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Critical Condition of the Branching Behaviour of Running Brittle Cracks in Steels

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Abstract: In this paper, using the devised under-matched welded joint to change the volume of high stress areas near the crack tip, the mechanism of crack propagation is investigated by experiments and the dynamic finite element method (FEM) analysis in which the rational shape of the crack front line are assumed. For evaluating the crack running behaviour, ESSO tests were performed under -100deg.C and several stress conditions and strain gauges and crack gauges were instrumented in measuring the crack propagation velocity which is used for input data of FEM analysis. The results of experiments show that the crack propagation velocity tends to be a little higher in the material with soft welded joint in which the expansion of high plastic strain region is significantly concentrated in the softer material and consequently the exceedingly-high stress region over 4-5 times σ_{y0} (yield strength at ambient temperature and in static) is widely distributed than in the homogeneous material. Interestingly crack bifurcations were observed in both specimens at low crack velocity position (around 800 m/s), contrary to the findings of the elastic dynamic fracture mechanics. Further, the soft welded joint tends to branch in a shorter distance. This is also thought to be due to the high stress concentration in the vicinity of the crack tip in soft welded joint. The triaxiality situations were computed by FEM analysis and the result shows agreement with the above estimate.

Key words: brittle crack propagation, steel, dynamic fracture, strength mismatch, crack branching

1. Introduction

High tensile strength steel(HTSS) is definitely effective in reducing the weight of material, but HTSS is hardly applied to large-scale structures, because of the problem about hydrogen cracking caused by imperfect welding. Using soft welded joint, in which weld metal whose strength is lower than that of base metal is used, can solve the problem. Applying soft welded joint can lead to decreasing preheat temperature, and then improve better weldability. Dynamically singular behavior is thought to be generated around soft welded joint and several investigations have been conducted to study the strength, fracture initiation, and fatigue properties of soft welded joint [1]. However, rapid fracture problem in soft welded joint, such as brittle fracture or ductile fracture, has not been examined until now. In this paper, for evaluating the basic property, brittle crack propagation at constant temperature in the material with soft welded joint is compared with that in the homogenous material.

Another aspect of this paper is the obvious branching behaviour in fast running crack. In our all ESSO tests including both of homogeneous plate and soft welded joint conducted at low temperature, crack branching was observed. Regarding to crack branching behaviour in fast crack, there are several candidate mechanisms in brittle material [2-5]. However, it is not satisfactory for elastic-plastic materials. In this paper, the critical condition was studied from the viewpoint of the stress-strain state at the vicinity of the crack when the crack branching.

2. Experiment

Specimen used in the experiment is shown in Fig. 1.

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The specimen is composed of part A (around the crack propagation area), part B (crack propagation area), part C (segregated from part A and B), and tab plates. Tensile load is applied on both sides of the specimen. In the experiment, the top of the specimen was stroke by air gun and the brittle crack was propagated. For minimizing the effect of impacting, input energy for crack initiation is set to low value.

Crack gauges and strain gauges are instrumented in the crack propagation area (Fig. 2) for measuring the crack propagation velocity. Also, thermocouples are instrumented for controlling the temperature. The temperature was maintained at -100deg. C at entire region in test specimen. In the specimen with soft welded joint, high nickel steel is used as part A and N30 steel is used as part B. Mechanical properties of both are shown in Tables 1 and 2. Applied stress, σ_g and the length of part B are changed in several experiment conditions. Each condition is shown in Table 3.

3. Experimental Results

From the crack gauges and strain gauges, dynamic data exemplified in Fig. 3 are acquired. The time when

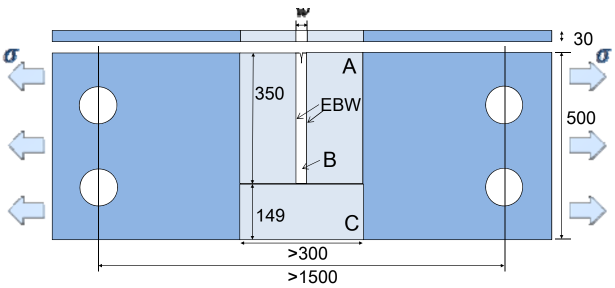

Fig. 1 Configuration of whole test specimen.

