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EFFECT OF SHOT-PEENING ON SURFACE CRACK PROPAGATION IN PLANE-BENDING FATIGUE

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ABSTRACT

In most cases, fatigue failure of structures starts from the surface of materials and propagates into the inside. Therefore, various surface treatment processes accompanied with compressive residual stress are adopted to improve the mechanical characteristics of surface layer. Understanding fatigue surface crack propagation is essential to investigate the fatigue characteristics of surface strengthened materials. About the effect of residual stresses on the through-thickness crack propagation, it has been shown that the decrease of growth rate by compressive residual stresses and the increase by tensile residual stresses in welding, induction hardening, quenching and tempering, shot-peening [1] and cold working. It is also recognized that the crack growth rate in the specimens with residual stresses can be correlated with that in the ones without residual stress in terms of the effective stress intensity based on the crack closure. Meanwhile in the case of semi-elliptical surface crack propagation, Kawahara [2] suggested that the direct application of Paris formula using numerical solutions of stress intensity factor had not much advantages in precision nor in simplification of analyses.

This report presents the effect of compressive residual stresses after shot-peening on the surface crack growth and on the crack opening behavior along semi-elliptical crack front which is estimated under the assumption that the data for the crack growth rate at local crack front should obey Paris law.

KEYWORDS

Shot-peening, fatigue, crack propagation, residual stresses, Paris Law.

EXPERIMENTAL PROCEDURE

The testing material was medium carbon steel S45C annealed at 810°C for 20 min. Mechanical properties are shown in Table 1. The specimens tested had the thickness of 2.46 mm and a small hole notch in the center of upper surface as shown in Fig. 1. Specimens were of two kinds: (1) unpeened specimens which were tempered at 650°C for 1 hr after drilling the hole notch, (2) shot-peened specimens which were notched after smoothening the surface roughness due to shot-peening. Shot-peening conditions are shown in Table 2.

TABLE 1 Mechanical properties

Mechanical Properties (S45C)

σ_S (MPa)	σ_B (MPa)	δ (%)	ϕ (%)	H_v
346	581	31	36	210

[Heat Treatment 810 °C, 20min., A]

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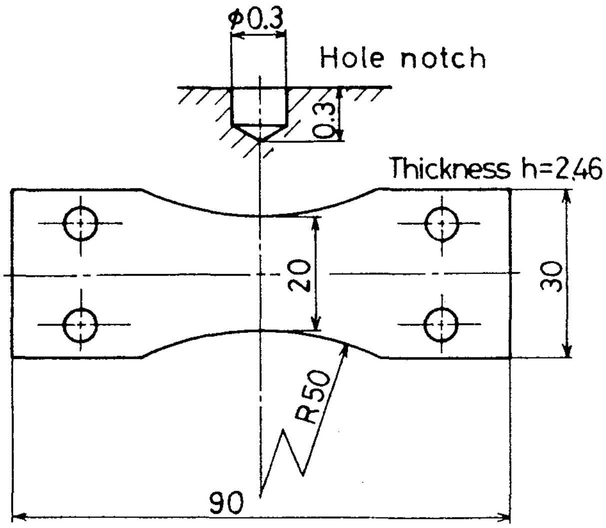

Fig. 1 Specimen configuration

A fully reversed bending load was produced by a Schenck type bending fatigue machine. The half crack length b at the surface was measured by replicating method using a microscope with X50 magnification. The crack shape evolution behavior was observed by temper color technique.

The residual stress distribution in the direction of the depth was measured by the successive chemical polishing method using 20% nitric acid. Changes of surface residual stress in the axial direction were measured during the fatigue process by the 0°-45° X-ray method, using Cr anode.

TABLE 2 Shot-peening conditions

Shot-peening Conditions

Shot-size	φ0.6 cut wire
Wheel speed	78.5 (m/sec)
Flow rate of shot	35 (Kg/min)
Intensity (Arc height)	0.3 (mm)
Coverage	≒100 (%)

The crack closure behavior was observed by the elastic compliance method [3]. The crack opening level α_{op} was determined on the diagram representing the relationship between the maximum bending stress and the output of a strain gauge located on the central point of the bottom surface.

$$\text{Crack opening ratio: } U = (\sigma_{max} - \sigma_{op})/(\sigma_{max} - \sigma_{min}) \quad (1)$$

$$K_{eff} = U \cdot \Delta K \quad (2)$$

ΔK at an arbitrary point on a semi-elliptical crack front was calculated by Newman-Raju's equations [4], in which tensile stress component was calculated from the shifting of neutral plane accompanied with the surface crack growth.

