CONSIDERATION OF LIFE PREDICTION MODEL FOR CERAMIC MATRIX COMPOSITE(CMC) WITH COOLING HOLE

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Abstract: Ceramic matrix composites (CMCs) have higher heat resistance and specific elasticity than Ni-based alloys, thus it is desired to be applied to aircraft engines such as turbine parts. In high temperature parts, small holes should be pierced to inject cold fluid. However, there are few research on the effect of small hole against the CMC fatigue life. This study focused to this phenomenon. Fatigue tests were conducted using flat plates pierced with single hole and multiple holes. Multiple holes were allocated vertically against load direction. Multiple holes have more advanced hole shapes which is called diffuser hole.
In the test results, different fracture mode and crack propagation were observed between single holed and multiple holed type. Multiple holed specimens had shorter lives than single hole. In addition, the fatigue lives of diffuser hole were shorter than circular hole. For evaluating life shorting of multiple holed specimens, life prediction models were reconsidered, which includes stress prediction and life prediction. The strength parameters were calculated by averaging stress field, which were predicted by finite element analysis (FEA), in area of CMC unit cell. After evaluating lives of hole specimens, multiple holed lives were predicted by using a smooth test S-N curve. Furthermore, to improve the stress prediction, the strength parameters were recalculated after resizing diffuser hole shape to fit the actual specimen. After that, all specimen lives were predicted around smooth specimen's S-N curve regardless of the number of holes. Finally, we have established the life prediction model for the holed CMCs.

Keywords: CMC, Cooling hole, LCF, Life prediction

Introduction

Introduction.

The International Air Transport Association (IATA) stated the future goal to achieve net-zero carbon emission by 2050 [1]. To achieve it, technical improvement of aero craft engine is indispensable. To improve of engine performonce, increasing the turbine inlet temperature (TIT) are effective and for them, reducing the cooling air at hot temparature parts are required. Figures 1 shows the material performance on the heat duarable temperature and specific strength [2]. Ceramic matrix composites (CMCs) have higher heat resistance and specific elasticity than Ni-based alloys, thus they should be applied to aircraft engines such as turbine parts.

JAXA launched environmentally compatible core engine technology research (En-Core) project in 2018, whose aim is to obtain competitive technologies to reduce NOx and CO2 [3]. JAXA and IHI proposed turbine vane concept as next generation (figures 2) and planed for developing the design technology and for design validation.

In the past research, consideration of cooling system for performance improvement was conducted in case that CMCs are applied to high temperature parts [4][5]. However, there are few research about small hole effects for mechanical characteristics. This paper focused to investigate the relationship between cooling hole specifications (size, shape, distance between holes) and fatigue lives, fatigue tests with use simplified fatigue specimens were conducted. The fatigue life around hole was predicted by stress of structural analysis that assumed CMCs as homogeneous materials [6]. Finally, the appropriation of the life model for holed CMCs is discussed.

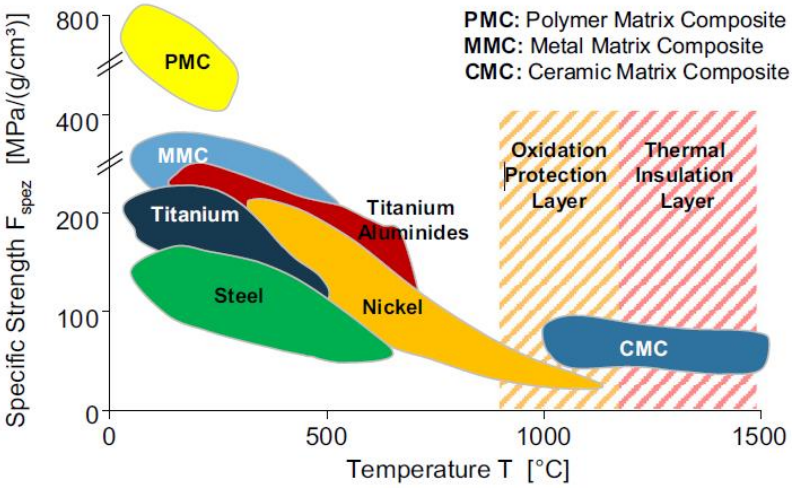


Figure 1: Relationship between temperature and specific strength [7]