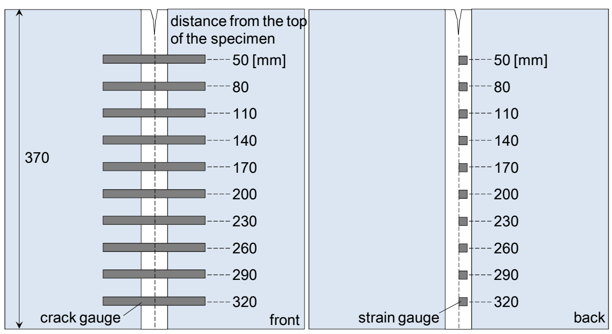

Fig. 2 Schematic illustration of the instrumentation.

Table 1 Mechanical properties of steel used in part A.

Manufacturing Process	Tensile test			Charpy impact test	
	YS [MPa]	TS [MPa]	EL [%]	vE_{-196} [J]	vTrs [deg.C]
Quenching & Tempering	677	718	29	202	<-196

Table 2 Mechanical properties of steel used in part B.

Manufacturing Process	Tensile test			Charpy impact test	
	YS [MPa]	TS [MPa]	EL [%]	vE_{-196} [J]	vTrs [deg.C]
Normalizing	416	541	27	295	-40

Table 3 Experimental conditions.

#	Homogenous/ Soft welded joint	Width of part B	Experimental Condition (applied stress/temperature)
S-1	Soft welded joint	30	100MPa/-100deg.C
S-2	Soft welded joint	20	300MPa/-100deg.C
H-1	Homogenous	-	300MPa/-100deg.C

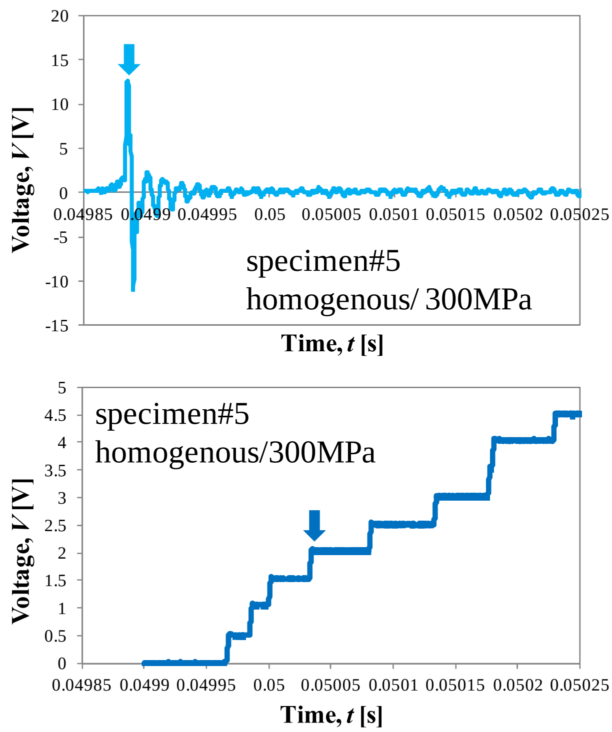

Fig. 3 An example of signals acquired by crack gauges and strain gauges at crack length of 140 mm.

the crack gauges detected the crack passage is considered to be the point where the voltage rises by 0.5 V due to disconnection of each crack gauge. In the data by strain gauges, the peak of the strain, indicated by an arrow, is thought to be the time when the strain gauge detected the crack propagation. Crack propagation velocity is calculated from the time when the gauges detected the crack and the position of the gauges.