RESULT AND ANALYSIS OF THE TESTING

The micro-Vickers hardness (load: 200 gf) of shot-peened surface was 320, which was 110 higher than that of the unpeened one. Figure 2 shows the residual stress pattern. The residual stress in the equi-biaxial stress condition showed the maximum value just below the surface, as often seen in the case of centrifugal type machine, and a constant tensile stress in the central part of the specimen. The compressive residual stresses at the surface went down to the half of the initial value until 10^4 cycles under the stress amplitude ranging from 83% to 110% of the yielding stress, after that small decrease followed, and dropped rapidly before final failure (Fig. 3).

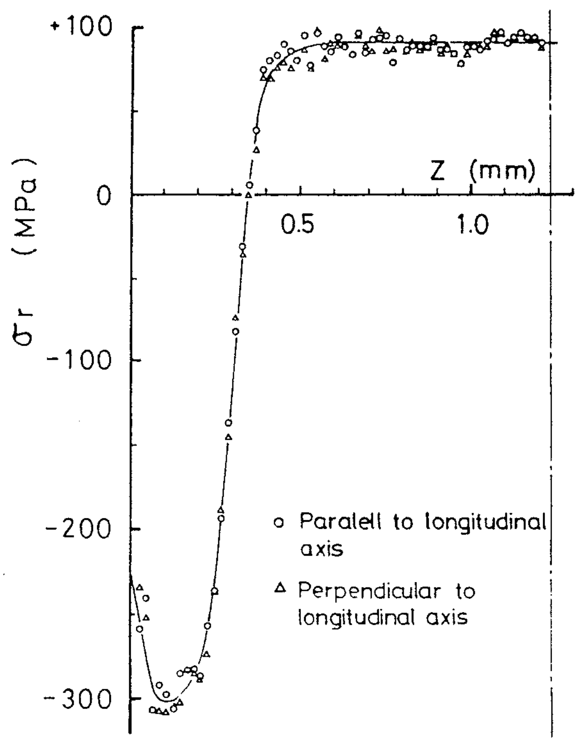

Fig. 2 Residual stress pattern

The crack initiation at the edge of hole notch was observed early when the cyclic ratio n/N_f was about 0.1 both in the unpeened and shot-peened specimens, then crack propagation period occupied a substantial part of the total life. The

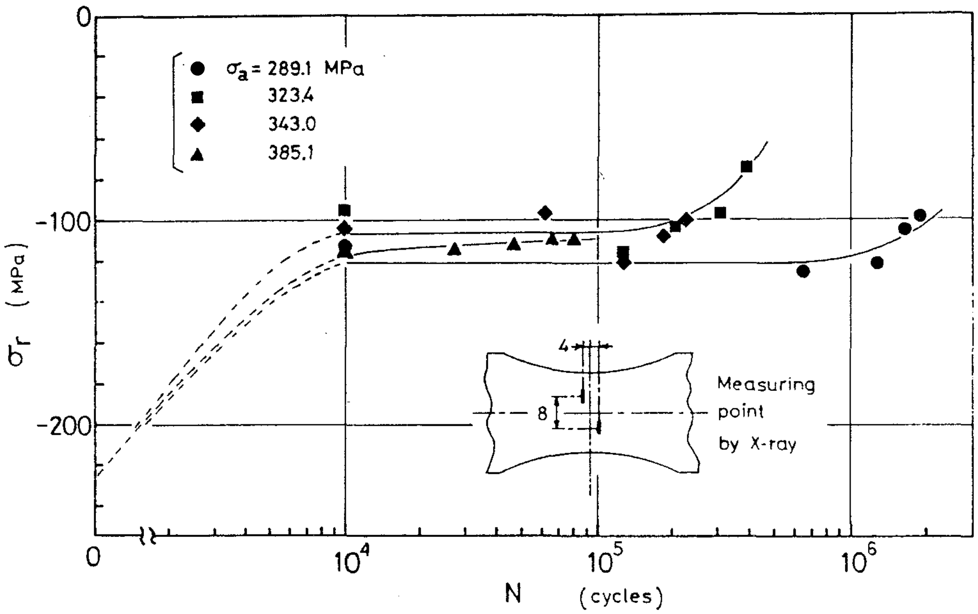

Fig. 3 Change of residual stress due to stress cycles

crack shape evolution diagram (Fig. 4) shows that the crack shape evolution does not depend on stress amplitude and residual stress and work hardening after shot-peening. The relationship between the crack length b and the crack depth a can be established by least square method, as in the case of short and deep initial flaw, as follows,

$$a = \sqrt{Ahb} \tag{3}$$

where experimental constant A = 0.169.

