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Fatigue crack growth under compressive loading

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Abstract

S/C magnets have many components which were designed to be compressively stressed. This paper describes a possible fatigue crack growth even under fully compressive stresses. In general crack is thought to close under compressive stress condition. But, if there is a tensile residual stress field in the specimen, the crack can open and grow to a considerable length. Compressive cyclic loading tests were made on the compact tension specimen with a hole at the center of ligament region where a tensile residual stress field was introduced by an excessive compressive pre-stress. Elastoplastic Finite Element Method (FEM) analysis indicated that the crack growth relaxed and re-distributed the residual tensile stress to some extent. In consequence it is experimentally verified that the crack grew to the length nearly to the fracture.

1. Introduction

It has passed more than a hundred years since research was started on fatigue of material, but the most fracture of mechanical structure is still due to the fatigue of material. It is sometimes associated with a stress field in the material. In general a crack is thought to be closed while it is being loaded by cyclic compressive stress, and because of the difficulty of estimating residual stress field in the material, the importance of the compressive fatigue problem has tended to be ignored. However, if there is a tensile residual stress field in the material and the stress is greater than the fatigue limit, the crack will be able to open and grow to a considerable length. The condition of tensile residual stress field and compressive cyclic stress is often a case of the structure, especially for welds of fusion reactors which experience a large thermal stress and electromagnetic force. Greasly et al. [1] reported the initiation and propagation of fatigue cracks in compact tension specimens of mild steel in a tensile residual and compressive cyclic stress condition. They showed that fatigue cracks grew several millimeters at a diminishing rate and arrested at last. Herman [2] conducted similar experiments and showed that the final crack length increased with an increase of the tensile residual stress field and the mean compressive stress. In their experiments, the tensile residual stress field was generated by applying a compressive excessive pre-stress to the plain ligament, and the residual stress was continuously relieved with increase of crack length. In the welding parts of the structure of fusion reactors, the tensile residual stress is large and applied cyclic stress is clearly divided into tensile and compressive regions in a specimen, which is a little different from Herman's cases. Fig. 1 shows an example of a conduit of central solenoid magnet conductor. It is an airtight rectangular hollow shell structure and has welded parts (sometimes it is a spot welding), so large residual tensile stress can be generated in this structure at initial state. On the other hand, most structural components of fusion reactors experience compressive stress caused by electrical forces at the excitation of superconducting magnets. As a result, large tensile residual stress and following compressive varying stress condition is easily realized especially in the spot welding parts of the above conduit. In this report, we made a hole in the center of the ligament of a compact tension specimen to enlarge the residual stress field in the vicinity of the notch and obtained a field with mainly compressive applied cyclic stresses between notch and center hole and tensile

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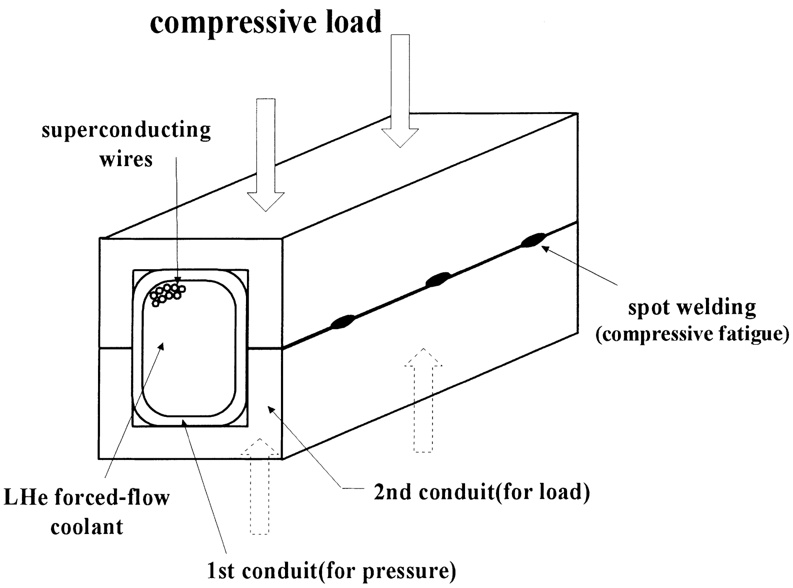

Fig. 1. Example of the conduit of central solenoid magnet.

stresses between center hole and edge. Therefore the failure of the CT specimen in this report means the crack reaches center hole, that is, break of the former part.

