SHAPES AND COALESCENCE OF SURFACE FATIGUE CRACKS

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INTRODUCTION

It certainly seems that the issue of Summer 1973 Addenda of Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," of ASME Boiler and Pressure Vessel Code acted as a powerful stimulus to hard efforts of developing research works in Japan on practical applications of fracture mechanics to an evaluation of the integrity of structural components in nuclear power plant. Although project researches widely participated by universities, institutes and industries had been carried out in Japan from around 1965 on the subjects of fracture toughness and fatigue behaviour of vessel materials and their welded joints, a recognition of Section XI's philosophy that a flaw, of which sizes exceed specified limits, may be accepted if the flaw will be evaluated by fracture mechanics to be acceptable for continuous operation, encouraged an active and wide research works related to fracture mechanics with the purpose of verifying the Section XI's procedure.

In such circumstances a research committee chaired by the author and named AFC Committee (Assessment of Fatigue Crack Porpagation) started in 1956 in order to execute three years research works on fatigue crack propagation from multiple planar surface flaws. Main items included are: (1) Tests on fatigue crack propagation from single or multiple surface notches in a plate under repeated axial tension or repeated out-of-plane bending, (2) Tests on fatigue crack propagation from surface flaws in a cylinder under bi-axial tension, and (3) Numerical analysis of stress intensity factors for two surface cracks subjected to tension or bending. Notched plate specimens, 119 in total, of dimensions 180 mm to 1,000 mm in test section width and 20 mm to 40 mm thick, as well as 14 of surface notched cylindrical specimens, 15 mm thick and 200 mm in outer diameter were fatigued. The main objects of the research works were to examine some points of question about fracture mechanics evaluation procedure given in the Section XI: (1) Distance between adjacent planar flaws in a same plane and in parallel planes, which is considered to be a critical distnace for consideration as a coalesced single flaw, (2) Membrane and bending correction factors for surface flaws, (3) Fatigue crack growth rate versus stess intensity factor range relations, (4) An assumption in the analytical calculation procedure that a flaw grows to a geometrically similar, larger flaw, provided that the maximum stress intensity factor range along the periphery of a crack is taken for the calculation of stepwise growth of fatigue crack.

After the completion of AFC Committee works, a research executing committee chaired by the author and named FRC Committee (Fatigue Properties of Reactor Component Materials) was organized in order to carry out fatigue tests for the purpose of accumulating data useful for discussion of the safety margin in fatigue design curves as well as crack propagation rate curves for nuclear component materials and for the purpose of checking the validity of Palmgren-Miner's hypothesis in the cumulative fatigue damage calculation. Main items investigated are: (1) Effects of mean stress on fatigue strength of nuclear vessel material in the life range less than 10^6 cycles, (2) High cycle fatigue strength of austenitic stainless steel in the life range up to 10^8 cycles, (3) Low and high cycles fatigue strengths of austenitic stainless steels in BWR environment, (4) Cumulative fatigue damage of nuclear vessel material under p-distribution programmed block loading, (5) Fatigue crack propagation behaviour of nuclear vessel materials under p-distribution programmed block loading, and (6) Fatigue crack propagation behaviour of nuclear vessel materials in BWR environment. The research works in the frame of FRC Committee was completed at the beginning of 1983.

On the basis of results of the above-mentioned research works and then individual investigation carried out further, the following deals with the aspect ratio expressions of surface fatigue crack and coalescence conditions of multiple surface fatigue cracks.

ASPECT RATIO OF SURFACE FATIGUE CRACK

1. Experimental Data

Experimental data used for a statistical analysis of aspect ratio of a part-through fatigue crack were obtained from constant amplitude, repeated axial loading, repeated out-of-plane bending loading or repeated combined axial-and-bending loading of surface notched specimens 20 mm to 40 mm in thickness and 180 mm to 1,000 mm in test section width(1). The specimens were machined out from rolled plates of a nuclear vessel material, A533B Cl.1 steel (yield stress = 509 to 521 MPa and tensile strength = 642 to 661 MPa), and a piping material, 304 type stainless steel (yield stress = 275 MPa and tensile strength = 608 MPa). Surface notches, of which aspect ratio was ranged from 0.09 to 1.87, were introduced in the direction crosswise to the loading direction.

