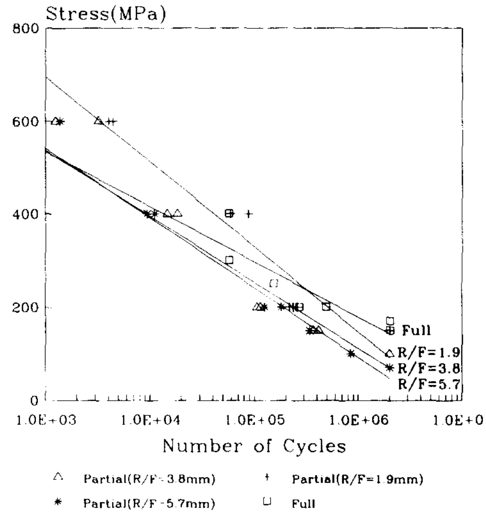


Fig. 3 S-N curve for full penetration weld and partial penetration weld

for $R/F = 5.7$ mm (6)

where, the applied stress S is in MPa and the number of cycle N is valid for relatively long fatigue cycles $10^4 < N < 2\times10^6$.

Finally, from the above linear least square fit equation, the fatigue limits for full penetration weld and partial penetration weld are determined respectively as follows ;

$\sigma_f = 142.3$ MPa for full penetration weld (7)

$\sigma_f = 91.2$ MPa for partial penetration weld with $R/F = 1.9$ mm (8)

$\sigma_f = 68.7$ MPa for partial penetration weld with $R/F = 3.8$ mm (9)

$\sigma_f = 46.3$ MPa for partial penetration weld with $R/F = 5.7$ mm (10)

where, σ_f is the fatigue limit based on 2×10^6 cycles. Therefore, the fatigue life for partial penetration welds are relatively shorter than full penetration welds and the fatigue life degradaded most for the weld type with the largest nominal root face($R/F = 5.7$ mm).

3. Conclusion

Fatigue tests are performed to evaluate the fatigue strength of high strength steel containing partial penetration butt weld. For full penetration welds, the fatigue crack initiated at the weld toe and propagated to the HAZ. For partial penetration welds, however, the fatigue cracks initiated at the LOP section and propagated to the weld metal(or weld toe) for the considered LOP sizes(from 2 mm to 4 mm) yielding the reduction of the fatigue strength. Consequently, the increaments of LOP size yieled in fatigue life degradation by some extent. This fatigue life data can be quantitatively used for the partial penetration weld joint design where the working stress levels are explicitly known and controllable.

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