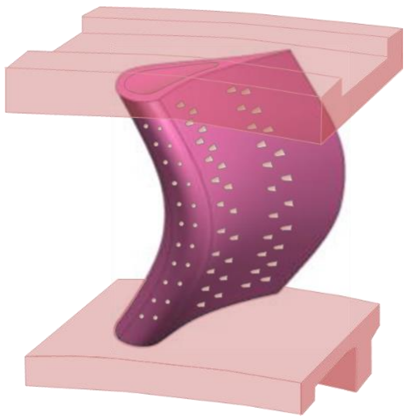


Figure 2: Next generation turbine vane concept proposed in En-Core project

Test Preparation.

Material

Fabric is consisted of continuous fibres and structure called 3D woven fabric. Fibre type is Hi-nicalon type-S that manufactured by NGS Advanced Fibres Co, Ltd. SiC fibres are formed by chemical vapor infiltration (CVI) and fibre bundles are solidified with rare earth material by melt infiltration (MI) process.

Specimen

Dimension of representative specimen is shown in Figure 3. The holed type specimen was designed as simple plate with small hole which was manufactured by laser processing. The type of hole shapes is shown in figure 4. In mesoscopic, positional relationship between hole and fibre bundle is significant for mechanical property. In this study, hole location was adjusted to become the centre of fibre bundles.

In this study, smooth shaped specimens whose shape follows ASTM 1275 [8] without hole were prepared as reference data.

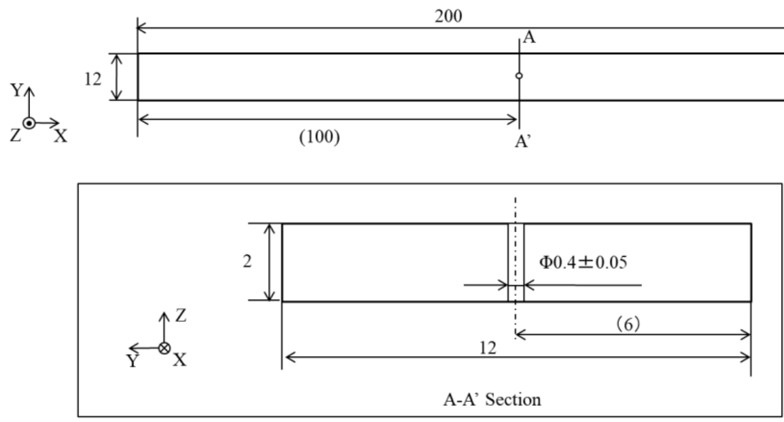


Figure 3: dimension of single hole test piece

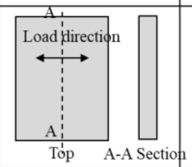
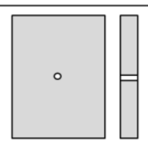
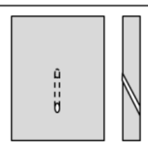
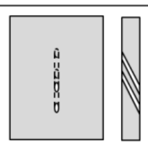
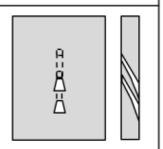
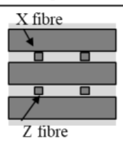
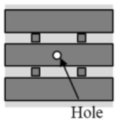
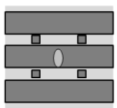
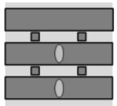
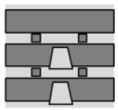
The number of holes	0	1	1	2	2
Projection hole shape	-	circle	ellipse	ellipse	trapezoid
Throat angle	—	90°	30°	30°	30°
Top and cross section view					
Meso-scopic structure					

Figure 4: Properties of all type of specimen

<u>Tests setup</u>

Test condition and measurement setup system are shown in figure 5. Stress survey tests were conducted to investigate structural analysis model before doing fatigue tests.

