PREDICTION OF RESIDUAL STRESS PROFILE IN SINGLE-SIDED BUTT WELD USING COMPLIANCE METHOD

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ABSTRACT

It depends on the joint configuration, dimensions and constraints on the joint whether the residual stress at the root of single-sided butt weld is tensile or not. Therefore, recommendation is generally made that high R ratio should be used in the fatigue test of this type of joint in order to prevent excessively long life caused by compressive residual stress. In this research, the residual stress profile in butt weld joint was obtained through compliance method, using successive extension of a slot and measurement of the variation of strain during the slot extension. The residual stress profile was firstly assumed to be the linear summation of Legendre polynomials up to 9th order excluding 0th and 1st order. Strain variation on the surface was measured while the slot was being extended by cutting to find out the 8 unknown coefficients of each polynomial term. The cut was made by the electric discharge machine. It was concluded that the residual stress near the surface stayed positive, however, it turned into the negative value as soon as it passed through 2 or 3 mm depth. Several fatigue tests were also carried out under zero stress ratio. Test results showed that fatigue life coincides well with the design curve of butt joint in British Standards, which supports that it is tensile residual stress that exists near the weld root.

KEYWORDS

Residual stress, Compliance method, Electric discharge machine, Finite element method, Butt weld

1. Introduction

It is well known that the residual stress near welded zone plays a significant role in the failure of the welded structure, especially in case of the fatigue failure that is caused by continuously repeated loading, which is thought to be the most frequent in ship and offshore structures. On the whole, it is not always obvious whether the residual stress at weld toe is tensile or not, since residual stress itself heavily depends on the joint configuration, dimensions and constraints of the joint. Therefore, recommendation is generally made that high R ratio should be used in the fatigue test for some particular joints in order to prevent excessively long life caused by compressive residual stress. Toe crack emanating from the root of single-sided butt weld is one of them, so much attention should be paid on the determination of fatigue test condition. Measuring stress at the toe of the root of single sided butt weld would clarify this, hence decision can be made according to the results.

Compliance method, or crack compliance method is one of the strain measuring techniques that is originally introduced by Vaidyanathan and Finnie in 1971, and later studied by many researchers such as Cheng and Finnie[3], Ritchie and Legatt[4], Kang, Song and Earmme[5]. It utilizes successive extension of a slot into the part containing residual stress along with the measurement of strain on the surface near weld toe using conventional strain gages. Measured strain variation along the slot depth combined with some numerical calculation can reveal the residual stress near the weld toe. With the aid of the finite element method, compliance method become widely used for any kind of geometry whose mechanical behavior can be simulated precisely.

2. Theoretical background

Fig.1 shows schematic view of unknown residual stress in butt weld joint. The very first thing that has to be done is to assume the unknown residual stress pattern using linear summation of polynomial terms as denoted in the Fig.1. The function $P_i(y)$ can be a simple power series, Legendre polynomials, Fourier series, etc. The unknown coefficients, A_is, are to be solved through the compliance method hereafter.

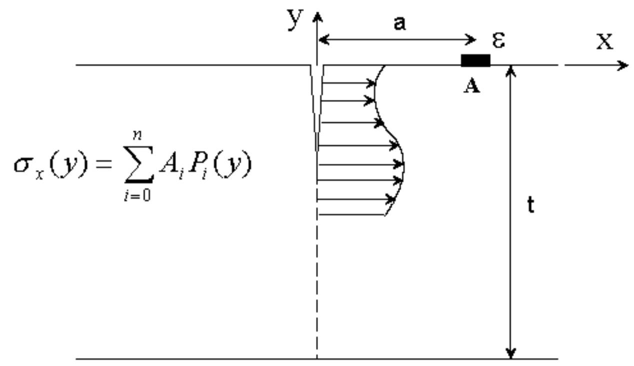


Fig.1 Residual stress in butt joint

Using finite element analysis, the strain variation at point A as a function of the slot depth that would be measured for each stress term in the series are calculated. These are called the compliance function C. Using superposition, the strains given by the series expansion can now be written as

$$\varepsilon_x(y) = \sum_{i=0}^{n} A_i C_i(y) \tag{1}$$

Eqn(1) stands for assumed strain variation during slot extension which would be measured using strain gage later on. Coefficients A_is will be determined in such a way that discrepancy between those two is minimized. Therefore, a least squares fit is performed to minimize the error between the strains given by Eqn(1) and the measured one. This gives the A_i, and can be written in matrix form as

$$\{A\} = \left([C]^T [C]\right)^{-1} [C]^T \{\varepsilon_{measured}\} \tag{2}$$

Based on the obtained coefficients in Eqn(2), stress distribution can be determined by the equation in Fig.1. As for this calculation, Legendre polynomials up to 9th order are used excluding 0th and 1st order which does not satisfy self equilibrium of force and moment, indispensable condition for residual stress pattern. Eight stress terms are given to the finite element model as an initial stress, and subsequently, model was cut progressively with element removal techinic.