2. Experimental details

We used 18Cr-8Ni Austenitic Stainless Steel: the dimension of the specimen is shown in Fig. 2. This compact tension specimen has a hole in the center of the ligament which enlarges the residual stress field in the vicinity of the notch. A clip gauge is attached in region A to evaluate crack closure. The relation between crack length and stress intensity factor for a general compact tension specimen is not applicable in these specimens due to the peculiar shape of them with the center hole of the ligament. We used the energy release rate method making use of a finite element method with quarter point node elements to calculate the stress intensity factor, and made a relation curve between the crack length and stress intensity factor beforehand.

A tensile residual stress field was generated by applying an excessive compressive pre-load of 3.4×10^4 N (Model CT01) and 3.9×10^4 N (Model CT02) in region B. Fig. 3 shows Finite Element Method (FEM) model and Fig. 4 shows predicted residual stress distribution after a 3.4×10^4 N pre-loading–unloading cycle for crack lengths of 0.75 and 1.50 mm. In the initial residual stress state, a transition from tensile to compressive residual stress in this CT specimen was calculated to be 2 mm from the notch root, and it was also found that the point moves towards the ligament as the crack grows. It

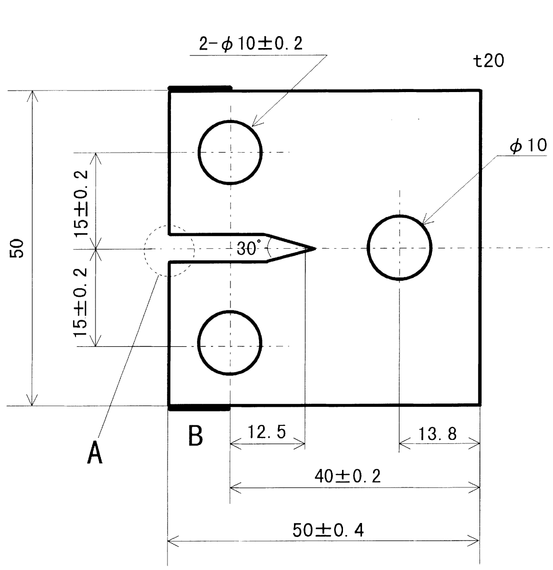

Fig. 2. Compact tension specimen.

is true that the change of the transition point of residual stress is accompanied by reduction of peak tensile residual stress, but tensile residual stress is always supplied near the crack tip, which can be thought to help the crack extend to considerable length. This result also indicates that the residual stress distribution at each cycle is needed to know the exact mean stress of com-

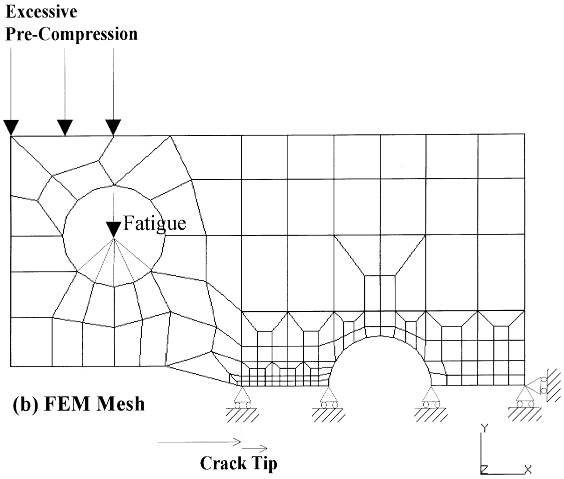

Fig. 3. FEM model.

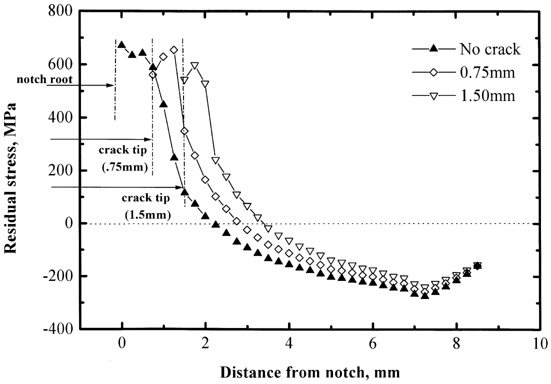

Fig. 4. FEM result of residual stress distribution (crack length 0, 0.75, 1.50 mm).

pression fatigue, which is thought to effect the initiation of a crack.