In order to leave traces of a fatigue crack front line on the fracture surface, the so-called beach marking method was applied by keeping the maximum load at a given constant value and increasing the minimum load from approximately zero to a half of the maximum laod. An initially introduced surface notch and a crack just after coalesced, of which representative dimensions a_o and b_o are defined as shown in *Fig. 1*, were regarded to propagate in semi-elliptic shape, with a of half length and b of depth. Total number of data of aspect ratio used for the analysis is 857, which were obtained from 99 specimens.

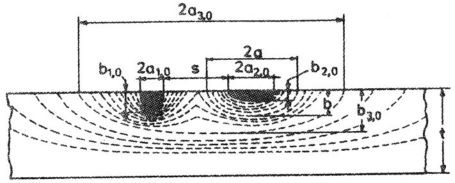

Fig. 1 Schematic representation of beach marks and definition of crack size parameters

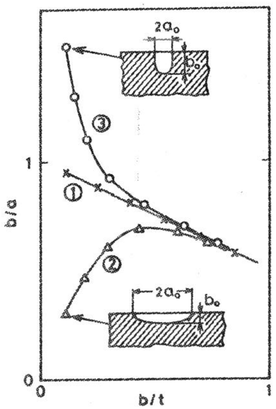

Fig. 2 Conceptual representation of b/a vs. b/t relation

2. Expressions for Aspect Ratio

As a general rule, the aspect ratio of a part-through fatigue crack will change by tracing any of curves illustrated in *Fig. 2* as the crack depth ratio b/t will increase. Curve (1) represents a fundamental relation between b/a and b/t, showing continuous and linear decrease of b/a against b/t. This relation is observed in the case where the initial aspect ratio of a notch at the b/t value less than 0.1 is ranged between 0.8 and 1.0, that means a nearly semi-circular surface notch. Curve (2) indicates the behaviour of a crack, which propagates from a shallow and long surface notch, and a steep increase of b/a in the beginning is a result of more preferential crack propagation to the thickness direction than the plate surface direction. In the case of a deep and short notch, crack propagation to the surface direction stays predominant over to the thickness direction, and thus curve (3) shows a steep drop at the beginning stage.

The following empirical expressions were proposed by Kawahara and Kurihara[2] for curves (1) and (2) respectively.

$$b/a = A - B \cdot b/t \tag{1}$$

$$b/a = (A - B \cdot b/t)[1 - (e/a)^n]^{1/n} \tag{2}$$

where A, B and e are constants, and e is defined depending on the initial condition of b/a. And for curve (3), Iida and Kawahara[3] derived the following expression by introducing a similar concept of modification as that for eq.(2).

$$b/a = A/[1 - (f/a)^n]^{1/n} - B \cdot b/t \tag{3}$$

where f is defined by the initial condition of b/a.

Applicability of the three expressions above-mentioned was examined for 857 data of aspect ratio[4]. The parameters A, B and n were determined by a direct searching method using computer to minimize D, that is expressed as follows:

$$D = \sum\{ln\ b/a(Exp) - ln\ b/a(Assum)\}^2 \tag{4}$$

where $b/a(Exp)$ and $b/a(Assum)$ are experimental and assumed aspect ratios. All the parameters A, B and n were changed as variables. For test series of combined loading of axial-and-bending loads, A and B were assumed on the basis of observation of experimental data as follows:

$$A = C_1 + C_2 R_b \quad , \quad B = C_3 + C_4 R_b \tag{5}$$

where C_1, C_2, C_3 and C_4 are constants, and R_b is a bending stress component parameter, that is expressed as

$$R_b = \Delta S_b/(\Delta S_m + \Delta S_b) \tag{6}$$

where ΔS_m and ΔS_b are axial stress range and bending stress range respectively.