3. Experiment

In order to measure strain variation during slot extension, a strain gage was attached on the specimen and a cut of progressively increasing depth was made. Fig.2 shows cutting machine and test specimen where strain gages are installed with water proof finish.

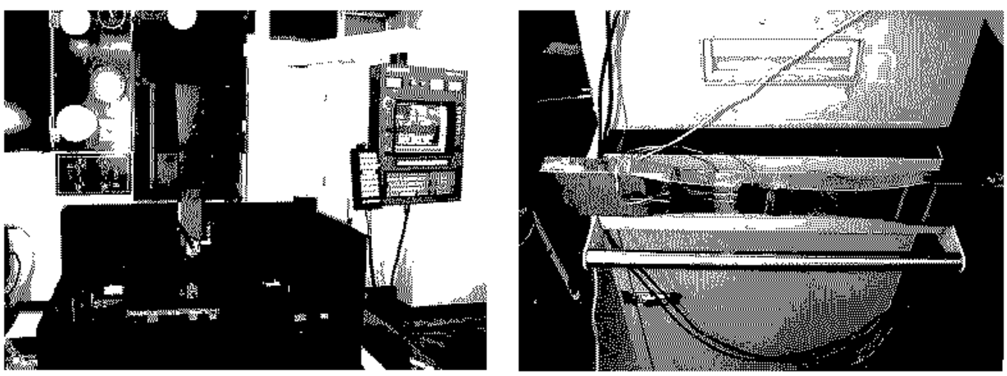


Fig.2 EDM(Electric Discharge Machine) and test specimen

The specimen was welded in the way as shown in Fig.3. FCAW process was used maintaining the current 190~270A and the voltage 24~28V, as is summarized in Table 1. Total 12 paths were deposited to fill the grooved area. 25 mm thick plate was welded under the severe restriction that is embodied by the two strong backs to minimize the angular distorsion caused by welding, and the specimen were made by slicing the plate into several pieces.

Strain gages were attached at the points 6 mm and 11 mm apart from the weld toe respectively, and a cut was made from the toe of the weld root toward opposite side in a perpendicular direction. The slot was extended in a very low speed that is optimized after several trials and errors. Strain data were recorded every 1 mm extension of the slot through data acquisition system.

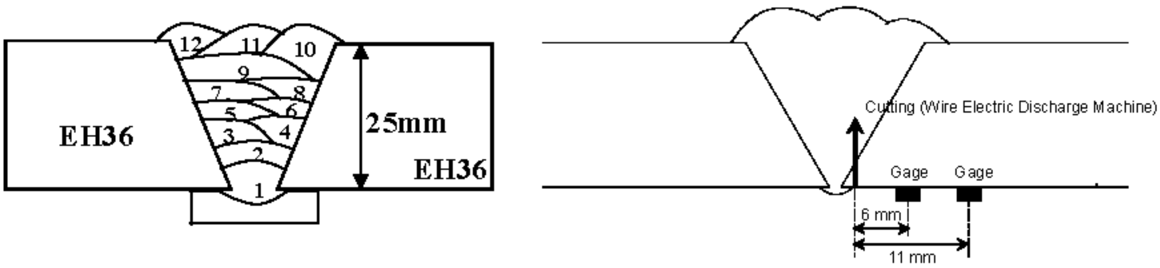


Fig.3 Weld detail and test setup

Table 1 Welding conditions

Layers	Process	Position	Type & Pol.	Current (A)	Voltage (V)	Speed (cm/min)
Root	FCAW		DCRP	192~220	23.9~26.1	18~24
Fill	FCAW	1G	DCRP	258~291	28.2~30.1	29~40
Cap	FCAW		DCRP	240~269	26.0~28.0	32~44

Fig.4 shows measured strain variation for two specimen during slot extension. Basically, strain change from No.1 gage is significantly higher than that from No.2 gage as expected. What draws attention in this graph is that the strain values change drastically within the region below 10 mm depth, but after a certain point, it is stabilized not to change any longer. In the estimation of the stress, strain data above 10 mm slot depth were excluded intentionally because strain variation above this point does not behave in compliance with the increase of the slot depth. Differences between two specimen might be caused by various sort of uncertainties associated with the welding.