The plot of time vs. crack length measured in each experimental condition is showed in Fig. 4. As Fig. 4 shows, the output of the crack gauges is considerably later than that of the strain gauges. This means the crack tip in the center of plate thickness precedes than near the plate surface. From the data, the plot of crack propagation velocity is calculated by strain gauge record and showed in Fig. 5. The velocity measured in

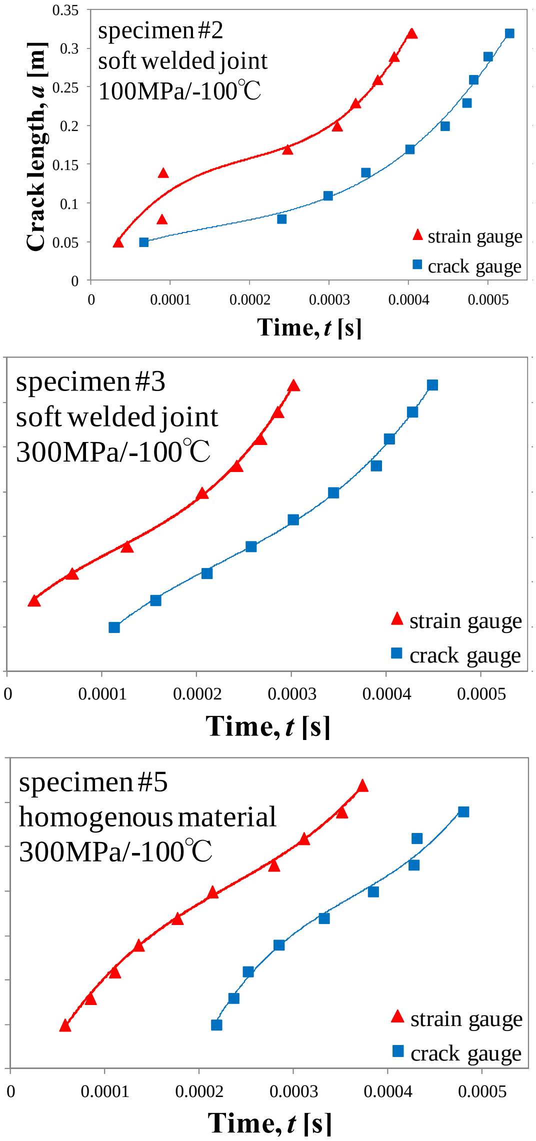

Fig. 4 Signal histories of strain gauges and crack gauges.