As a result of statistical calculation[4,5] the following constants

were derived.

$$A = 0.92 + 0.03R_b \quad , \quad B = 0.10 + 0.80R_b, \quad n = 2.8 \tag{7}$$

where standard deviation is 0.136.

Figure 3 illustrates an example of good agreement of experimental results with estimation curves calculated by eqs.(2), (3) and (7). In this case, two fatigue cracks started from two EDM notches, one deep notch of 10 mm long and 10 mm deep and one shallow notch of 20 mm long and 5 mm deep, which were initially arranged with inside edges distance s of 29 mm, showed a coalescence at b/t of nearly 0.38. It is observed that changing behaviour of b/a for the crack from the deep notch (open triangles) and for the crack from the shallow notch (solid triangles) followed the tendencies of curves (3) and (2) in *Fig. 2*, respectively. Just after the coalescence, the crack length increases discontinuously to the sum of two crack lengths, remaining the depth at an given value, as implied in *Fig. 1*. Therefore, it is quite natural that the b/a value shows discontinuous drop in the moment of coalescence, followed by the crack propagation from a newly formed shallow shape crack.

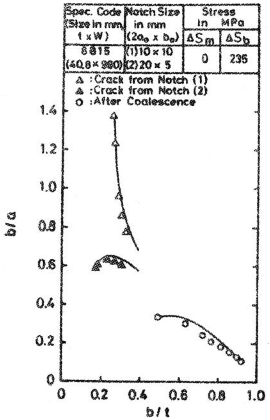

Fig. 3 Experimental results of crack shape with estimation curves

COALESCENCE OF CO-LINEAR CRACKS

1. An Analytical Procedure Proposed

Plate and pipe specimens containing co-linear surface notches were fatigued in AFC Committee's research: 17 and 27 plate specimens by repeated axial loading and repeated bending loading respectively, 4 plate specimens by combined axial-and-bending loading and one pipe specimen by internal pressure cycling. Observation of beach marks on fracture surfaces obtained in the research afforded evidence showing that one of assumptions contained in an analytical procedure described in Section XI of ASME Boiler and Pressure Vessel Code is not realistic one.

The assumption in the ASME's procedure says that adjacent surface cracks should be regarded as a single coalesced crack when the inside distance is equal to or less than twice the deeper crack depth. But in experiment all the fatigue cracks started from adjacent notches propagated radially in an individual shape as a function of initial aspect ratio and applied stress mode without any interaction due to an adjacent crack, and then two cracks coalesced finally when inside edges of two cracks touched each other, as illustrated in *Fig. 4*. The experimental evidence implies that the ASME's procedure including the other assumption of constant crack shape may provide possibly a conservative estimation in case of axial loading, and on the other hand a non-conservative estimation in case of out-of-plane bending loading.

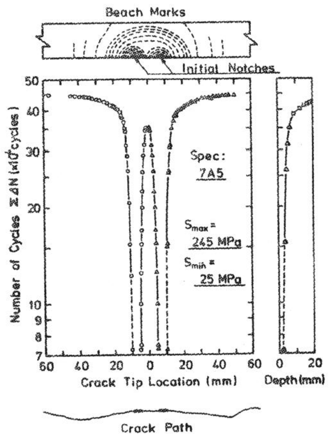

Fig. 4 Examples of fatigue crack propagation from double co-linear notches by repeated axial tension

On the basis of the experimental data taken during the fatigue tests in AFC Committee work, a method of predicting fatigue life of adjacent co-linear cracks was investigated, with a basic concept of dividing a prpagation process of fatigue crack into two parts: each individual propagation of crack before coalescence and then propagation of a coalesced crack.[6]

Assumptions introduced are as follows.

(1) Modeling of initial crack shape: A detected surface crack is modeled as a semi-elliptical surface crack inscribed in a rectangle which circumscribes a flaw. The different points from the ASME's procedure are that even if the b/a ratio in the initial condition is greater that unity, this crack is not regarded as a semi-circular crack but as a deep semi-elliptical crack, and that even if multiple series surface cracks are arranged very close to each other, these cracks are not regarded as a coalesced crack.