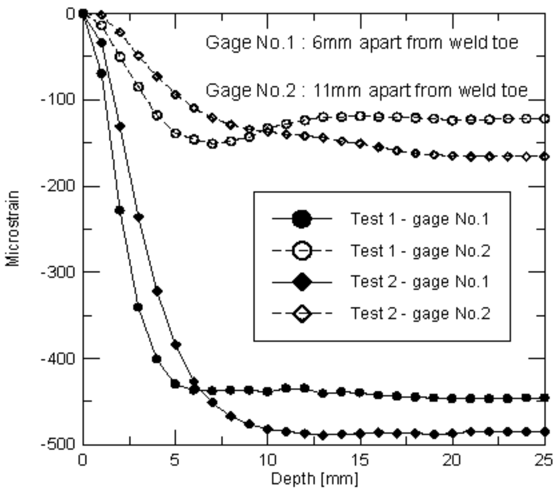


Fig.4 Measured strain variation with slot depth

4. FE analysis

As mentioned before, strain variation during slot extension for each term of polynomial should be calculated through finite element analysis in order to find out the compliance function. 2 dimensional plane strain element was employed to model the specimen and half of the specimen was considered even though it is not strictly symmetric, but it nearly is. Fig.5 shows a detail finite element model near the cutting area. Element adjacent to the symmetric line is sized to be 0.2 mm that is thought to be the size of the material cut out by the saw. These elements will be removed from the model to simulate the cutting process.

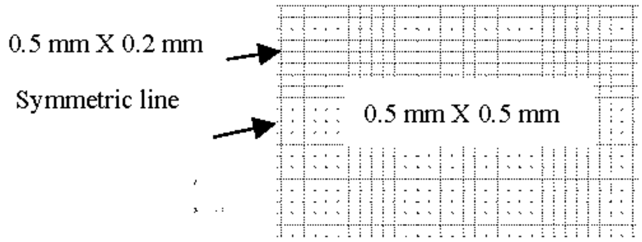
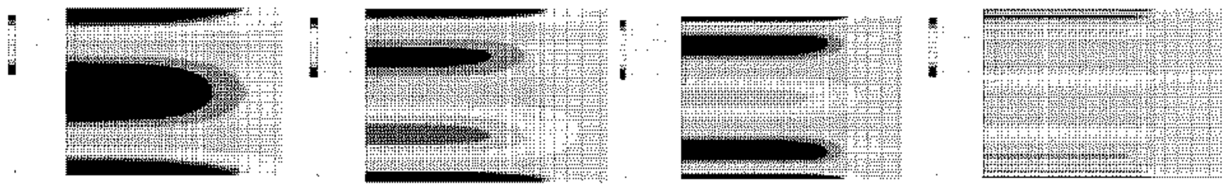


Fig.5 FE model

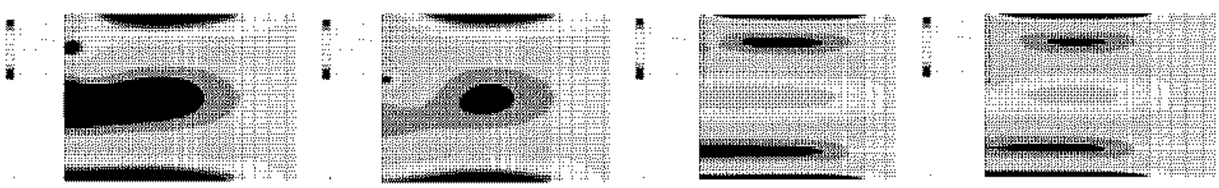
Residual stress pattern according to the Legendre polynomial was input to the model as an initial stress and was forced to equilibrate without any other external force at first load step. Initial stress was input to the model using user subroutine SIGINI in ABAQUS, a commercial FE analysis program. Material behavior is assumed to be purely elastic, which means there will be no plasticity no matter how high stress values go up near the slot, or crack tip. This assumption is reasonable because the limited size of plastic zone near slot tip does not affect the strain variation on the top surface. Fig.6 shows equilibrated initial stress distribution for 2nd, 3rd, 4th and 9th order polynomial term. Stress distribution in the right half region changed a lot in order to satisfy force equilibrium, which original initial stress distribution given artificially could not satisfy. However, the stress pattern along the cutting line, or symmetric line, still remains unchanged that is crucial thing to be kept.