Low load was applied for deformation in room temperature during stress survey test, and the displacement and strains of specimen were measured with various measurement. Strains in smooth area were measured with strain gauge and extensometer. Displacement distribution around hole were measured with Digital Image Correlation (DIC). To verify displacement value analysed with DIC which was calculated as equation 1, displacements of smooth region were compared with extensometer and with FEM. The displacement around holed region were prepared for comparison with FEM.

Cyclic loading was applied in atmosphere at 1200 °C to investigate fatigue life in elevated temperature. Load was given by load control and target of load ratio was set to 0.1.

(a) Measurement system

Device	Mesurement
extensometer	displecement
DIC	displacement
gauge	strain
load cell	load value

(b) Test condition

Parameter	Test condition
air/vaper	air
temperature	strain survey: RT
	fatigue test: 1200°C
stress ratio	R=0.1
load control system	load control
cyclic shape	sine wave
frequency	1 Hz

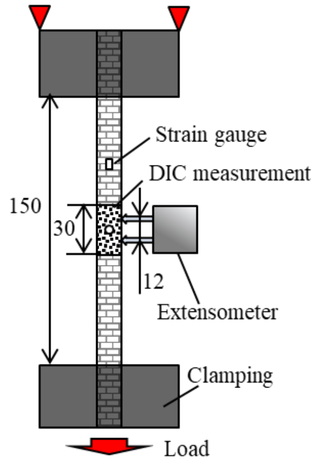


Figure 5: Measurement system and test condition

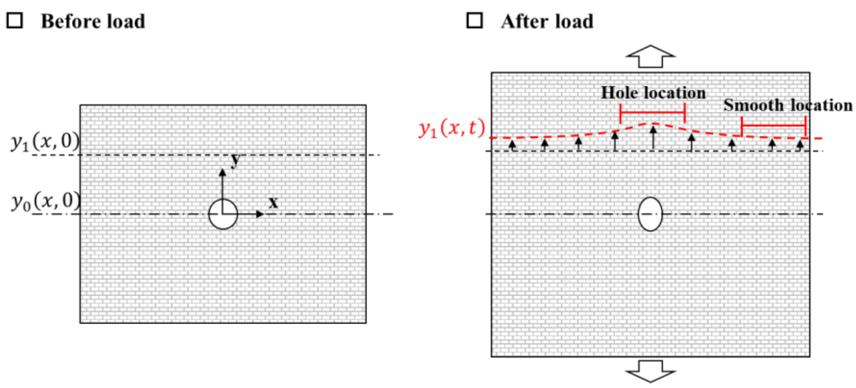


Figure 6: DIC measurement path

$$u_y(x,t) = y_1(x,t) - y_1(x,0) \quad (1)$$

Prediction model.

Stress prediction model

Structural analysis was conducted to predict stress distribution. CMC is assumed as continuum substance and elastic orthogonal anisotropic model. The material data was obtained by coupon tests which followed to ASTM1275 etc.

Normally, the shape of simulation model followed to nominal dimension except for diffuser holed type. The shape of diffuser hole was rearranged to follow to actual size, because manufactured hole size was over 10% larger than nominal. Stresses computed with this actual shaped model.

Life prediction model

Evaluated Stress for life calculation that are computed by averaging in a certain range of stress distribution field. This is applied for life prediction in order to take account the effect of stress distribution. The case of straight holed specimen was shown in figure 7. Section orientation is vertical toward the load direction. Size of section plane is equivalent to a CMC unit cell. Fracture prediction was judged by comparing the evaluated stress and failure strength obtained by S-N curve of smooth test without hole.