(2) No effect of mutual interaction on propagation behaviour due to adjacent cracks.

(3) Propagations in surface direction as well as in thickness direction follow to Paris' law.

(4) Stress intensity factor at the deepest point of a semi-elliptical surface crack is assumed to be given by eqs.(8) and (9), which were derived semi-empirically by referring Kobayashi's solution.[7,8]

$$\frac{K}{\alpha_m \sigma_m \sqrt{\pi b}} = \begin{cases} M_m(b/a,\ b/t)/\sqrt{Q(b/a)} & \text{for } b/a \leqq 1 \\ M_{f\cdot s} \times \{a/b\}/\sqrt{Q(a/b)} + (2 - b/a) \times [M_m(b/a = 1, b/t) - M_{f\cdot s}]/\sqrt{Q(b/a = 1)} & \text{for } 1 \leqq b/a \leqq 2 \\ \{a/b\}/\sqrt{Q(b/a)} & \text{for } b/a \geqq 2 \end{cases} \quad (8)$$

$$\frac{K}{\alpha_b \sigma_b \sqrt{\pi b}} = \begin{cases} M_b(b/a,\ b/t)/\sqrt{Q(b/a)} & \text{for } b/t \leqq 0.6 \\ 2.5(1 - b/t) \times M_b(b/a,\ b/t = 0.6)/\sqrt{Q(b/a)} & \text{for } b/t \geqq 0.6 \end{cases} \quad (9)$$

where K is stress intinsity factor and $M_{f\cdot s} = 1 + 0.12(1 - 0.5b/a)^2$. As for M_m and M_b, Kobayashi's solutions are used.

(5) Effect of finiteness of plate width: A solution by Newman and Raju [9] cannot be applied to the case of co-linear cracks. Thus, eq.(10) for axial load and eq.(11) for out-of-plane bending load were derived considering changes in tensile and bending rigidities.

$$\alpha_m = Wt/\{Wt - \sum_i (\pi/2) a_i b_i\} \quad (10)$$

$$\alpha_b = (Wt^3/12)/\{Wt^3/12 - \sum_i a_i b_i (3t^3 - 6tb_i + 4b_i^2)/6\} \quad (11)$$

(6) Surface crack length is given by eqs.(1), (2), (3) and (7).

(7) When depth of a crack becomes larger than 85 percent of plate thickness, the crack is assumed to penetrate the plate.

(8) Adjacent two cracks are assumed to coalesce when their inside edges touch each other, and just after the coalescence the cracks are assumed to become immediately to a single semi-ellipse, that is drawn through the outside edges of a coalesced crack and the deepest point of either deeper crack just before coalescence. The total length $2a_e$ and depth b_e of the newly formed crack just after coalescence are given as follows:

$$2a_e = 2\sum_i a_i\ , \quad b_e = Max\{b_i/\sqrt{1 - (x_i/a_e)^2}\} \quad (12)$$

where x_i indicates the distance between the i-th crack center and the coalesced crack center.

2. Factors in Calculation

Accuracy of an estimated fatigue life by the present method may depend on the size of incremental propagation depth of a crack, Δb (mm). As a result of trial calculation, it was found that the estimated fatigue life can be obtained in a good agreement with experimental result, if the calculation is done with Δb smaller than 0.1 mm. On the basis of the result, fatigue life estimation in the following was calculated by increasing Δb with incremental step of 0.1 mm instead of incremental increase of number of cycles applied ΔN.

Equation(9) in assumption (4) was derived by modifying Kobayashi's solution. The figured $\Delta b/\Delta N$ from two adjacent beach marks on the fracture surface was assumed as da/dN and was substituted into Paris' law. Thus, the stress intensity factor range at the deepest point of a semi-elliptical surface crack was derived as follows:

$$\Delta K_b = (1/c \cdot \Delta b/\Delta N)^{1/m} \qquad (13)$$

where c and m are material constants.

