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Deceleration of small crack growth by shot-peening

Ralentissement de la croissance de petites fissures par 'shot peening'

Verlangsamung des Wachstums kleiner Risse durch Oberflächenkugelstrahlen

ショットピーニングによって生じる小亀裂伝幡の減速

Masaaki Misumi and Masafumi Ohkubo
Department of Mechanical Engineering, Seikei University
Kichijoji Kitamachi 3, Musashinoshi, Tokyo, Japan

Abstract: The effect of shot-peening on surface crack growth behaviour was observed in a mild carbon steel specimen with a relatively large hole notch under rotating bending stresses. A new damage curve based on crack propagation was proposed by quantifying fatigue damage by surface crack area. This damage function can follow crack growth behaviour well even in a surface treated specimen in which crack growth rate is affected strongly in the early stage of fatigue, and shows that the fatigue damage accumulation process can be expressed by a compound Weibull function. Compressive residual stress in thin work-hardened surface layer decreased crack growth rate only when the crack was small, and the crack grew faster than in unpeened specimens after crack length reached some extent. Shot-peening definitely increased both crack initiation and propagation period much more under lower stress level.

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Key words: Fracture mechanics, surface crack growth, shot-peening, carbon steel, damage analysis, fatigue damage, Weibull function, residual stresses.

Résumé: L'effet du 'shot peening' sur le comportement de la croissance de fissures en surface a été observé sur des spécimens d'acier de construction de carbone avec une rainure perforée relativement grosse sous pliage rotataf. Une nouvelle courbe de dommage basée sur la propagation de la fissure a été proposée à l'aide de la quantification du dommage en fatigue à la suite de la surface superficielle de la fissure. Pour cette fonction de dommage on peut décrire le comportement de la croissance de la fissure même sur des spécimens traités en surface dans lesquels la vitesse de croissance de la fissure durant l'étape initiale de fatigue se trouve influencée et on démontre aussi que le procédé de cumulation de dommages par fatigue peut être exprimé à l'aide d'une fonction de combinaison Weibull. La tension de pression résiduelle dans la fine couche superficielle, moulée à froid, ne réduit la vitesse de croissance de la fissure que tant que la fissure est petite. Pour celles plus longues, la fissure croft plus vite que dans le spécimen sans 'shot peening'. Le 'shot peening' agit définitivement sur l'augmentation de la phase initiale de la fissure permettant d'enregistrer un effet plus fort lors d'un niveau de tension plus faible.

Mots-clés. Mécanique de la rupture, croissance de la fissure en surface, shot-peening, acier de construction, analyse de dommages, dommages de fatigue, fonction Weibull, tensions propres.

Zusammenfassung. Die Wirkung des Kugelstrahlens auf das Wachstumsverhalten von Oberflächenrissen wurde in Kohlenstoffbaustahlproben mit einer relativ großen Lochkerbe unter Unlaufbiegung beobachtet. Eine rißausbreitungsbezogene neue Schadenskurve wurde durch Quantifizierung der Ermüdungsschädigung zufolge der Oberflächenrißfläche vorgeschlagen. Durch diese Schadenfunktion läßt sich das Rißwachstumsverhalten sogar in oberflächenbehandelten Proben, in welchen die Rißwachstrumsgeschwindigkeit in der Frühphase der Ermüdung beeinflußt wird, beschreiben und sie zeigt auch, daß der Ermüdungsschadensakkumulationsprozeß durch eine Kombinations-Weibull-Funktion ausgedrückt werden kann. Die residuale Druckspannung in der dünnen kaltverformten Oberflächenschicht reduzierte die Rißwachstumsgeschwindigkeit nur solange der Riß klein war. Für größere Rißlängen wuchs der Riß schneller als in der unbestrahlten Probe. Das Kugelstrahlen bewirkte definitiv sowohl eine Verlängerung der Rißinitiations-phase, wobei sich ein stärkerer Effekt bei niedrigerem Spannungsniveau ergab.

Sachwörter. Bruchmechanik, Oberflächenrißwachstum, Kugelstrahlen, Baustahl, Schadensanalyse, Ermüdungsschaden, Weibull-Funktion, Eigenspannungen.

