Fatigue life prediction of gas tungsten arc welded AISI 304Lcruciform joints with different LOP sizes

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Abstract

Gas tungsten arc welded (GTAW) load-carrying cruciform joints of AISI 304L stainless steel with lack of penetration (LOP) have had their fatigue lives evaluated using the traditional S-N and crack initiation-propagation (I-P) techniques. The two main phases of the crack process are typically the crack initiation life (Ni) and the crack propagation life (Np). The crack initiation life of welded joints is predicted using the local stress-life approach, while the crack propagation life is predicted using a fracture mechanics approach. Using a 100 KN servo-hydraulic DARTEC universal testing machine with a 30 Hz frequency, constant amplitude fatigue tests with stress ratio, R = 0 were performed. The crack initiation and propagation data during the fatigue phase were discovered using an automatic crack monitoring system based on crack propagation gauges. The experimental values and expected lives were contrasted. In comparison to joints with other LOP sizes, it was discovered that joints with LOP of 2 mm for 6 mm thick plate had considerably longer fatigue lifetimes. The test findings were compared to the design curve from BS 5400: part 10 (formerly known as BS 7608).

Keywords: Stainless steel; Gas tungsten arc welding (GTAW); Cruciform joints; Lack of penetration (LOP); Fatigue life

1. Introduction

Stainless steels are widely used in the chemical processes and power generation industries. However, increasingly they are also being considered for structural applications, for example, in facading and transportation industries. Stainless steels offer the advantages over conventional structural steels where painting or other corrosion protection coatings would not be necessary. Many applications in the structural areas involve welded components, which have to be designed to avoid fatigue failure. Though considerable fatigue data exist for welded joints in structural carbon steels [1–4], there are very sparse design data for stainless steel welded joints [5]. Further, the fatigue crack growth behaviour in stainless steel weld ments appears to be least investigated. In the present work, an attempt has been made to fill up this lacunae through a detailed investigation on the fatigue performance of load carrying transverse fillet weldedcruciform joints of AISI 304L stainless steel with different LOP sizes.

There are two types of fatigue cracking in fillet-welded joints: (a) root cracking and (b) toe cracking. In welded cruciform joints, the lack of penetration (LOP) occurs in the joint due to the lack of access to the root. The structures in which such joints used are often subjected to fatigue loading. This may result in the initiation of fatigue cracks at the LOP tip as well as from the toe region, which depends on the LOP size, fillet geometry and leg length. One of the formulae for stress intensity factors for the root of cruciform welded joints containing lack of penetration was presented by Frank and Fisher using a finite element method [6] and then improved in BS 7910 [7]. Frank has also analyzed the fatigue lives of cruciform joints [8]. Other investigators have also studied the fatigue behavior of cruciform welded joints of carbon steels failing from the root (LOP) [9–12].

Usami and Kusumoto determined a solution for the maximum principal stress intensity factor by considering both K_I and K_{II} in the case of cruciform joints with root crack [11]. The stress intensity factors K_I and K_{II} of cruciform joints were calculated by the finite element method [13]. The fatigue limit and the direction of crack propagation under mixed load loading are well expressed by the maximum principal stress criterion. In this analysis, the cracks were considered to be grown in Mode I type and the Frank's stress intensity factor solution for cruciform joints with LOP [6] is used here.

Fatigue life prediction of cruciform welded joints is very complex, costly and time consuming. This is due to its complex joint geometry, number of stress concentration points and heterogeneous weld metal property making the joint. Traditionally, the fatigue life of the joint for structural applications followed the S-N type of approach covered by BS 5400: part 10 and IIW [14]. For critical structural applications, both initiation and propagation behavior are equally important for the purpose of safety. The linear elastic fracture mechanics (LEFM) approach which estimates the crack propagation life (N_p) was used to calculate the total life (N_T) of welded joints. However, the LEFM approach always gave conservative results of N_T when compared with those of modern weldments experimental data [15–17]. These results led to the crack initiation–propagation model (IP model) in which the crack initiation life (N_I) was added to the weldment total life [18]:

$$N_T = N_I + N_p \quad (1)$$

This investigation has been carried out to study the influence of LOP sizes on fatigue life of gas tungsten arc welded cruciform joints, failing from root. The fatigue lives of these joints were predicted using the I-P model.