Figure 5 shows the relation between b/t and M_b which is the experimental ΔK_b normalized by $\Delta\sigma\, b\sqrt{\pi b/\Phi}$ for specimen 6B2, 7B1Q and 8B2 with various ratios of plate width to plate thickness. The experimental M_b value does not agree with Kobayashi's solution, and the difference becomes larger as the b/t ratio becomes larger than 0.6, especially for specimens of small width-to-thickness ratio. The effects of finite width should exist really. Then, dividing the experimental M_b value by α_b given by eq.(11), the relation between M_b/α_b and b/t is plotted in *Fig. 6*. Decreased deviation of the experimental data from theoretical curves may imply that the effects of finite width are almost disappeared. However, the difference between the experimental M_b/α_b and Kobayashi's solution still exists in the range of $b/t > 0.6$. Then, Kobayashi's solution in this range was modified experimentally and the above-mentioned eq.(9) was proposed. For reference, comparison between the experimental and estimated ΔK values for a single notched specimen subjected to out-of-plane bending is shown in *Fig. 7*, in which it is observed that the present method and Newman-Raju's method show fair agreement.

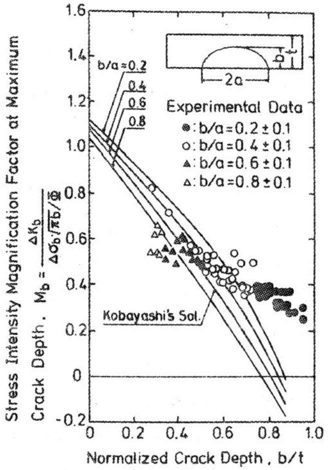

Fig. 5 M_b vs. b/t

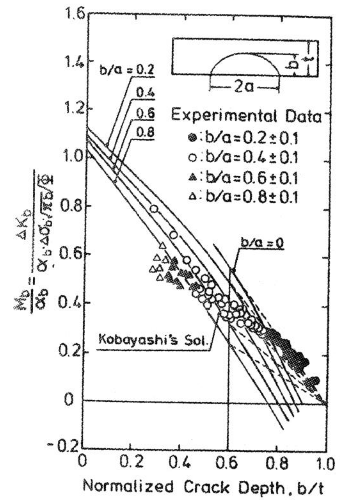

Fig. 6 M_b/α_b vs. b/t

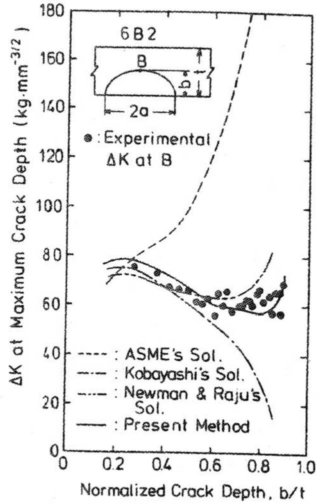

Fig. 7 Comparison between theoretical and experimental ΔK at the point of the maximum crack depth

3. Accuracy of Estimated Fatigue Life of Co-Linear Cracks

The mean value of the ratio of the estimated fatigue life to coalescence of two surface cracks to the experimental one, $(N_{coal.})_{Cal}/(N_{coal.})_{Exp}$ is 1.05 and the standard deviation is 0.12 for axially loaded specimens. On the other hand, in the case of out-of-plane bending load, the mean value is 0.96 and the standard deviation is 0.17. Namely, the deviation of the accuracy of the estimated fatigue life in the case of out-of-plane bending load is larger than that in the case of axial load. The error of the mean is ± 5 percent for both cases.

Secondly, an examination was made of the ratio of the estimated fatigue life to plate-thickness penetration to the experimental one, $(N_{pene.})_{Cal}/(N_{pene.})_{Exp}$. In the case of out-of-plane bending load, fatigue cracks initiate at the back surface of a plate when the crack depth becomes about 85 percent of plate thickness. This situation can be regarded to be the start point of plate-thickness penetration in the engineering sense. Then, the fatigue life to the crack depth of 85 percent of plate thickness was regarded as the fatigue life to plate-thickness penetration.