要約。比較的大きな切欠き穴をもつ軟炭鋼の試験片に回転曲げ応力を加え，ショットピーニングが表面亀裂の拡がりに対して与える影響を観察した。亀裂伝播に基づく損傷曲線は，表面亀裂部分の疲労損傷を定量化することによって得られた。この損傷曲線の利点は，初期段階の疲労によって大きく左右される表面処理済み試験片の亀裂伝播をも正しく傾わせる点にある。疲労損傷の蓄積過程は合成ワイブル関数で示される。

加工硬化された薄い表面層における圧縮残留応力が亀裂伝播をくいとめるのは，亀裂が少ない場合においてのみであり，亀裂が一定の大きさに達した後は，ショットピーニングされていない試験片よりも速く拡がるようになる。低い応力レベルにおいて，ショットピーニングによって亀裂の開始と伝播が増大することが判明した。

キーワード。破損プロセス，表面亀裂の伝播，ショットピーニング，炭素鋼，損傷分析，疲労損傷，ワイブル関数，残留応力。

Introduction

he fatigue life of a structure with a strengthened or degraded surface layer is ›minated by small surface crack behaviour. Changes of mechanical characteristics ıd residual stress associated with it have a complex influence on crack initiation and opagation. Therefore, understanding surface crack behaviour is essential to assessent of the fatigue life of surface treated materials.

Damage is something irreversibly accumulated in materials. Many studies have tried to make clear the concrete relations between damage and physical properties (Fong, 1982). The idea that damage corresponds to crack behaviour was shown about thirty years ago (Yokobori, 1953), and recently, the number of cracks (Kitagawa *et al.*, 1983), the crack length at the surface (Ibrahim and Miller, 1980; Hua and Socie, 1984), crack depth (Hua and Socie, 1984) and crack density (Hua and Socie, 1984) were considered as a measure of fatigue damage. The fatigue damage process has been treated successively by dividing it into two phases (Ibrahim and Miller, 1980; Manson and Freche, 1967), but the correlation between damage and crack behaviour has not been clarified yet.

In this study, the fatigue damage curve corresponded to crack behaviour and the effect of shot-peening on it were investigated.

2 Fatigue damage based on crack propagation

Newmark (1952) and Marco and Starkey (1954) proposed the simple form for fatigue damage.

$$D(x) = x^m, \quad \text{where} \quad x = n/N_f \quad \text{and} \quad m = f(\sigma_a) \tag{1}$$

Under two-level stress loading the following equation is got by using equation (1) if there is no interaction of the first level with the second

$$\left(\frac{n_1}{N_1}\right)^{m_1/m_2} + \left(\frac{n_2}{N_2}\right) = 1 \tag{2}$$

Hashin and Laird (1980) suggested that the power m was in inverse proportion to $(\sigma_a - \sigma_w)$ under the condition that the S–N curve is straight in semi-log space.

We recognized that equation (2) was got also from the following function

$$D(x) = D_0^{(1-x^m)} \tag{3}$$

where D_0 is initial damage which is decided by crack origin flaw size. Equation (3) satisfies the following criteria

$$D(0) = D_0 \quad D(1) = 1 \tag{4}$$

It would be recognized that the differences between equation (3) and other damage models (Newmark, 1952; Chaboche, 1979; Lemaitre and Plumtree, 1979; Fong, 1982) as shown in Figures 1 and 2(a), are the existence of initial damage and initial growth rate ranging from zero to infinity.

$[\mathrm{d}D/\mathrm{d}x]_{x=0} = \infty$ for $m < 1$

: short crack and non-propagating crack behaviour.

$[\mathrm{d}D/\mathrm{d}x]_{x=0} = 0$ for $m > 1$

: threshold behaviour of long crack (threshold value is decided by the flaw size from which the crack initiates).

The more general form of equation (3) is got by introducing the crack initiation cycle ratio x_i and coefficient B

Figure 1 Comparison of four damage models

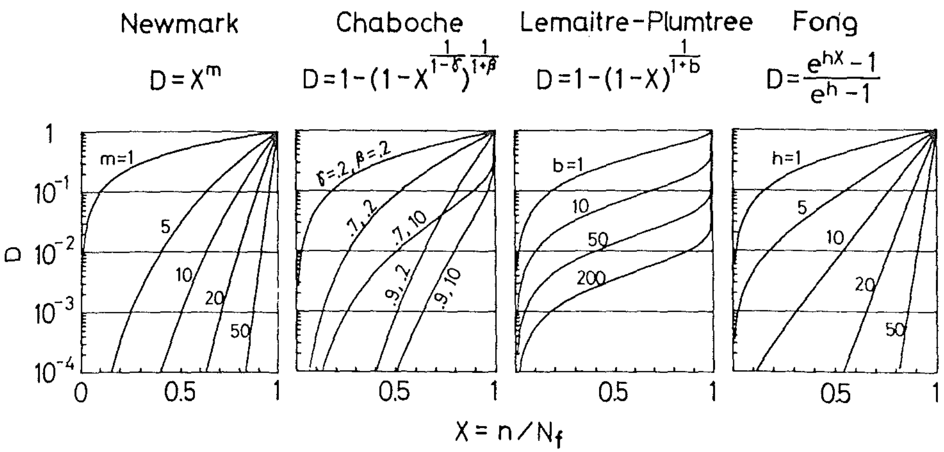
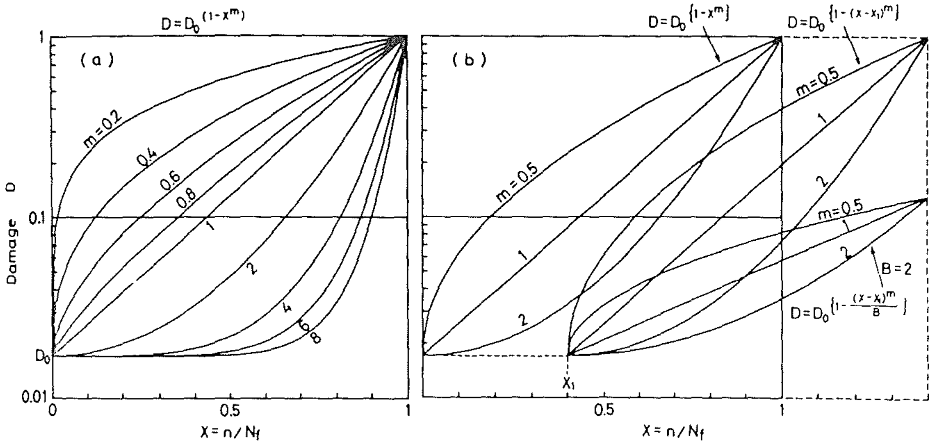