2. Experimental

The material used was an AISI 304L austenitic stainless steel in the cold rolled form of 6 mm thickness. These plates were cut into the required sizes by shearing. The initial joint configuration in the case of load-carrying cruciform joint is obtained by securing the long plate (300 × 100 mm^2) and stem plate (300 × 50 mm^2) in a cruciform position by tack welding keeping in a fixture. Subsequently, fillets were made between the long plate and stem plate by laying weld metal using the GTAW process with filler wire 308L. The double pass technique was used with argon as the shielding gas. All the four fillets forming the joint were made, leaving a non-fused gap between the pair of fillets. This gap, called LOP, was controlled by providing proper root faces obtained by a prior machining process, known as beveling. This enabled the joints to have different LOP lengths after welding. The dimensions of the cruciform joint shown in Fig. 1 considered in the present investigation are given as: $2a$ = 2, 3, 4 and 6 mm, $2W$ = 14 mm, L = 4 mm, T_p = 6 mm and q = 30° (concave fillet). All the necessary care was taken to avoid joint distortions and the joints were made without applying any clamping forces. After welding, the fatigue samples were cut into the required sizes (20 mm) using a power saw. The cut samples were again machined for better surface finishing. Welds were tested by X-ray radiography for their soundness.

Fatigue experiments with a stress ratio R=0 were carried out in a 100 kN servo-hydraulic DARTEC universal testing machine with a frequency of 30 Hz. For each condition, 12–16 specimens were tested. The specimens were tested to complete failure or to an endurance of 2 million cycles (in some cases, it was 3 million cycles), if there was no evidence of fatigue cracking. In all tests, it was ensured that the crack always started in the LOP and propagated through the weld metal.

An automatic crack monitoring system based on the crack propagation gauges was used to find the crack initiation and propagation data during the fatigue process with an accuracy of 0.25 mm. The crack propagation

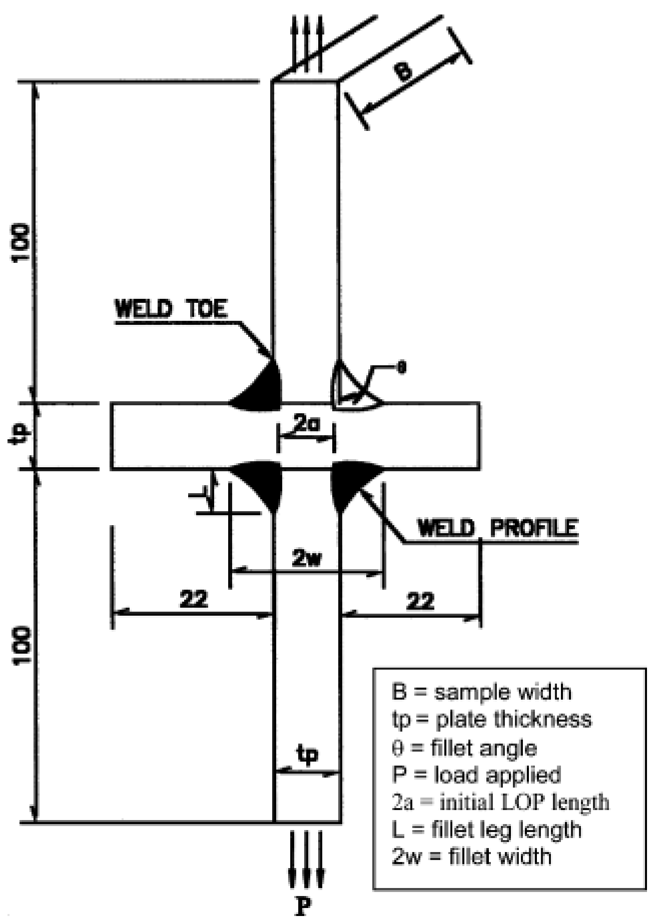

Fig. 1. Schematic diagram of load carrying transverse fillet welded cruciform joint with LOP defect (all dimensions in mm).