In the case of axial load, the mean value of $(N_{pene.})_{Cal}/(N_{pene.})_{Exp}$ for a single surface crack is 0.93 and the mean value for two surface cracks in series is 0.92. However, the standard deviation for two surface cracks in series is larger than that for a single surface crack. On the other hand, in the case of out-of-plane bending load, the mean of $(N_{pene.})_{Cal}/(N_{pene.})_{Exp}$ for a single surface crack is 1.08, and the mean value for two surface cracks in series is 0.84. The standard deviation of $(N_{pene.})_{Cal}/(N_{pene.})_{Exp}$ in the case of out-of-plane bending load is 0.17 - 0.18 for both a single surface crack and two surface cracks in series and is larger than that in the case of axial load.

Figure 8 illustrates the estimated crack growth curves and experimental data for specimen 6A3, which was fatigued by axial loading. The ASME method gives too conservative crack growth curves in comparison with the experimental data. The estimated crack growth curves by the present method, curves 2, are close to the experimental results. It is observed that the ASME's method gives poor estimation for crack shape, too flat surface cracks as shown in *Fig. 9*.

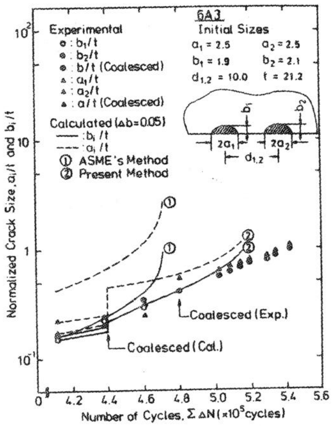

Fig. 8 Estimated crack growth curves for specimen 6A3 fatigued by repeated axial loading

Figure 10 shows the estimated crack growth curves for specimen 8B4, which was fatigued by out-of-plane bending load. Also found is that the present method provides good estimation of crack size. The accuracy of the estimated fatigue crack growth curve by the ASME's method depends on an initial crack-shape ratio of a coalesced crack. It is the same thing as the case of a single surface crack. The estimated results by the ASME's method for specimen 8B4 shows non-conservative estimation in the longer life range as shown by curve 1 in the figure. In *Fig. 11* estimated crack shapes are compared with experimental results. It is observed that the ASME's method provides too short length of crack as compared with experimental results.

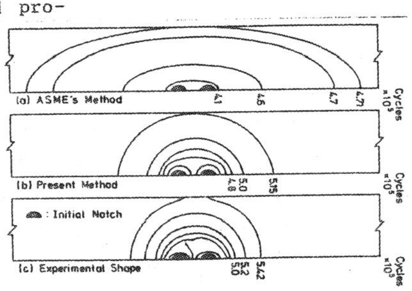

Fig. 9 Estimated and experimental crack shapes in specimen 6A3

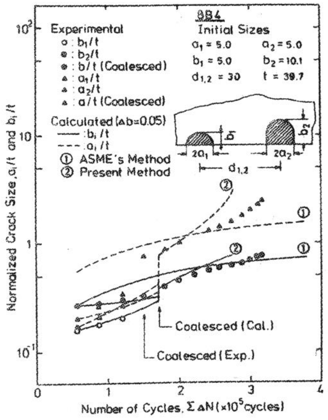

Fig. 10 Estimated crack growth curves for specimen 8B4 fatigued by repeated out-of-plane bending loading

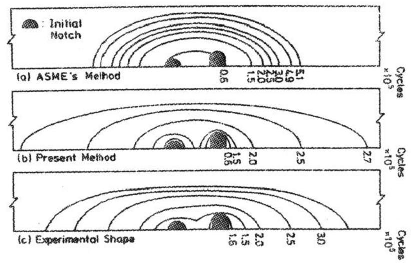

Fig. 11 Estimated and experimental crack shapes in specimen 8B4

COALESCENCE OF PARALLEL CRACKS

1. Fatigue Tests

It is specified in Section XI of ASME Boiler and Pressure Vessel Code that discontinuous indications whose area are oriented primarily in parallel planes, and other than parallel to the surface of the component, shall be considered as a single, coalesced flaw if H in *Fig. 12* is equal to or less than 12.7 mm and if s is equal to or less than twice the deeper depth out of b_1 and b_2.