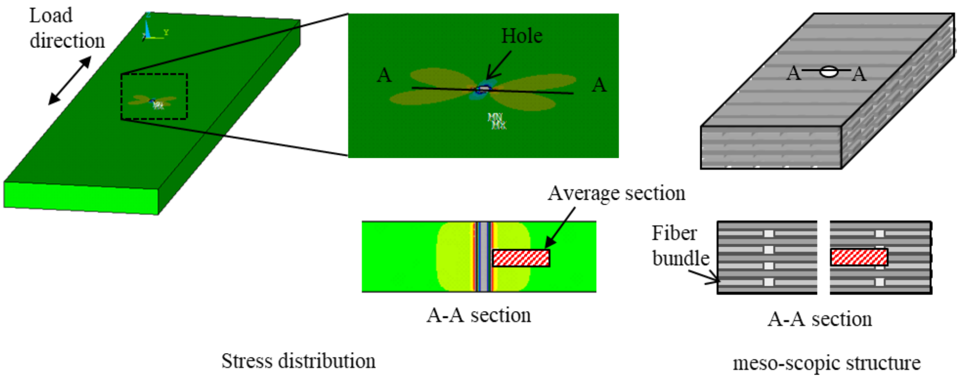


Figure 7: Section size and direction on the calculation for evaluation stress

TEST RESULT

Test result.

Stress survey test

Strains were measured by 3 instruments in stress survey test. Strain measured with gauge is shown in figure 8. Strain in measured with extensometer is shown in figure 9. In figure 8 and 9 diagram, strain analysed with FEM is drawn for comparison. Both measured strains show good agreement with FEM. This means the material input of analysis is proper in low load condition.

Figure 10 shows displacement value averaged along the line drawn from DIC analysis. Displacements were averaged in both of near side from maximum strain location and far side. All DIC displacement value against FEM shows the similar tendency that DIC displacement value on the hole location is higher than FEM, but smooth side DIC displacement value is close to FEM. Smooth side displacement of DIC corresponds to the value of extensometer. There would be a reason why DIC displacement showed higher value than FEM. Since the hole was located on the centre of fibre bundles, elastic modulus around hole as continuum material indicated lower value than FEM assumption.

It was challenging to measure strain fields in holed area because the analysis region was too small for verified measurement value in terms of image resolution and heterogeneous effect. Expandable optical equipment should be prepared, and the strain analysis should be proceed with using higher resolution images to gain more confidential measurement.

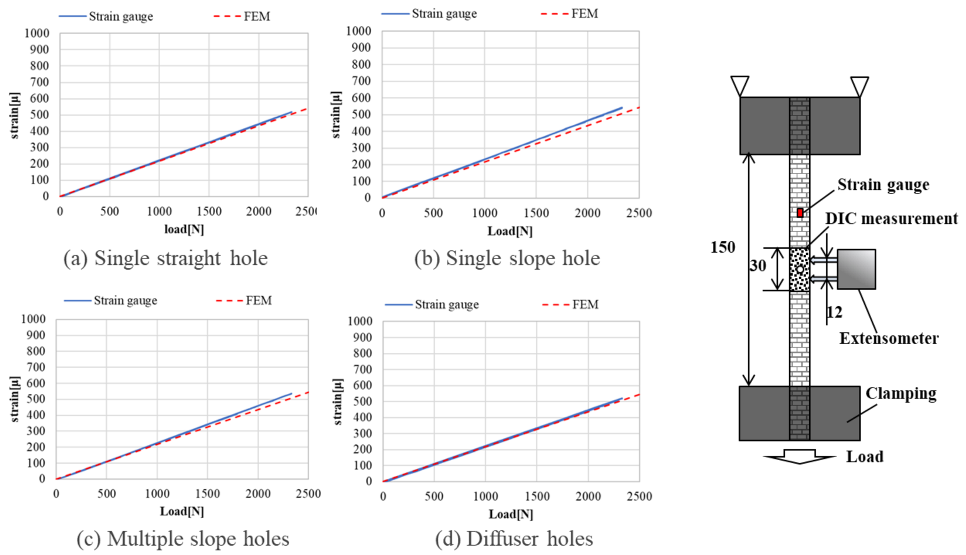
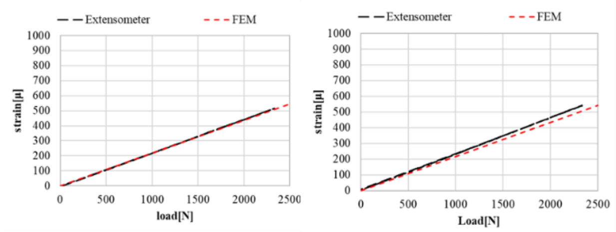
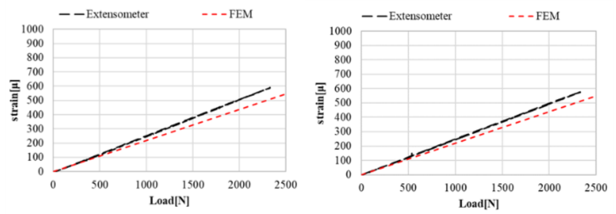