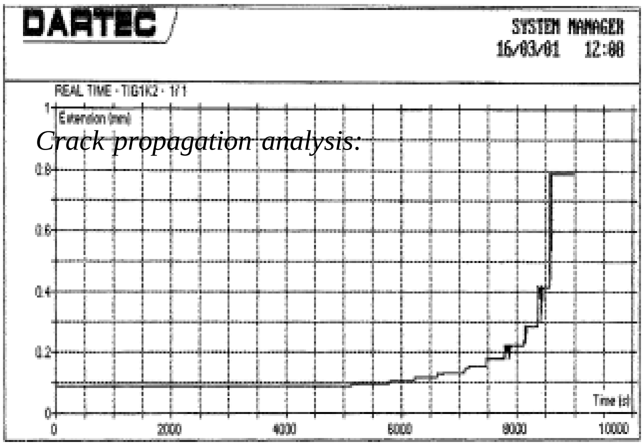

Fig. 2. A step curve of crack propagation gauge strands broken versus time during crack propagation stage.

ducted for various stress levels and the variations in crack length (a) with the corresponding number of cycles (N) were obtained.

The fracture mechanics analysis for most structural steels is based on the Paris power law [19],

$$da/dN = C(\Delta K)^m \quad (2)$$

where da/dn is the crack growth rate, ΔK is the stress intensity factor (SIF) range, and C and m are Paris constants. Eq. (2) can be normalized and adopted for cruciform joints, in the form given below

$$\frac{d(2a/2W)}{dN} = \frac{C(\Delta K)^m \Delta s^m}{\Delta s^m \quad 2W} \quad (3)$$

where Δs is the nominal stress range at the base plate,

Table 1
Chemical composition (wt%)

Material/electrode	C	Si	Mn	P	S	Cr	Ni	Nb	Cu	Co	N	Mo
Base metal AISI 304L	0.022	0.35	1.79	0.026	0.001	18.32	8.23	0.002	0.40	0.08	0.055	
GTAW AWS A5.9 ER 308LSi	0.007	0.84	1.67	0.022	0.011	19.77	10.21	–	0.14	–	–	0.22

gauges consist of a number of resistor strands connected in parallel. This is bonded to a specimen at the tip of the root gap through a connector circuit and progression of the crack through the gauge pattern causes successive open circuiting of the strands, resulting in an increase in total resistance. The output is amplified and a step curve of strands broken versus time can be obtained in the computer (Fig. 2). The chemical composition and mechanical properties of base metal and filler metal are given in Tables 1 and 2. The welding process parameters used to fabricate the joints are presented in Table 3.

3. Results and discussion

The LOP size will influence the fatigue life of cruciform joints. Fatigue crack growth experiments were con-

'a' is half of the LOP size, and 'W' is half of the fillet width as shown in Fig. 1.

After re-arranging the equation

$$\frac{da^*}{dN} = \frac{C}{2}\cdot[f^*(a)]^m\cdot\Delta s^m W^{(m/2)-1} \quad (4)$$

where $f^*(a)$ is the normalized SIF range which is $\Delta K / \Delta s \cdot W^{1/2}$, and a^* is the normalized crack length a/W.

The crack growth rate, da/dn for crack propagation stage was calculated. For all calculations, the ASTM E-647 guidelines were followed. The stress intensity factors for cruciform joints were calculated using Frank and Fisher [6] and BS 7910 [7] and the values are compared in Fig. 3. Since the authors found negligible variation, it is proposed to use Frank's formulae for calculating SIF range. The polynomial expression for SIF range (ΔK), for a crack at the weld root of a load carrying

Table 2
Mechanical properties

Material/electrode	Plate thickness/electrode diameter	Proof strength, R_p (MPa)		UTS, R_m	Elongation	Hardness
	(mm)	0.2%	1%	(MPa)	(%)	(HB)
AISI 304L	6	297	328	622	54	170
GTAW ER 308LSi	1.6	425	–	610	38	–

Table 3
Welding process parameters

Process	Electrode diameter (mm)	Voltage (V) *V*	Current (amp) *A*	Welding speed (mm/s)	Gas flow rate (argon) (l/min)
GTAW (manual) DCEN	1.6	I-PASS 16.5 II-PASS 16–17	I-PASS 180 II-PASS 170–180	I-PASS 0.813 II-PASS 1.25–1.30	6