In order to check the validity of the specification about the distance of 12.7 mm, that is one of criteria for immediate coalescence or non-coalescence of parallel flaws, plate and pipe specimens containing parallel surface notches oriented perpendicular to the specimen surface as well as the loading direction were fatigue tested in AFC Committee's research: 16 and 21 plate specimens by repeated axial loading and repeated bending loading respectively, and 9 pipe specimens by internal pressure cycling.

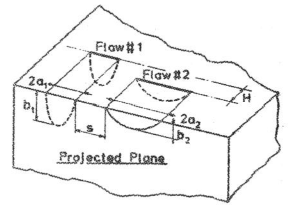

Fig. 12 Parallel flaws

Due to wide variety of experimental parameters of H and s and insuficient number of specimens, no definite conclusion was obtained, only showing a marked tendency that two fatigue cracks started from two parallel, surface notches make coalescence, if a line connecting two tips of the notches makes an angle less than 45° to the notch length direction.

To obtain further available data, an experimental investigation[(10)] was carried out using wide plate specimens: 20 mm thick, 180 mm wide and 900 mm long for zero-to-tension fatigue loading, and 20 mm thick, 700 mm wide and 1,400 mm long for repeated out-of-plane bending loading. Two out of four EDM notches, 5 mm long × 2 mm depth, 5 mm long × 5 mm depth, 10 mm long × 2 mm depth, and 10 mm long × 5 mm depth, were machined on a surface of 16 specimens of ASTM A533B Cl. 1 steel. Seven kinds and 9 kinds of notches layout were arranged for axial and bending loadings respectively. Examples of notches layout are shown in *Fig. 13*.

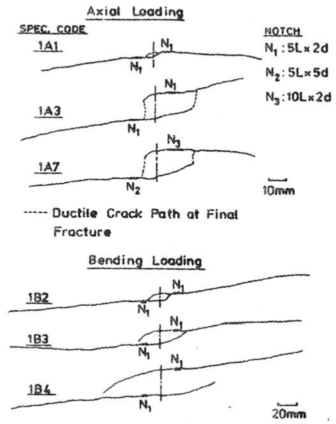

Fig. 13 Crack paths from parallel notches subjected to axial or out-of-plane bending loadings

Fatigue crack propagation tests were carried out using one side notched, square section specimens, confirming no difference between crack propagation rates in thickness direction and in surface direction of the test plate.

2. Experimental Results and Discussion

The vertical chain line in *Fig. 13* indicates an imaginary coalesced point where a part of two cracks were overlapped on a projected plane perpendicular to the specimen surface as well as the notch length direction. It is observed that each crack propagated in general in a straight line up to the imaginary coalesced point regardless of loading mode. The small solid circle shows a result of analysis, that is a point where the elasto-plastic boundary ahead a crack touched to the crack surface of the another crack.

In *Fig. 14* coalescence condition is shown as a function of inside

distance s and parallel distance H. Cross-marked points indicate the results of AFC Committee. Coalescence or non-coalescence behaviour is classified into 5 categories. It may be concluded that the coalescence will be realized, if the following conditions will be satisfied.

$$H \leq 5 \text{ mm} \quad \text{if} \quad s \leq 10 \text{ mm}, \qquad H < 0.5\,s \quad \text{if} \quad s > 10 \text{ mm} \tag{14}$$

A comparison of eq.(14) with the coalescence conditions after ASME Section XI may suggest that the ASME's specification provides too conservative conditions for both cases of axial and bending loadings.