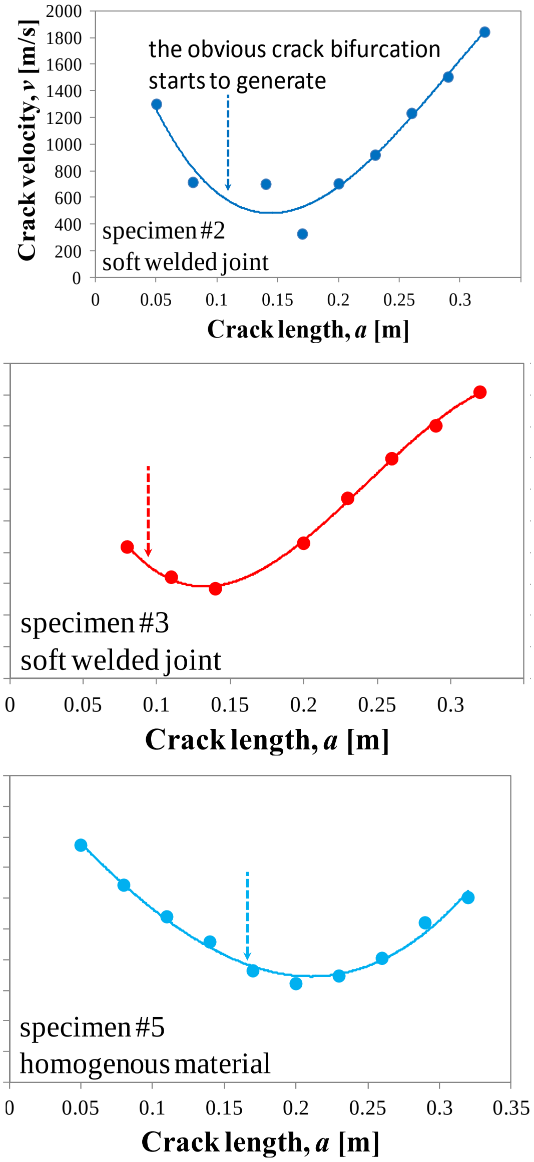

Fig. 5 Comparison of crack propagation velocity.

the material with soft welded joint is lower in the beginning of the propagation and higher in the end of the propagation than the velocity measured in the homogenous material. Final speed of soft joint is accelerated to more than 1800 m/s. This is thought to be the result of concentration of the strain in the soft material centered in the specimen.

Fig. 6 shows the picture of the crack path of specimen H-1 as an typical example. The point where the unevenness of fracture surface become apparent and the obvious crack bifurcation starts to generate is observed on the way of propagation. From this picture and the data of crack propagation history, the meandering of the crack occurs when the crack speed gets around 800 m/s. According to the previous study on elastic dynamic fracture theory, crack branches at subsonic speed [5]. The crack propagation behaviours are quite similar to that observed in elastic material, i.e., PMMA [3], mirror, mist and hackle, However, it is curious that the critical condition for the change to start unevenness fracture surface and bifurcation event is much different.

Authors think this reason may be derived from the plasticity at the vicinity of running crack and crack tip shape, therefore the detailed stress distribution in plastic region at running crack tip is investigated by dynamic FEM analysis.

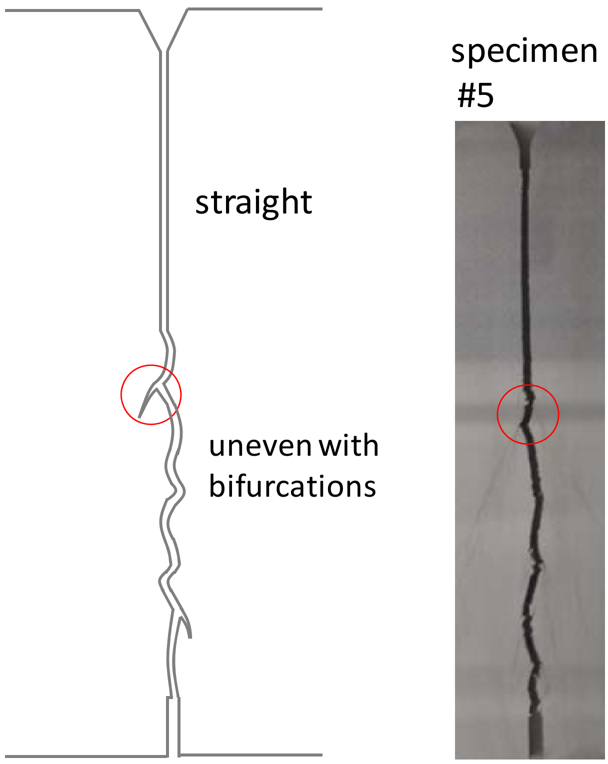

Fig. 6 Crack meandering of specimen#5.

Table 4 The point where obvious crack bifurcation starts to generate.