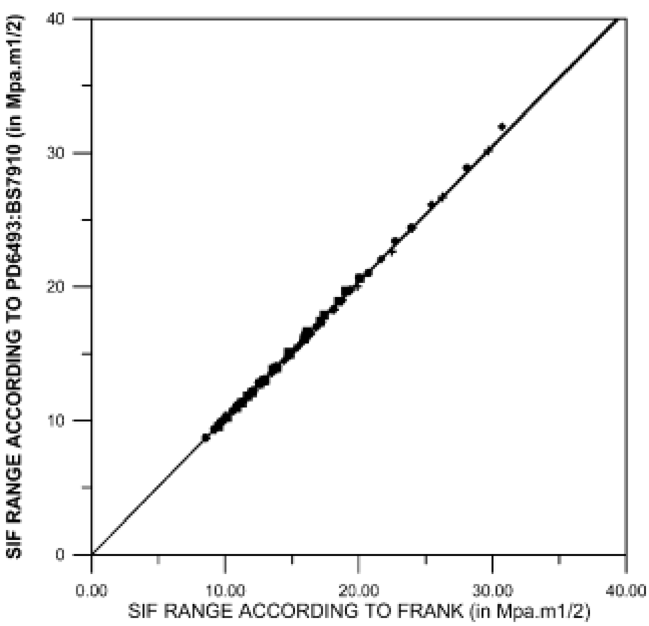

Fig. 3. Comparing the stress intensity factor values for cruciform joints with different LOP lengths calculated using Frank and Fisher [6] and BS 7910 [7]

cruciform joint developed by Frank and Fisher [6] is given below

$$\Delta K = \frac{\Delta s}{1 + 2(L/T_p)}[A_1 + A_2 a^*][pa^* \sec(pa^*/2)]^{1/2} \quad (5)$$

where L/T_p is the weld size and A_1 and A_2 are functions of weld size (L/T_p) given by,

$$A_1 = 0.528 + 3.287(L/T_p) - 4.361((L/T_p)^2 + 3.696(L/T_p)^3 - 1.874(L/T_p)_4 + 0.415(L/T_p)^5$$

$$A_2 = 0.218 + 2.7717(L/T_p) - 10.171(L/T_p)^2 + 13.122(L/T_p)^3 - 7.775(L/T_p)^4 + 1.785(L/T_p)^5.$$

The ΔK term in Eq. (5) for a cruciform joint can be inserted into Eq. (3) to obtain

$$\frac{da^*}{dN} = \frac{C[f^*(a)]^m \Delta s^m W^{m/2}}{2W} \quad (6)$$

The terms can be rearranged for integration to give

$$\int_{a_i^*}^{a_f^*} \{d(a^*)/[f^*(a)]^m\} = \frac{C}{2}\Delta s^m W^{(m/2)-1} \int dN \quad (7)$$

where a_i^* is the initial defect size after the number of cycles necessary for crack initiation (N_I) and a_f^* is final defect size at failure. The above equation can also be expressed as:

$$I_p = (C/2)\, \Delta s^m W^{(m/2)-1} N_p \quad (8)$$

where I_p is the value of the integral in Eq. (7) for the number of crack propagation cycles leading to failure (N_p). It was found that the value of integration I_p is a function of crack length a^* with respect to crack growth exponent values (m). It can be seen that for all values of m, the function

$$f^*(a)^{-m}$$

falls on a single straight line against I_p [20]. The straight-line relationship can be expressed by the following empirical equation:

$$I_p = r\{[f^*(a)]^{-m}\}^h \quad (9)$$

where the constants, r = 0.16 and h = 0.84 depend on the crack geometry. Rearranging Eq. (8) gives

$$N_p = 2I_p/(C\Delta s^m W^{(m/2-1)}) \quad (10)$$

The relationship between the SIF range (ΔK) and the corresponding crack growth rate, da/dn on a log–log scale in terms of best fit line is shown in Fig. 4 for all the cases. The data points mostly correspond to the second stage of the sigmoidal relationship of the Paris equation. The crack growth rate is found to be the same (slope is almost same) in all the cases and the Paris constants 'm' and 'C' are given in Table 4. The intercept 'C' varies with respect to LOP sizes.

The propagation lives of the joints are shown in Fig. 5. It can be seen that the joints with LOP = 2 mm show large propagation lives and the joints with LOP = 6 mm show less propagation lives. This is due to the fact that the crack has to propagate a longer distance in the weld metal when LOP = 2mm and smaller distance when LOP = 6mm.