From equation (3)

$$da/dN = \frac{1}{2} \quad \frac{A\ h}{b} \cdot (db/dN). \tag{4}$$

Besides, the crack opening ratio U was expressed approximately as follows,

$$U = 0.6 + 0.027\ b \ : \text{Unpeened}, \ : \ U = 0.56 \quad \text{Shot-peened} \tag{5}$$

An analysis of the geometry of Fig. 5 gives the local crack growth distance dl, then dl/dN is calculated by using the data of N - b relations and equation (3). Figure 6 shows the relations between local crack growth rate dl/dN and K_{eff}, which cannot be treated by Paris formula. The through-thickness crack growth rate in axial loading test was $dl/dN = 3.12 \times 10^{-8}\ (K_{eff})^{2.77}$, two-dot chain line as seen in Fig. 6. The growth rate in shot-peened specimens was lower than that in unpeened ones both in the direction of the width and the depth, and nearly equal to that when b was longer than about 3 mm.

The crack opening ratio along semi-elliptical crack front for unpeened and shot-peened specimens was estimated by comparing the Newman-Raju's K_{eff} with the K_{eff} on the solid line in Fig. 6 corresponding to the same growth rate for each stress amplitude (Fig. 7). The changing behavior of estimated U with the depth from surface did not depend on the length of crack b, and the difference of U

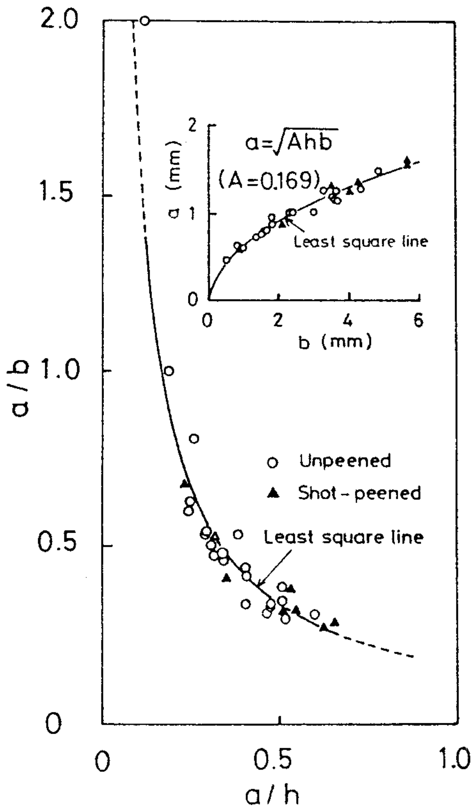

Fig. 4 Crack shape evolution diagram

between at the surface and the maximum depth point was about 0.3 for unpeened ones and 0.2 for shot-peened ones, when b was about 3 mm. It is clearly recognized that the compressive residual stress in the surface layer decreases the crack opening ratio, sharply when the stress amplitude is low.

The results obtained in this study suggest that the surface crack opens gradually from the surface to the inside with the increase of bending stress (Fig. 8), and based on this model the application of Paris formula has much advantages in surface crack propagation analyses.