Figure 8: Displacement measurement with strain gauge



(a) Single straight hole (b) Single slope hole



(c) Multiple slope holes (d) Diffuser holes

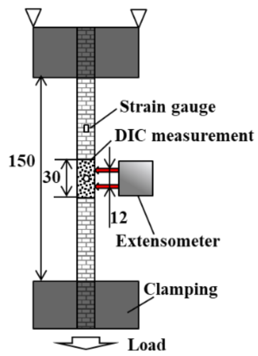
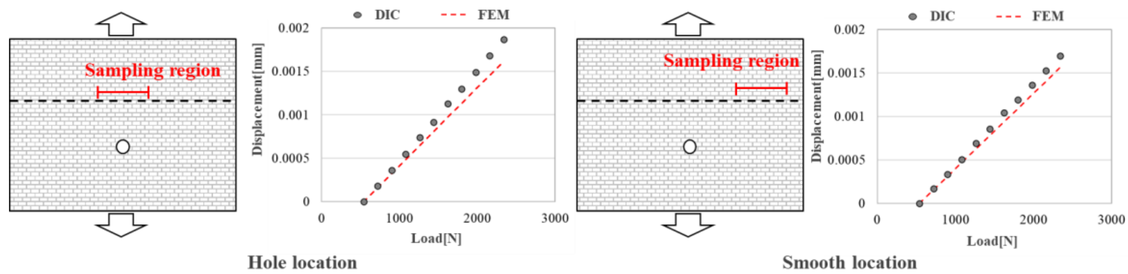
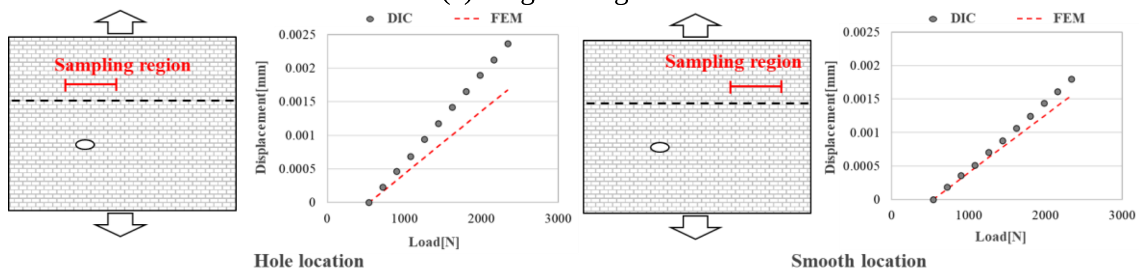


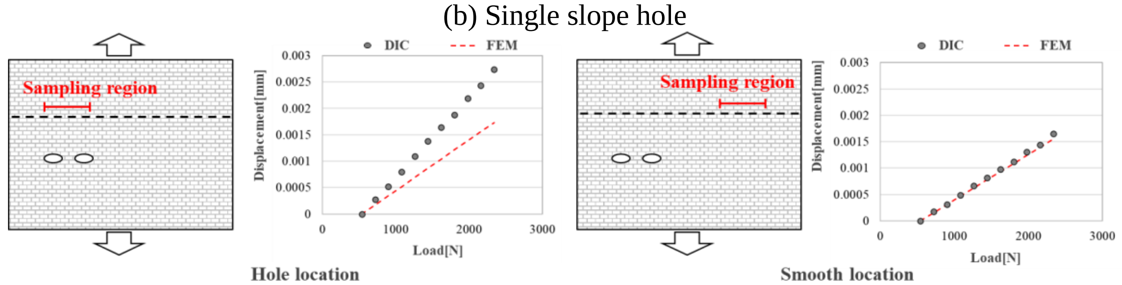
Figure 9: Displacement measurement with extensometer



