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Fatigue life estimation by an indentation method for irradiated materials

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ABSTRACT: An indentation fatigue test method was developed to determine fatigue properties of irradiated materials. A hard steel ball or ceramic ball was used for cyclically loading the specimen, and an S-N curve was subsequently obtained. To represent true S-N relation by the curve, micro behavior in the specimen was compared with that in the axial fatigue test specimen. At hemisphere contact, it was observed that the persistent slip band accumulated near the surface as expected from the strain field density. S-N curves obtained the indentation method compared well with that common fatigue test.

Effect of the over load cycles in the reactor structure on the residual fatigue life was tested using non-irradiated material.

1 INTRODUCTION

Fatigue characteristics are of fundamental importance when choosing a structural materials, especially when deciding upon the materials for the reactor wall, where long-term safety is of primary importance. However, the fatigue properties of highly radiated wall materials have not been studied in detail. This is due to lack of appropriated fatigue testing method for the irradiated materials.

Gripping of the specimens in the fatigue test requires circumspection, and becomes a serious problem in the hot cell remote operation. Though the fatigue test specimen usually be lager than the other mechanical test specimen, dangerousness of secondary radiation is depend on the specimen size. The indentation method releases trouble in the gripping operation and also the specimen size.

Stress distribution in semisphere indentation was investigated. It is well known that the fatigue damage in metals initiates at the specimen surface. In the Hertz contact, point of maximum strain density locates inner part of the specimen just under the contact point. Therefore, cyclic loading in Hertz contact does not simulate the fatigue behaviour(Nunomura 1993).

Maximum strain density point locates on the contact surface in the semisphere indentation, then the cyclic indentation in semisphere contact may simulate the fatigue behaviour in metals. It has been proved by metallographical analysis. S-N curves obtained by this method agree well with those obtained from the rotary bend fatigue tests.

Residual fatigue life of an element received over load cycle is one of important matters in the reactor structure. Usually, overload damage is localized in a small area,

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*1 All research has been done at Precision and Intelligence Laboratory, Tokyo Institute of Technology, Nagatsuta, Yokohama, Japan then it was impossible to extract the proper specimen. The indentation fatigue test is applicable for this work, since it requires only 1mm cubic specimen. In this report materials tested were not irradiated due to the regulation by the law.