#	The points where obvious crack branching starts to generate (distance from top of the specimen)
S-1	110 mm
S-2	80 mm
H-1	160 mm

4. FEM Analysis and Discussion

FEM analysis is conducted for further investigation about brittle crack propagation in the material with soft welded joint. Major analysis conditions are summarized in Table 5. Crack propagation velocity which is acquired by experiment is used in the analysis. Fig. 7 shows the overview of the model used in this analysis. Considering the symmetry, the model of 1/4 size of the actual specimen is used. Mesh size of crack propagation area is 0.2 mm, which is smallest of all the mesh. First, the model for the material with soft welded joint is analysed with the element of flat shape in crack front line. In the analysis, the change of strength by heat affected zone is considered. Fig. 8 is the result of hardness test for the specimen with the Part B whose length is 20 mm. Hardness around heat affected zone is exclusively higher than base metal. Assuming that stress-strain relation and yield stress is in proportion to the hardness, stress-strain relation of heat affected zone was determined. Also, stress rise behavior due to high

Table 5 Analysis conditions.

Code	Abaqus 6.14-1
Analysis	Dynamic, Implicit
Element	3D-solid (8-nodes-isoparametric)
Minimum element size	0.2 mm

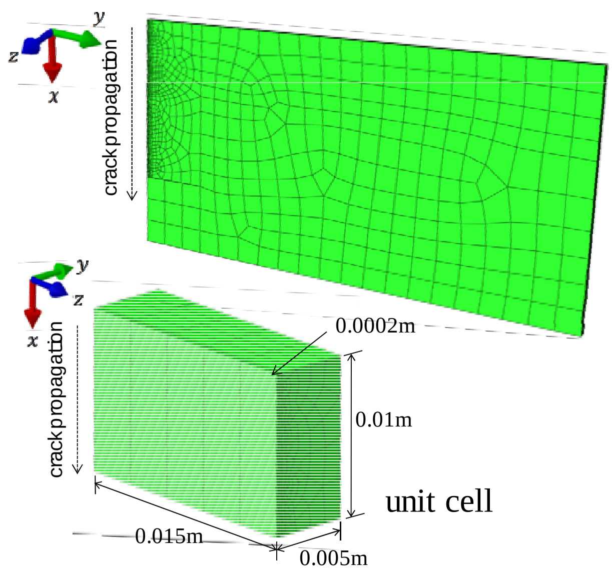

Fig. 7 Overview of the model used in FEM analysis.

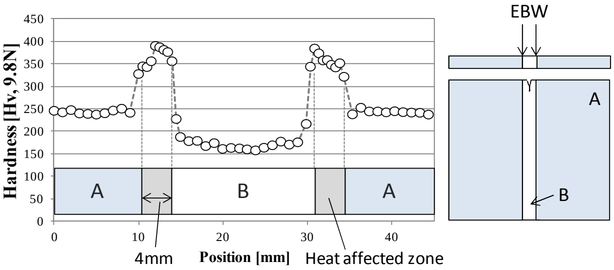

Fig. 8 Hardness distribution of soft welded joint.

strain rate condition was determined by Cowper-Symonds relationship whose factors were obtained by experiment [6]. With FEM analysis, opening stresses (σ_{yy}) are extracted from the ten nodes near the crack tip (as exhibited in Fig. 9) and stresses in proportion to $1/\sqrt{r}$ are used for computing dynamic stress intensity factor, K_d with the equation (1).