Figure 2 (a) Damage curves expressed by equation (3). (b) Parallel shift and rotation of equation (3) by introduction of x_1 and B



$$D(x) = D_0\left\{1 - \frac{(x-x_1)^m}{B}\right\} \tag{5}$$

igure 2(b) shows that x_1 shifts equation (3) in parallel and B rotates around the point x_1, D_0), clockwise when B is larger than unity, counterclockwise when smaller than nity.

In this study, fatigue damage was quantified by cracked area A, because crack ngth at the surface is not proportional to cracked area

$$D = A/A_f \quad ; \quad D_0 = A_0/A_f \tag{6}$$

quations (5) and (6) give the crack area growth equation.

$$A = A_0 D_0^{-\frac{(x-x_1)^m}{B}} \tag{7}$$

A_0 is initial projective area of notch or flaw and A_f is cracked area at final fracture.

Equation (7) becomes

$$\left(1-\frac{A_0}{A}\right)=1-e^{-\left(\frac{x-x_1}{\beta}\right)^m}, \quad \text{where } \beta=\left(-\frac{B}{\ln D_0}\right)^{1/m} \tag{8}$$

Equation (8) is identical with the Weibull distribution function with three parameters, that is, fatigue crack growth process can be expressed by the Weibull function.

It is interesting that $(1-A_0/A)$ obeys the Weibull function: fatigue crack grows under the domination of initial flaw size.

The three parameters in equation (8) represent the following crack growth characteristics.

Shape parameter m: exactly follows shape factor of crack propagation curve itself (the crack begins to grow slowly in the early stage and rapidly in the later stage when m is larger than unity, and the contrary situation applies when m is smaller than unity).

Location parameter x_1: crack initiation.

Scale parameter β: representation factor of crack propagation (the repression effect against crack growth becomes strong with increase of β).

3 Experimental procedure

The material tested was mild carbon steel. Chemical compositions and mechanical properties are shown in Tables 1 and 2. Figure 3 shows specimen configuration.

Unpeened specimens underwent 650°C stress relief treatment for 90 minutes in a vaccum followed by cooling in a furnace after drilling a hole notch.

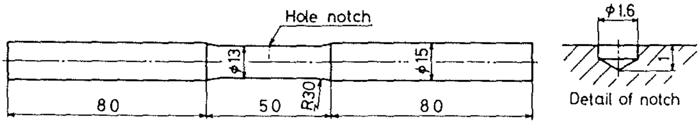
Table 1 Chemical compositions

C	*Si*	*Mn*	*P*	*S*
0.19	0.23	0.51	0.022	0.018

Table 2 Mechanical properties

Yield stress (MPa)	*Tensile strength (MPa)*	*Elongation (%)*	*Reduction of area (%)*
352	520	26	57

Figure 3 Specimen configuration



Shot-peened specimens were polished by emery paper to make crack length measurement possible. The bottom of the hole notch was not peened by using an epoxy resin filler which was removed after peening. Shot-peening conditions are shown in Table 3.