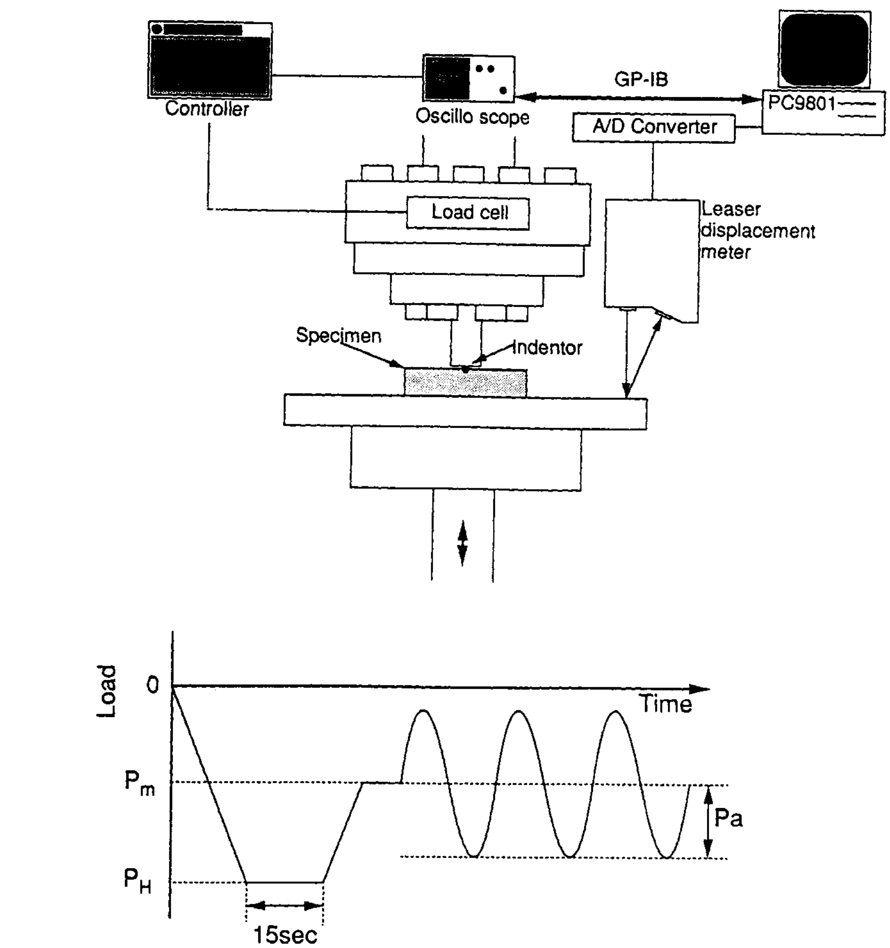

Fig.1 Flow diagram showing indentation fatigue testing

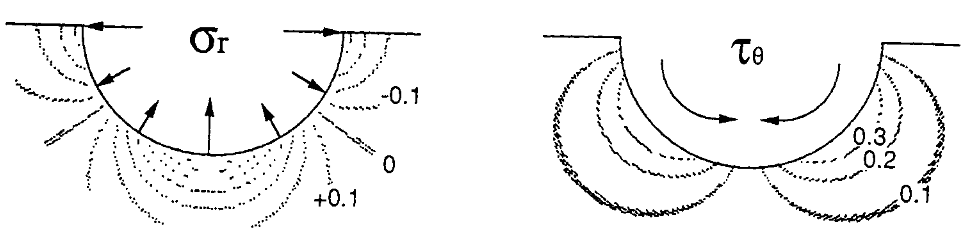

Fig.2 Blister field (mean contact pressure = -1.0)

2 EXPERIMENTAL PROCEDURE

A schematic diagram of the indentation fatigue system is shown in Figure 1. A hard ball is indented into the specimen surface that has previously been polished using 1 μ m diamond paste. The test procedure is as follows. Initially, a monotonous load, PH, is applied to the specimen surface so that the indentation depth equals the radius of the ball. The load is subsequently reduced to the mean load, P_m, and the cyclic load applied at an amplitude equals to P_a and R=0.1. The fatigue-testing machine adopted also was a servo-hydraulic fatigue-testing machine. The mean indentation displacement was monitored using a laser displacement meter (resolution 0.5 μ m).

Indentation fatigue test data of Sm58Q carbon steel, SUS316 stainless steel, S45C low carbon steel and a pure copper were reexamined using new stress field concept. Specimens damaged 0%,25%,50% and 100% by low cycle fatigue stainless steel were fatigue tested by the indentation method.

3 RESULT AND DISCUSSION

3.1 *Stress S of the S-N curve*

Repeated number to failure N of the S-N curves in the indentation fatigue test was illustrated in previous report(Nunomura 1993).

An applicable stress field, Blister field, was proposed by Lave(1920). To illustrate the cracking in brittle materials by penetration, Yoffe(1982) was superimposed this field on a point load stress field by Boussinesq(1885). The latter is negligible when materials to be ductile, then Blister field may represent the case of the indentation fatigue. Blister field represents a recovered elastic stress field in unloading. In Blister field, stresses, σ, and displacement, U, are as followings

$$p = P / \pi a^2$$

$$B = 0.06 p a^3$$

$$\sigma_r = 4B / r^3 \{(5 - \nu)\cos^2\theta - (2 - \nu)\}$$

$$\sigma_\theta = -2B / r^3 \{(1 - 2\nu)\cos^2\theta)\}$$

$$\sigma_\phi = 2B / r^3 \{(1 - 2\nu)(2 - 3\cos^2\theta)\}$$

$$\tau_{r\theta} = 4B / r^3 \{(1 + \nu)\sin\theta\cos\theta\}$$

$$U_r = B / Gr^2 \{(1 - 2\nu)\sin\theta\cos\theta\}$$

$$U_\theta = 2B / Gr^2 \{(1 - 2\nu)\sin\theta\cos\theta\}$$

where P is load removed, r and a are radii of ball and contact area respectively, θ is angle from the loading axis .

Radial and tangential stress fields illustrated in Figure 2. The radial stress altered from compression to tension on $\tau = \pi/4$ and the tangential stress is maximum on $\tau = \pi/4$. In semisphere contact a=r, then S in S-N curves is as followings

$$S = 2\tau_{\theta} = 0.24(1+\nu)p = cp$$

assuming the Poisson's ratio ν =0.3, the coefficient c becomes 0.312, while c=0.33 is used as an approximation value in previous report(Nunomura 1993).

3.2 *Metallographic analysis*

To prove above equations, cross section of the specimens interrupted the test at 0%, 15%, 25% and about 100% of fatigue life,N, were metallograpically observed(Fig.3). Persistent slip bands accumulated near the surface as expected from the strain field. Micro cracks were also observed in this region, which was only observed after a cycle number N as defined in previous report(Nunomura 1993).

3.3 *S-N curves*

Figure 4 shows the recalculate S-N curves. The solid lines in the figure represent the mean rotary bending fatigue S-N data, which abounded in quantity. Outlines of the plots in Figure 4 were also in agreement with the rotary bend S-N curves.