$$K_\mathrm{d} = \sigma\sqrt{2\pi r} \tag{1}$$

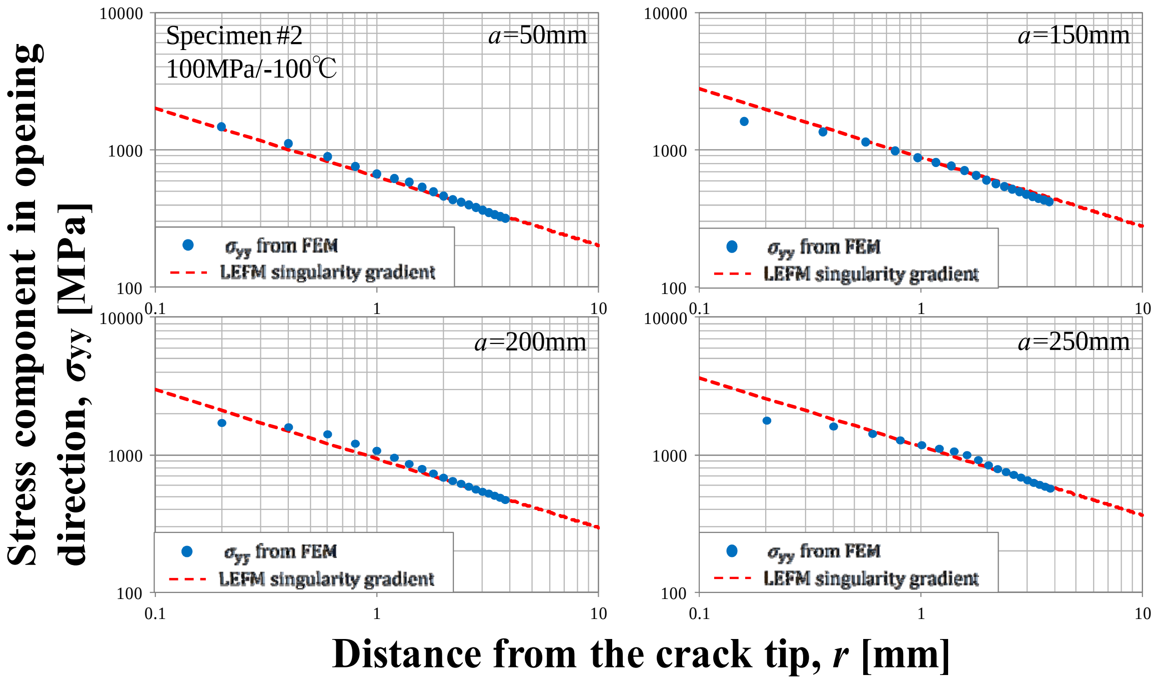

Fig. 9 Log-log plot of distance from crack tip vs. opening stresses.

Fig. 10 shows the plot of crack length vs. dynamic stress intensity factor. K_d rises as the crack length gets long. However, if K_d is assumed as a material constant, K_d should always be constant near the crack tip through the crack propagation. This problem is thought to be because the flat crack front is assumed as first trial of FEM analysis and this is thought to be against the real shape of crack tip. Actual brittle crack develops with the curved crack front, thus FEM model with the curved crack front needs to be considered. In this study, the model with different three types of curved crack front. Flat element on crack propagation area is transformed by coordinate conversion with the Eq. (2).

$$y = 2 - 2e^{-(cx)^2} \tag{2}$$

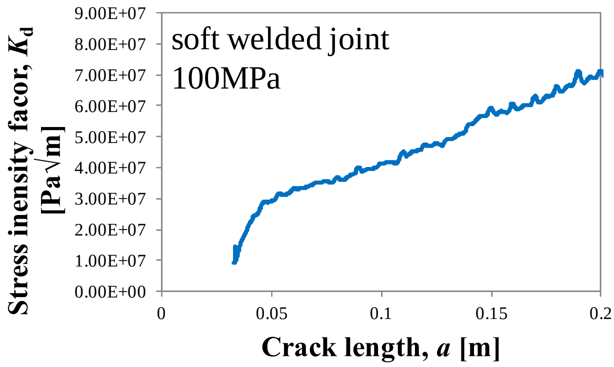

Fig. 10 The transition of K_d (flat crack tip).

The value of constant, c, gets bigger and the curve of crack front shape gradually gets steeper as the crack length gets long in the model. The steepness of the curve is changed in three types (Fig. 11). Type 1 has the elements of the steepest curve and Type 3 has the shallowest one. Fig. 12 shows the plot of crack length vs. dynamic stress intensity factor in ten models with curved crack front. These processes for curved crack tip are only expressed between 0 mm and 200 mm here. In all 3 types, K_d transitions more constantly than in the model with flat element on crack propagation area. Thus, model with curved crack front represents the real behavior more properly than the model with flat crack front. Among the curved crack front, type 3 model exhibits relatively constant transition of K_d. Therefore, type 3 model is used for investigation from now on.