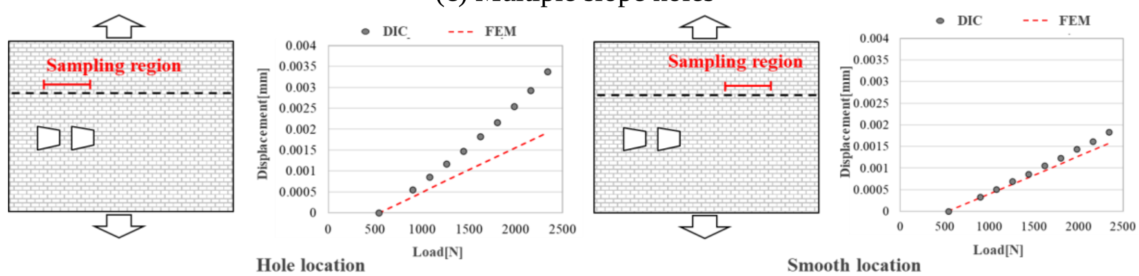
(a) Single straight hole



(b) Single slope hole



(c) Multiple slope holes



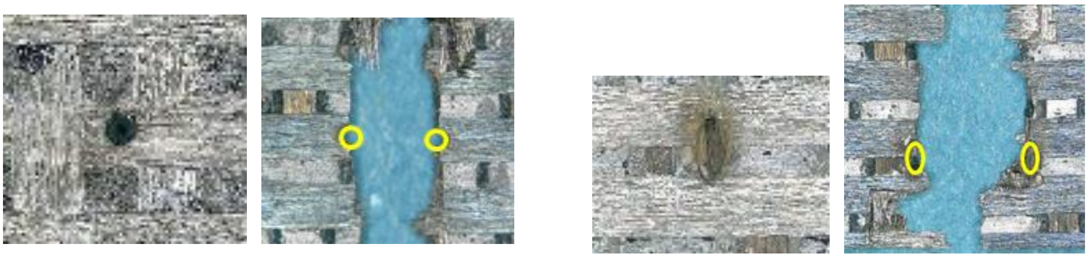
(d) Multiple diffuser holes

Figure 10: Local displacement measured with DIC

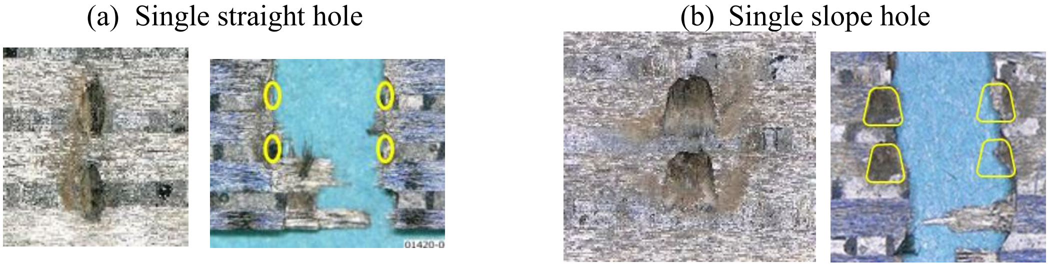
<u>Fatigue test</u>

Figure 11 shows the holed area of the specimen before and after the experiment. Fractured surface corresponds to cross section through the hole for all types of specimens.

Displacement history measured by extensometers are shown in the Figure 12. Displacements of single hole types show the exponentially increase as time advances, but those of multiple hole type was rising gradually. Failure timing of multiple holed specimens could be determined by the observation. One of the failure definitions is the timing of load drops. Compared load with displacement history diagram, load value was dropped after displacement rising which would imply the crack penetration between a series of holes. This crack penetration should be recognized as fatal to design engine parts. The timing of discontinuous displacement rising is one of the life definition. The difference of life definition is considered in the next paragraph.