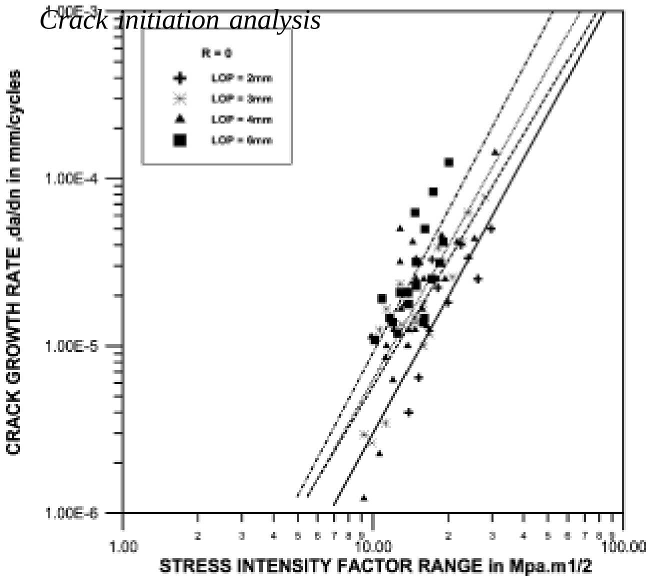

Fig. 4. Fatigue crack growth characteristics of cruciform joints with different LOP sizes.

Crack initiation analysis

The crack initiation life 'N_I' was evaluated experimentally using the crack initiation criteria [21–24]. Here, in our investigations the initiation criterion has assumed the number of cycles required to grow 0.5 mm length of crack in excess of its original LOP length under particular stress range. To estimate N_I, a local stress-life or strain-life approach is commonly used [16,18,24]. The simplest form of this approach is

$$N_i = \frac{1}{2}\left(\frac{\frac{\Delta s}{2}K_f}{s'_f - s_m}\right)^{1/b} \quad (11)$$

where $\Delta s/2$ is the stress amplitude, s'_f is the fatigue strength coefficient, b is the fatigue strength exponent, s_m is the mean stress and K_f is the fatigue notch factor. This model is based on the Basquin equation with the Morrow mean stress correction. The prediction method also requires that the fatigue notch factor (K_f) be calcu-

Table 4
Measured values

LOP size '2a' in mm	Ferrite number (%) in the WM	Paris constant		Macro hardness in the WM (Hv) 10 kg load	(ΔK_e) MPa $m^{1/2}$
		m	C		
2		2.7	$5.583\text{x}10^{-12}$		9.5
3	8.75	2.7	$1.796\text{x}10^{-11}$	181	8.6
4		2.8	$1.359\text{x}10^{11}$		8.4
6		2.8	$1.327\text{x}10^{-11}$		8.35

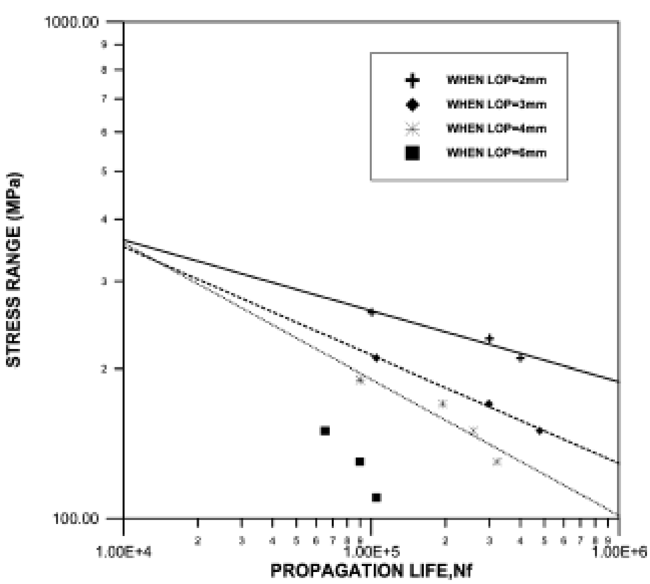

Fig. 5. Crack propagation lives with different LOP sizes.

lated. The fatigue notch factor for load-carrying cruciform joints with different LOP sizes is calculated according to Yung and Lawrence [25]. From Fig. 6, it is clear that in a load carrying cruciform joint with LOP defect, the joints with LOP = 2 mm have larger fatigue initiation life for 6 mm thickness plate. Fig. 7 shows the relationship between the initial SIF range (ΔK_i) and the number of cycles to failure (N_f). This relation is similar to the S-N relation giving the endurance SIF (ΔK_e) similar to the endurance fatigue limit. The value of the endurance SIF corresponding to 2 million cycles is given in Table 4. However, it should be noted that the endurance value obtained is for the case $R = 0$. The S-N curves in all the cases are compared in Fig. 8. It can be seen from the results presented that the LOP size has a stronger effect on the fatigue life.