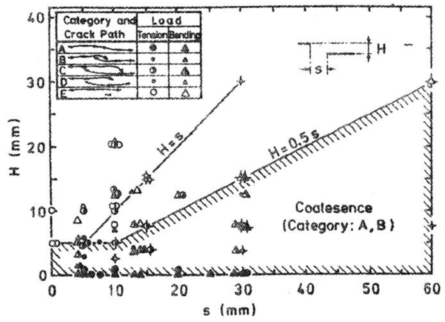

Fig. 14 Coalescence condition of parallel surface cracks

It should be mentioned here that a restricting condition of no full thickness penetration of a crack before the coalescence should be added from the viewpoint of structural integrity.

For example, in case of a single surface crack, the ratio of crack length and plate thickness at the full thickness penetration $2a_f/t$ is given as follows by modifying eqs.(1) and (7).

$$2a_f/t = 2.44/(1 - 0.939R_b) \tag{15}$$

As a simple example, let us assume that there are two parallel surface flaws of the same length of $2a$. If the fatigue crack propagation rate is assumed to be the same for two cracks started from the notches, the coalescence will occur when the crack length reaches to $(2a + (s/2) \times 2)$. Therefore, $(2a + s)$ should be at least less than $2a_f$. Thus, the following condition is obtained conclusively as an additional condition for the coalescence of cracks from two parallel flaws of the same initial length.

$$s < 2.44t/(1 - 0.939R_b) - 2a \tag{16}$$

CONCLUSIONS

As a result of the investigation described above, the following conclusions were obtained.

(1) The aspect ratio, the ratio of crack depth to half crack length b/a, of a part-through fatigue crack, that propagated from a semi-circular or a semi-elliptical surface flaw, can be expressed as follows depending on the initial aspect ratio b_o/a_o of the flaw. The following expressions are also applicable to a crack re-started from a coalesced fatigue crack, of which aspect ratio was b_o/a_o.

$$b/a = (A - B\ b/t)[1 - (e/a)^n]^{1/n} \quad \text{for } b_o/a_o \leq 1.0$$

$$b/a = A/[1 - (f/a)^n]^{1/n} - B\ b/t \quad \text{for } b_o/a_o \geq 1.0$$

where $A = 0.92 + 0.03\ R_b$, $B = 0.10 + 0.80\ R_b$, $R_b = \Delta S_b\ /(\Delta S_m + \Delta S_b)$, ΔS_m and ΔS_b are axial and bending stress ranges respectively, and $n = 2.8$. The constants e and f are determined by substituting a_o and b_o into the above expressions.

(2) A method of estimating crack propagation life from aligned co-linear flaws was proposed taking coalescence phenomenon into consideration. The method shows a good agreement with experimental results, because the fatigue life to plate thickness penetration is evaluated as a sum of the fatigue life to coalescence and the fatigue life to thickness penetration after coalescence, considering change in crack shape during propagation.

(3) The analytical procedure specified in Section XI of ASME Boiler and Pressure Vessel Code seems to be not always conservative. Especially in the case where aligned flaws, of which initial aspect ratios are more than unity, are subjected to out-of-plane bending loading, the procedure may give risky prediction.

(4) Experiments of fatigue crack propagation from parallel surface notches were carried out, showing that coalescence or imaginary coalescence which is regarded essentially as coalescence because of rapid curving of a crack path directing to adjacent crack, will occur, if the following conditions will be satisfied.

$$H \leq 5\ \text{mm} \quad \text{if} \quad s \leq 10\ \text{mm}, \qquad H < 0.5\ s \quad \text{if} \quad s > 10\ \text{mm}$$

where H is the distance between adjacent two planes, and s is the inside distance between two edges of adjacent projected surface notches or cracks.

(5) The coalescence conditions for parallel flaws or cracks specified in Section XI of ASME Boiler and Pressure Vessel Code, that H is equal to or less than 12.7 mm and s is equal to or less than twice the deeper depth of flaw, seems to be too conservative.

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