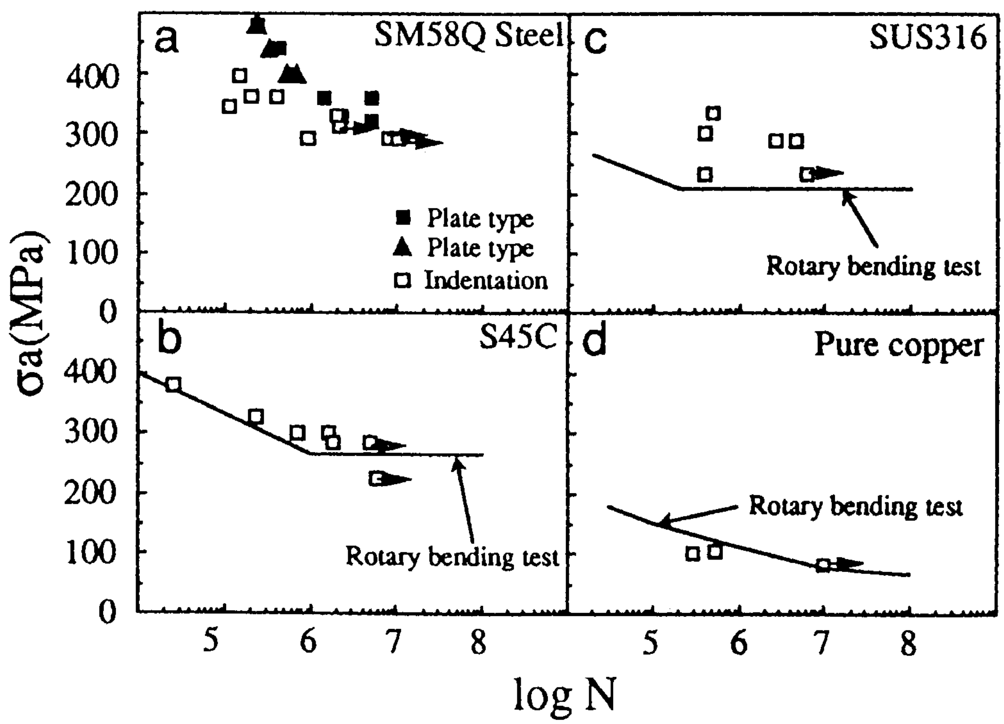

Fig.4 Indentation S-N data for (a)SM58Q steel, (b)S45C steel, (c)316L stainless steel and (d) Cu. Lines were rotary bend test results.

3.4 *Over load effect on residual fatigue life*

SUS316L stainless steel for the reactor structure was damaged by low cycle fatigue loading. The damage had localized in a narrow section, especially near 100% of the life. Figure 5 shows the displacement - number of cycles records. Residual life was extended in higher damaged specimen in the case of non irradiated steel. This is due to increase in yield stress as shown in figure 6. In the irradiated materials differ behaviour is expected because it should be more brittle and has lower strain hardenability.

4 CONCLUSION

Using cyclic indentation loading, a new fatigue test method for reactor structure materials was developed. Validity of Blister field for semisphere indentation was conformed experimentally. Effect of over load damage on residual life could be evaluated by this method. The life extension by the damaging was observed. It seems to be caused on increasing in yield strength of the metal.

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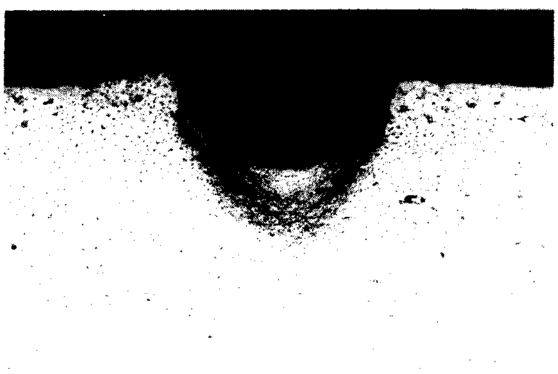