Fig. 13 shows the comparison of the results of FEM analysis of the model with consideration of soft welded joint and that of homogenous material. The latter is more gradual than the former. This reflects the concentration of strain in the part B, softer material. Fig. 14 shows the comparison of the length of high stress area (hereinafter referred to as core region) [6]. Core region in the material with soft welded joint is much

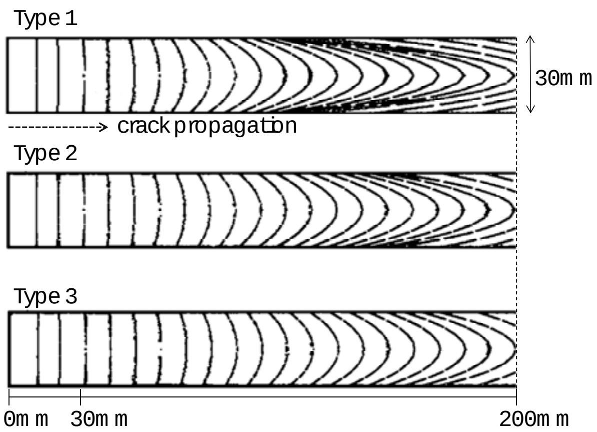

Fig. 11 Three types of curved crack tips.

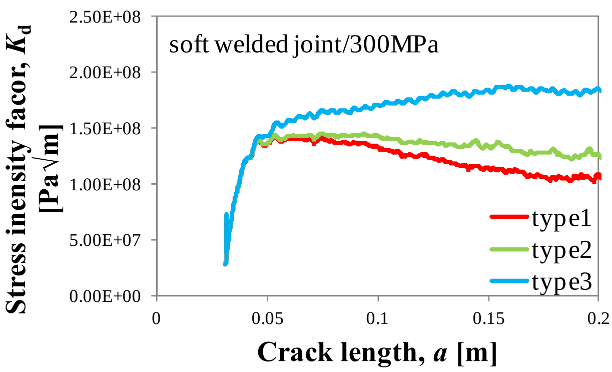

Fig. 12 Comparison of the three types of crack tip.

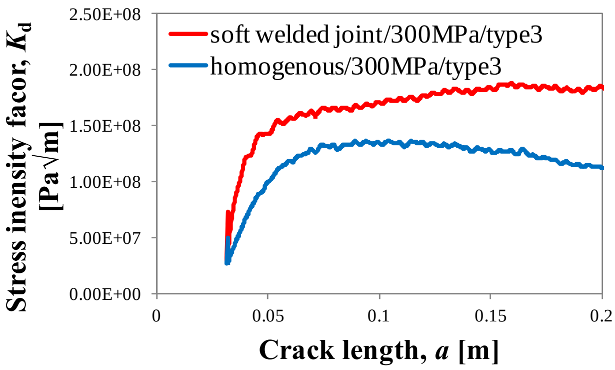

Fig. 13 Comparison of the transition of K_d.

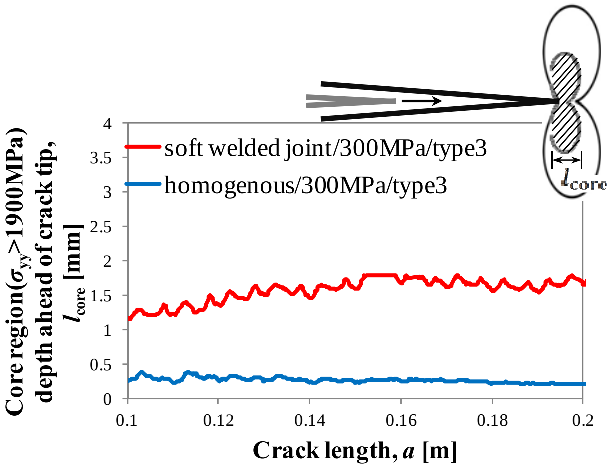

Fig. 14 Comparison of the length of high stress area.