(a) 2nd order (b) 3rd order (c) 4th order (d) 9th order

Fig.6 Initial stress distribution

Fig.7 shows redistributed stress pattern in the specimen along with the increase of slot depth. As shown in Fig. 7, stress in transverse direction changes during slot extension in order to satisfy equilibrium condition. As the cutting starts, stress free zone tends to be enlarged so that strain variation around the point where strain gages are attached diminishes. However, after the slot depth reaches 10 mm, stress free zone stops being enlarged, which means strain, or stress, does not change any more.



(a) 5mm depth (2^{nd}) (b) 10mm depth (2^{nd}) (c) 5mm depth (4^{th}) (d) 10mm depth (4^{th})

Fig.7 Stress redistribution with increase of slot depth

Fig.8 shows strain variation at the point apart from 6mm from weld toe for each case. As the order of polynomial increases, strain variation tends to decrease. Judging from the measured strain variation in Fig.4, it can be said that the lower order terms such as 2nd , 3rd order are dominant.

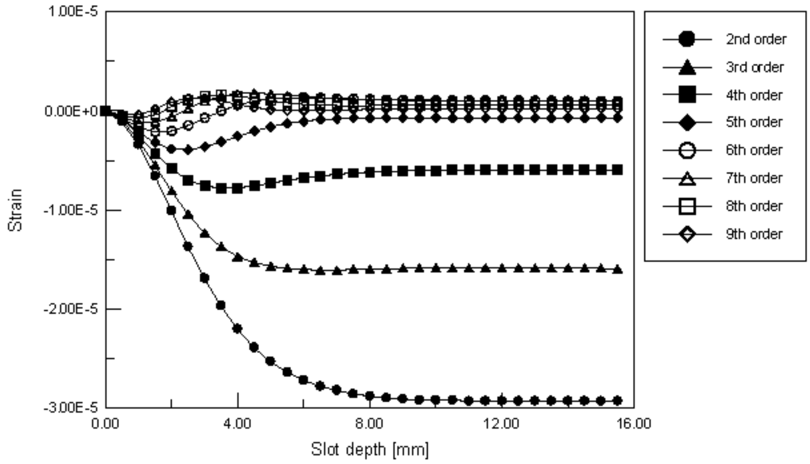


Fig.8 Strain variation (or compliance)

5. Result and discussion

Fig.9 shows transverse residual stress distribution along the specimen thickness up to 6mm, calculated using Legendre polynomial of 2~9th order. As shown clearly in this figure, residual stress near the toe of weld root falls in positive region, which means that high stress ratio doesn't necessarily have to be used in the fatigue test of this type of specimen. Fatigue test also have been done under the 0 stress ratio to verify the validity of the analysis results, and it was revealed that the fatigue life coincided well with corresponding one in BS, D curve.

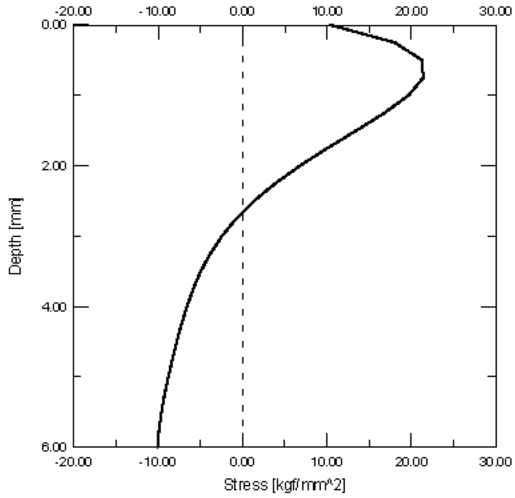


Fig.9 Estimated residual stress

6. Conclusions

Based on the studies performed in this research, several conclusions can be derived as follows;

- Compared to other destructive methods, crack compliance method is thought to be very reliable technique to measure the residual stress distribution in the material.
- It is confirmed that the tensile residual stress is present at the toe of weld root, therefore, high R ratio doesn't have to be used in the fatigue test.

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