Total fatigue life analysis

To predict the total fatigue life of the cruciform joints, it is necessary to account for the crack initiation life (N_i)

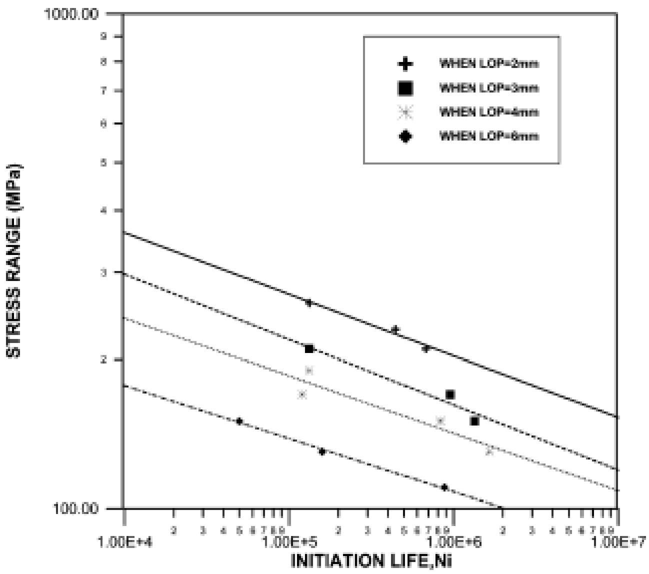

Fig. 6. Crack initiation lives with different LOP sizes.

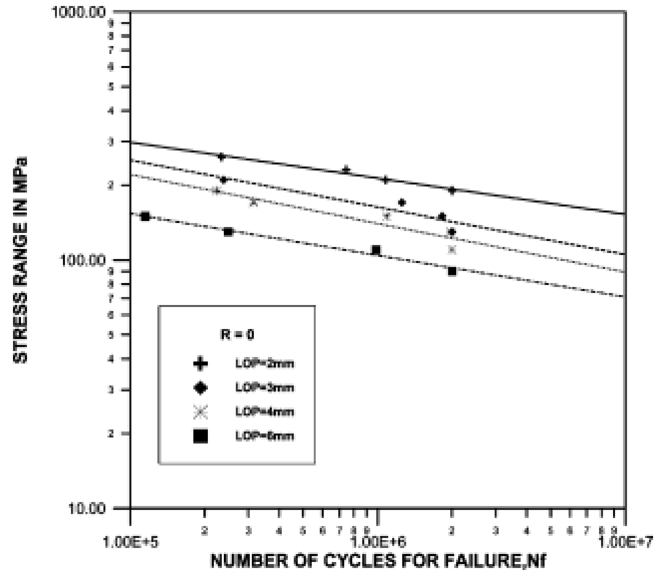

Fig. 8. S-N curves with different LOP sizes.

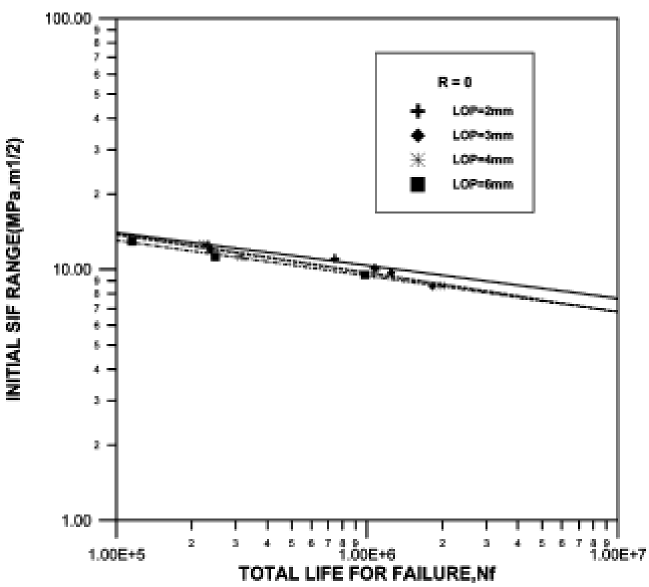

Fig. 7. Relationship between initial stress intensity factor range and the total life for failure with different LOP sizes.