larger than that in the homogenous material. This indicates the concentration of strain in the softer material. Fig. 15 shows the comparison of stress triaxiality. This figure is showing the relationship between opening stress, σ_{yy} and a parameter, $(\sigma_{zz}+\sigma_{zz})/\sigma_{yy}$ which represents the triaxiality. Stress value of each plot is calculated from the stress value in node in the vicinity of the crack tip. Circle mark shows the situation of crack tip of soft welded joint and triangle mark is of homogeneous material. It is revealed that the triaxiality is larger in the material with soft welded joint. It can be understood that the crack bifurcation is likely to occur σ_{xx} and/or σ_{zz} is higher because different fracture plane from principal plane is easy to be chosen from randomly oriented cleavage {100} plane. Also wide area with high stress condition is needed for choosing crack path with different angle. From these investigation and data,

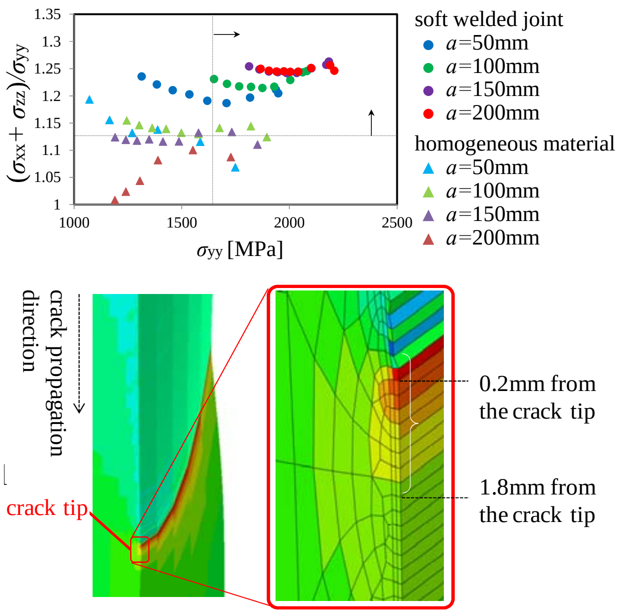

Fig. 15 Comparison of stress triaxiality.

critical conditions for crack bifurcation are that $(\sigma_{xx}+\sigma_{zz})/\sigma_{yy}$ is more than 1.1-1.2 and σ_{yy} is more than 1600 MPa.

5. Conclusions

Using the ordinary homogeneous material and the material welded with soft welded joint, ESSO test were conducted.

Crack propagation velocity measured in the material with soft welded joint is lower in the beginning of propagation and higher in the end of propagation than the velocity measured in the homogenous material. This is thought to be because of the concentration of strain in the centered softer material.

FEM analysis is performed with the crack propagation velocity obtained by the experiments.

FEM analysis is conducted by the model with flat crack tip shape model and curved crack tip shape model. K_d history is more constant in the model type 3, with curved shape. Thus, it can be thought that this model represents the real behavior most properly.

The results of FEM analysis with the model of the material with soft welded joint and homogenous material are compared. The transition of K_d is more steep in the welded material than that in the homogenous material. This is because of the concentration of the strain in the crack propagation area.

In both specimens, apparent bifurcations of the brittle crack were observed. From the results of FEM analysis, critical conditions for crack bifurcation are estimated to be that $(\sigma_{xx}+\sigma_{zz})/\sigma_{yy}$ is more than 1.1-1.2 and σ_{yy} is more than 1600 MPa.

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