In the calculation we assumed Young's modulus and 0.2% proof stress to be 195 GPa and 295 MPa, respectively. These values and the work-hardening exponent were given by a practical monotonic tensile test of the same material. We used FEM analysis code MARC [3] and assumed Von Mises' yield condition and isotropic hardening law in the elastoplastic analysis.

A compressive cyclic load with a sinusoidal wave form, load range 2.0×10^4 N (from 0.1 to 2.1×10^4 N) and a loading frequency of 5 Hz, was applied at the pin hole of the CT specimen. The tests were performed at room temperature with a 50 kN closed-loop electrohydraulic test system. A clip gauge with 4 wire strain-gauges was attached at region A to obtain crack closure. The crack length was measured on the surface of specimen.

3. Result

Fig. 5 shows the experimental result on the correlation of load and crack opening distance at the cycle of almost the end of life. The load range AJ in the figure is divided into 3 areas, corresponding to full open of crack surface JF, partial open FG and full close GA. In this paper we pay attention to an intersection point C of both slopes of line BI showing crack surface full open and line HA showing full close, and replaced real crack surface behavior with virtual behavior of full open and full close. Therefore we assumed the effective load for the crack to grow was value BD($=a$).

Fig. 6 shows the result of calculation of the stress intensity factor against the crack length of this CT specimen with a center hole in the ligament. Solid triangles show stress intensity factor ranges against each crack length at the tensile load range of 2.0×10^4 N. In that process the crack surface was assumed to be full open. According to the consideration in Fig. 5, the ratio

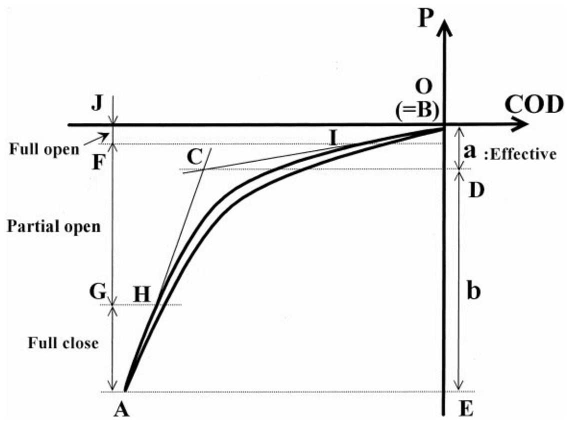

Fig. 5. Load–COD curve and definition of effective crack opening value.

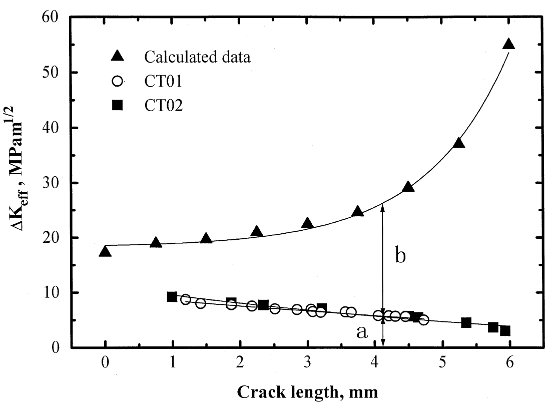

Fig. 6. Effective stress intensity factor range and crack opening.

of effective load was taken into account here. The full open crack model result of solid triangle line was multiplied by each actual crack opening ratio $a/(a+b)$, and the products are shown by open circles for CT01 and solid squares for CT02. Real electrical forces to the components in fusion reactor are thought to be independent of the crack length and to keep the same stress range at excitation of the magnet. Therefore the test was performed applying the same load range. Fig. 6 indicates that this same load range test corresponded to a K-decrease test.

Fig. 7 shows the crack growth rate of specimens CT01 and CT02 which had a residual tensile stress field and were subjected to a fully compressive cyclic stress. These plots seem to show Stage II, crack growth period, and near threshold period. In this figure a result of tensile cyclic stress is also shown for comparison. There seems to be some problems in evaluating crack closure in the way used in this paper, and more research is required to do it exactly especially in the threshold period. From Fig. 7, however it is shown that a crack can grow under fully compressive stress conditions, and its characteristics are essentially the same as the one under tensile stress conditions in the period of Stage II.