← 0.15 N_f

≒ N_f

↓

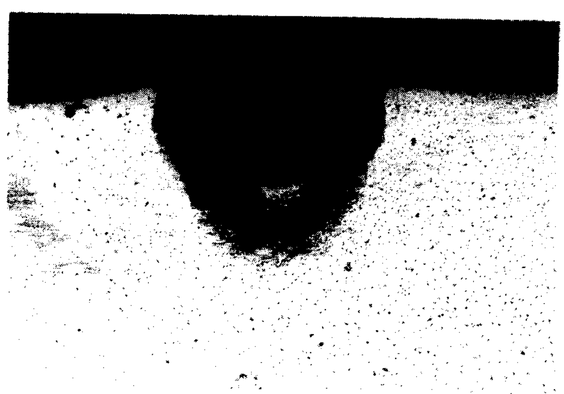

Fig.3 Persistent slip bands

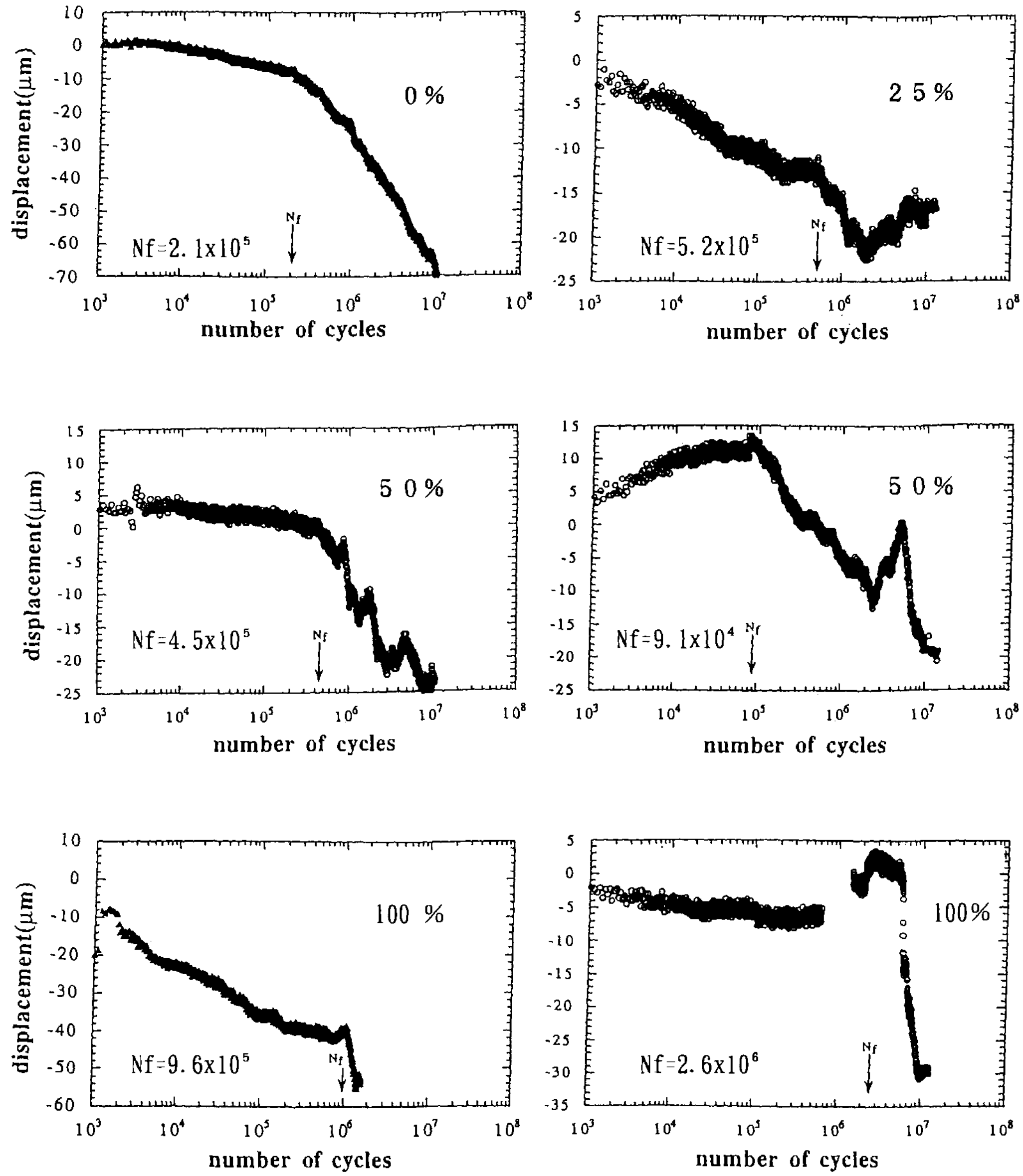

Fig. 6 Mean displacement - repeated number records in the indentation fatigue test of low cycle fatigue damaged stainless steel

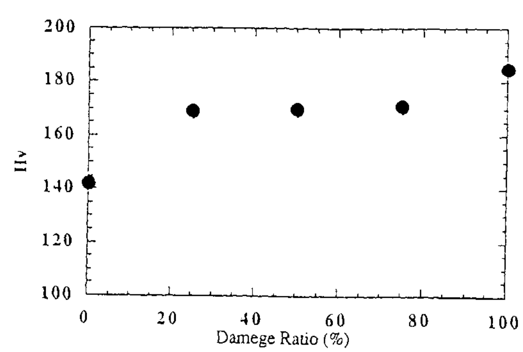

Fig. 7 The yield strength increased with increasing damage.