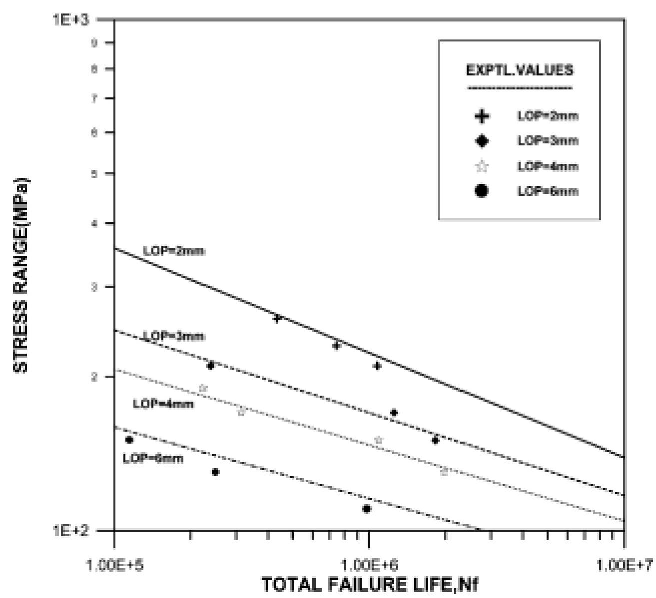

Fig. 9. A correlation between predicted and experimental fatigue endurance data.

and crack propagation life (N_p) separately. The total fatigue life is evaluated using Eq. (1). The accuracy of the predicted life is tested by comparing the predicted fatigue life data with the experimental data and the scatter diagram is shown in Fig. 9. Although relatively high residual stresses were likely to occur in the welds before cutting up the plates, they were relieved by the slicing operation [26]. The fatigue test results of these joints were compared with the BS 5400: part 10 (now replaced by BS 7608) design curve for cruciform joints with LOP and shown in Fig. 10. The results show good correlation with the standards.

4. Conclusions

From the experimental investigations carried out to study the fatigue crack growth behavior of gas tungsten arc welded load carrying cruciform joints of AISI 304L with different LOP sizes, the following conclusions have been drawn:

- The two-stage approach, including both the fatigue crack initiation and propagation phases, enables one to estimate total fatigue lives in the life regime of 10^5 to 2 million cycles, which agree within a factor of 2 with experimental data for cruciform welded specimens failing at the LOP.

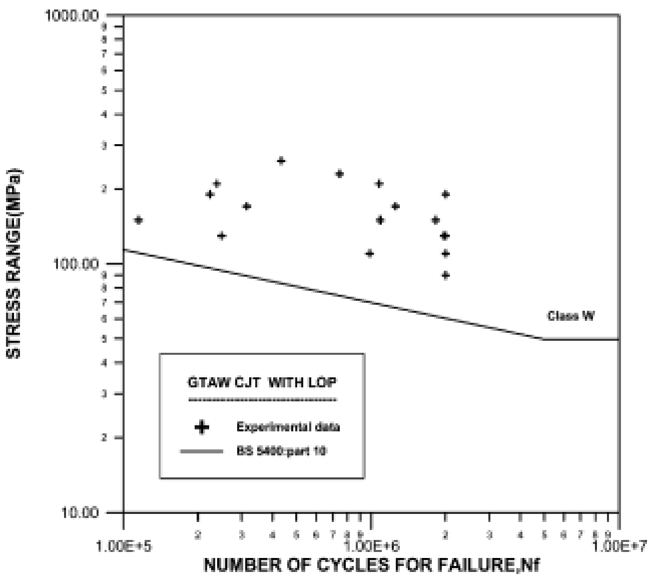

Fig. 10. Comparison of fatigue test results with BS 5400: part 10-design curve.

- The crack growth behaviour of load carrying cruciform joints with LOP follows the Paris equation.
- The relationship between the initial stress intensity factor range (ΔK_i) and the number of cycles to failure (N_f) can be presented in a similar way to that of the conventional S-N curve.
- In this experiment, the cruciform joints with LOP = 2 mm show superior fatigue properties compared to other LOP sizes for the 6 mm thickness plate.
- The fatigue life of load carrying cruciform joints with LOP for the GTAW process was predicted with reasonable accuracy. The results show good correlation with the BS 5400: part 10 design curve.

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