Fig. 8 show the shape of a surface crack induced under compressive ($K_{eff} = 12.0$ MPa m$^{1/2}$, $N = 1.13 \times 10^5$ cycle, $a = 2.24$ mm) fatigue conditions. The surface crack in Fig. 8 is found to be open in the unloading state,

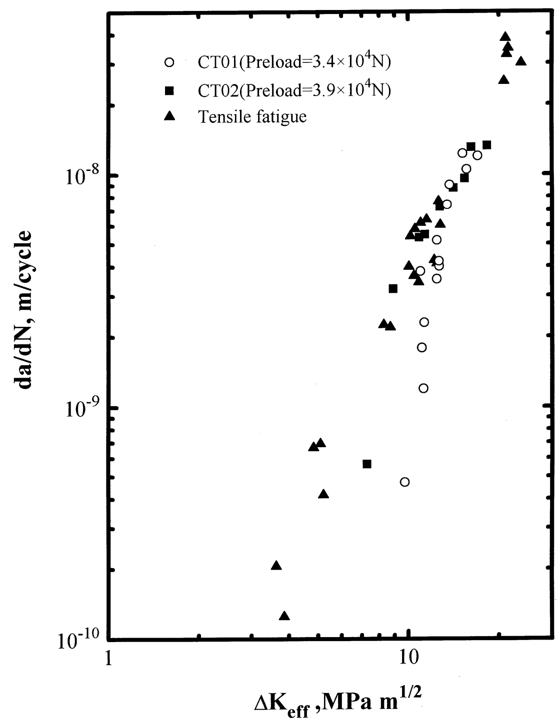

Fig. 7. Crack growth rate curve.

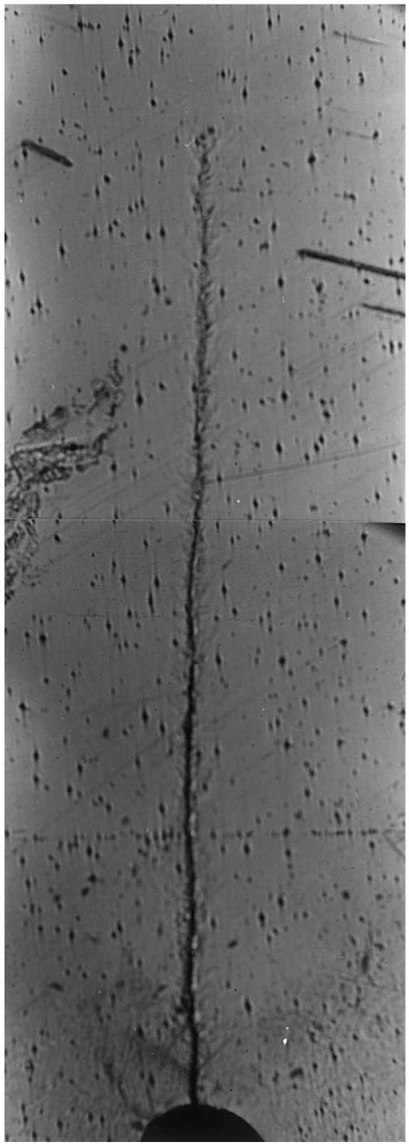

Fig. 8. Crack growth (compressive fatigue).

which is peculiar to this case (compressive fatigue in tensile residual stress field), while the surface crack under tensile fatigue condition has different open–close aspect. The surface crack which was open all through the crack length from root to tip was due to the relaxation of residual tensile stresses that remained until this cycle. A transition point from tensile to compressive initial residual stress in this CT specimen was calculated to be 2 mm from the crack tip (Fig. 4), but from Fig. 8, the crack opened and grew to the length over the point of 2 mm. It is caused by residual stress re-distribution with crack growth (result in Fig. 4), and the crack tip area is still in a tensile residual stress state, which could help the crack extend further.

In this report, the excessive pre-compressive load was used only for generation of such a residual tensile stress field that initial spot welding have. However, as a result of this experiment, the combination of only the compressive stresses, initial excessive pre-compressive stress and following cyclic compressive stress, caused crack initiation and made it extend to considerable length. Therefore, even if the structural material have no residual stress, a crack can be initiate and grow under compressive cyclic load depending on loading program and a shape of the notch.

4. Conclusion

1. A fatigue crack can be initiated and will grow even under fully compressive alternative external loading conditions. An initial tensile residual stress field which is sometimes produced by excessive compressive pre-load can help the crack initiate and extend nearly to the point of failure.

2. The tensile residual stress field is relaxed to some extent as the crack advances, but the field moves with the crack tip, and it makes the value of the positive mean stress sufficiently high to delay crack closure.

3. It is necessary to evaluate the crack closure related to a residual tensile stress field under compressive cyclic stress conditions, which make it possible to predict fatigue crack growth under compressive loading using a crack growth relation curve for fully tensile loading.

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