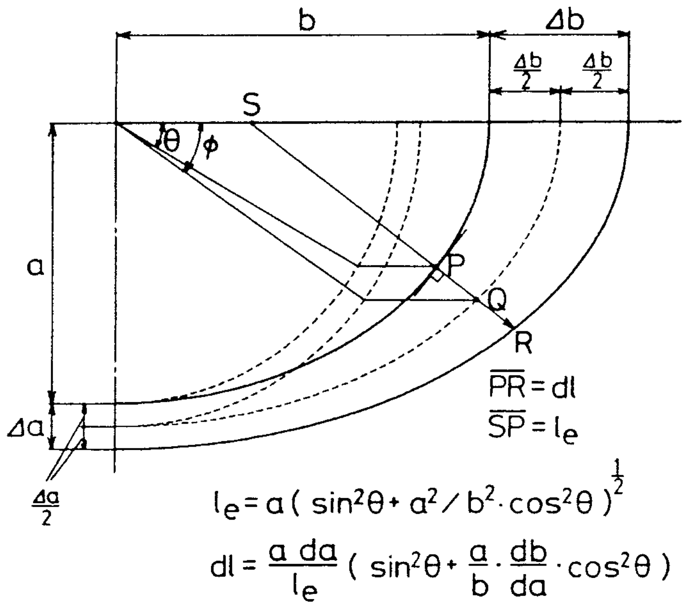

Fig. 5 A semi-elliptical crack extends into another semi-elliptical crack

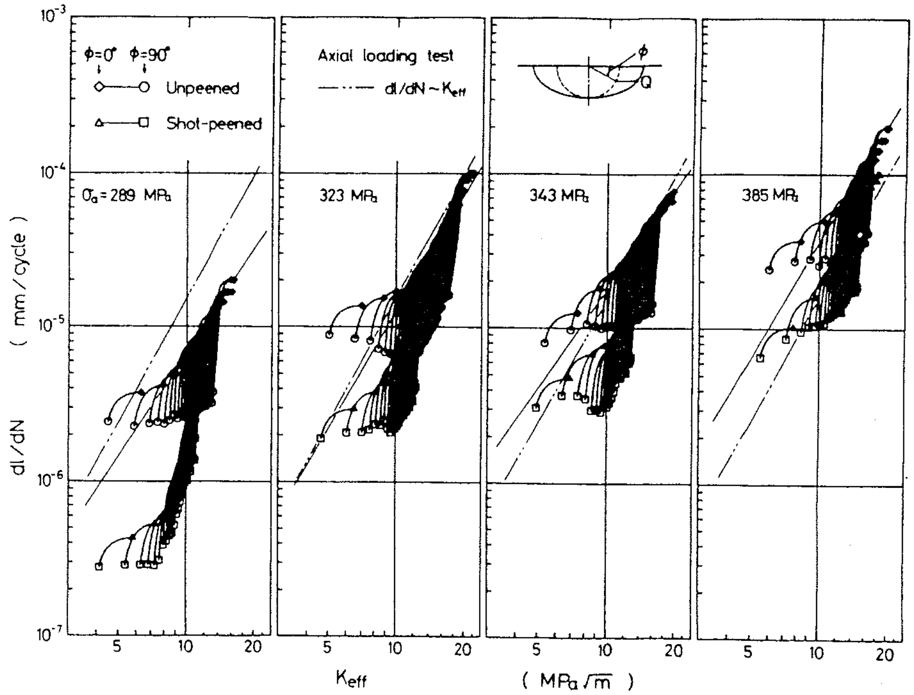

Fig. 6 Crack growth rate dl/dN at arbitrary points on elliptical crack front vs K_{eff} of unpeened and shot-peened specimens

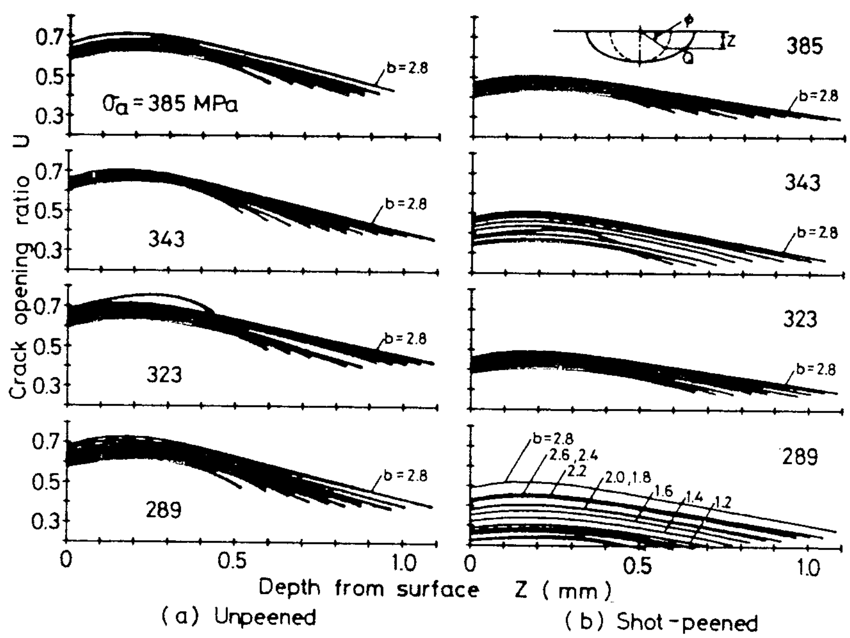

Fig. 7 Estimated crack opening ratio along semi-elliptical cracks

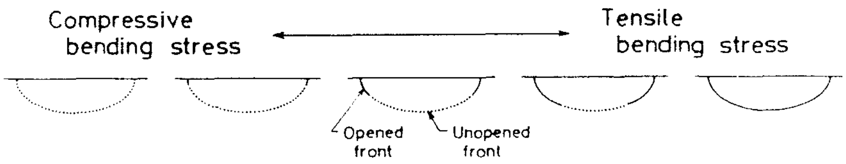

Fig. 8 Schematic of surface crack opening behavior under plane bending

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