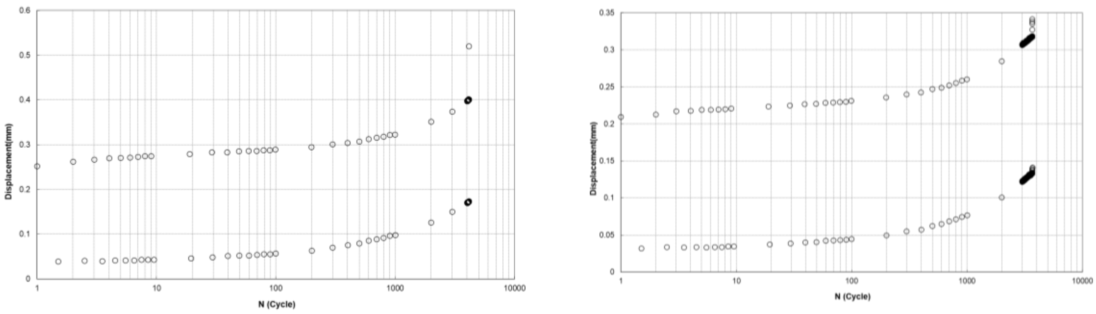


(a) Single straight hole (b) Single slope hole

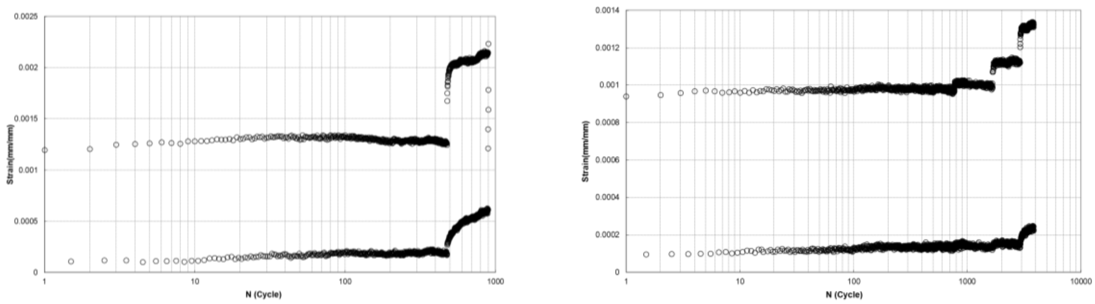


(c) Multiple slope holes (d) Multiple diffuser holes

Figure 11: Fracture pattern after fatigue test



(a) Single straight hole (b) Single slope hole



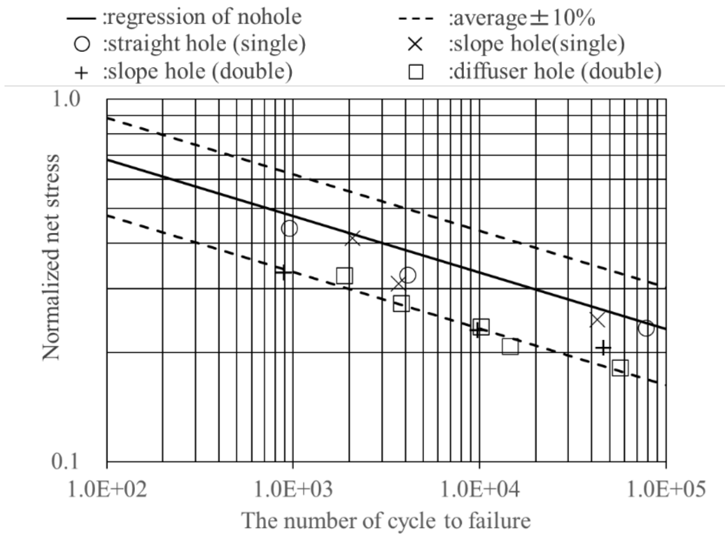
(c) Multiple slope holes (d) Multiple diffuser holes

Figure 12: Displacement history

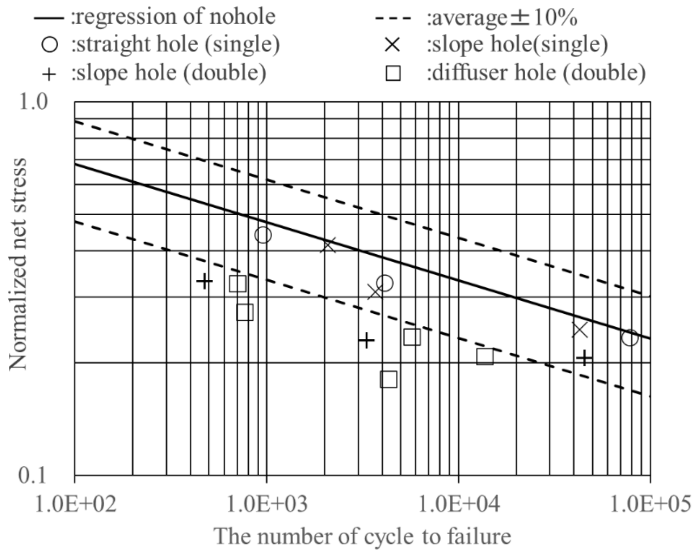
Consideration of life prediction model.

Figure 13 shows the result of life evaluation. Figure 13 (a) was predicted with use the net stress on the specimen's minimum cross section and life was defined as load drop cycle. Figure 13 (b) was redefined failure timing from (a). According to (b), multiple holed life was affected by this life reconsideration. multiple holed lives are predicted shorter than no hole regression and variation of plots were larger than (a) definition.

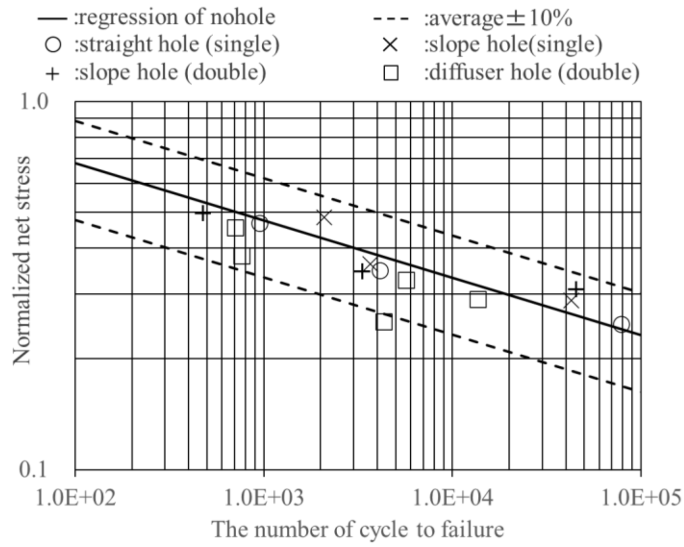
Figure 13 (c) was predicted by using the mean stress which was calculated to be averaged in the range of unit cell. Suppose to use (b) method, the strength of multiple holes (including slope and diffuser) was explained lower than no hole and single hole. On the other hand, lives of multiple holes predicted by (c) method were same within 20% of regression line of no hole specimen. When compared (b) with (c), (c) has potential to be applied to arbitrary sized parts because the stress gradient effect was taken into accounted in (b) method. Consequently, all specimen lives are predicted within a smooth curve as well as diffuser holes.



(a) Net stress – fracture life



(b) Net stress – discontious stiffness life



(c) Average stress – discontious stiffness life

Figure 13: S-N diagram corresponding to evaluation method

Conclusion.

In this study, 4 type of holed specimen were designed to survey the relationship between hole specification and their failure lives. Failure life was determined as timing of displacement jump at displacement history diagram. The failure lives of diffuser hole that had most practical shape, were not shorter than the other type of holes.

The damage processing mechanism was not clarified. Measurement and prediction of strain field around the hole was so complicated but understanding mechanism of this region is significant for verification of failure judgement. Higher resolution analysis and observation would be better to understand the mechanism of crack propagation for future work.

Acknowledgement.

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