Table 3 Shot-peening conditions

Shot material	Steel wire B (JIS)
Shot size	ϕ0.6 × 0.6 cut wire
Shot velocity	47–50 (m/sec)
Flow rate of shot	30 (kg/min)
Peening time	60 (min)

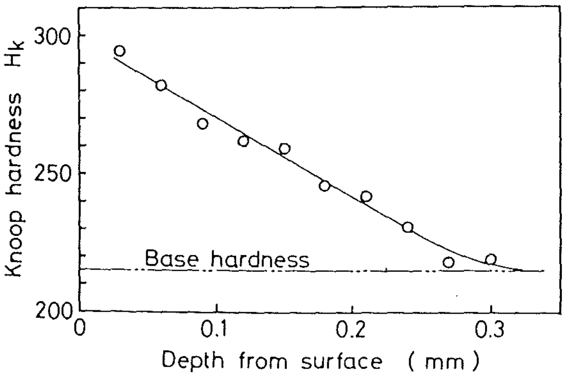
The arc length of the crack at the surface was measured by a replicating method to an accuracy of 0.01 mm by a microscope. Evolution behaviour of the surface crack was observed by a temper colour technique. Initial residual stress was measured by the 0°45° X-ray method using Cr anode.

Specimens were fatigued by rotating bending under 2840 rpm.

4 Results and discussion

The depth of surface layer hardened by shot-peening was about 0.3 mm (Figure 4), and the compressive residual stress at the surface was about 390 MPa. Endurance

Figure 4 Hardness distribution



limits were 148 MPa and 185 MPa, so 37 MPa was the increase by shot-peening. Fatigue life also increased, but not so much, as seen in Figure 5.

Figure 5 Number of cycles at failure N_f

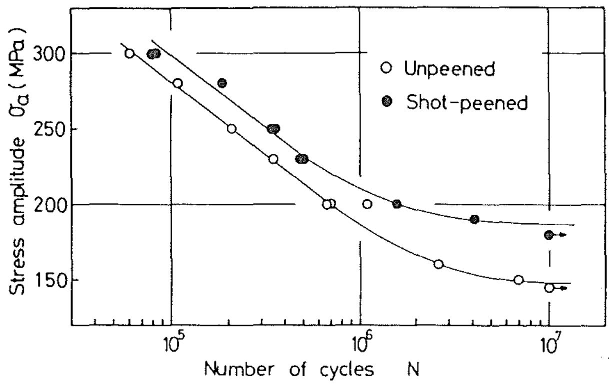
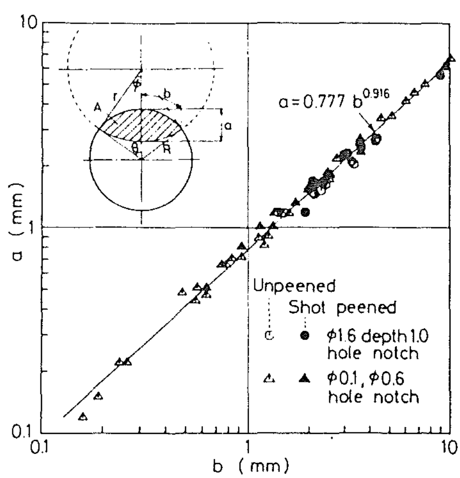


Figure 6 includes the data concerned with different hole notch sizes (Misumi and Ohkubo, 1985) and shows the shape evolution of the surface crack. Influence of hole notch size and shot-peening on the shape of crack front was not found. The curve of the crack front could be approximated to a part of circle.

Figure 6 Maximum crack depth versus half-arc crack length at surface



The relation between crack depth a and half-arc length at surface b was as follows

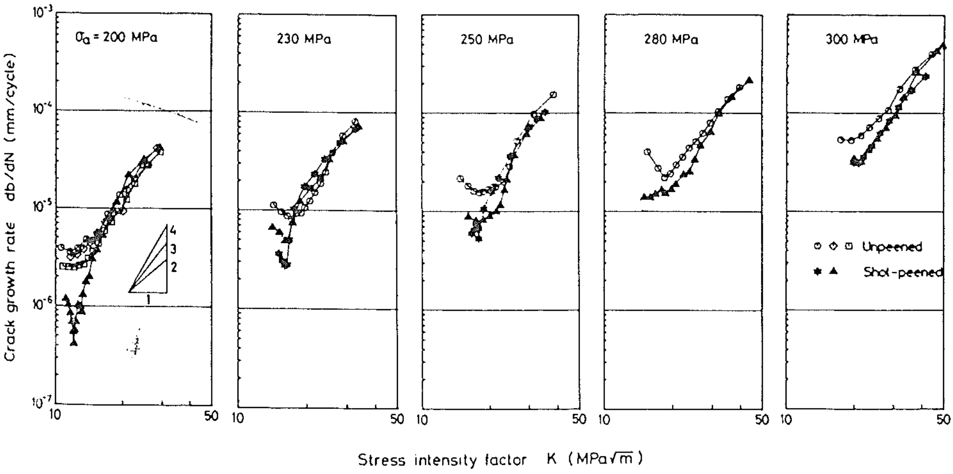
$$a = 0.777\,b^{0.916} \tag{9}$$

Figure 7 shows an example of temper coloured crack surface. Cracked area A was geometrically calculated using equation (9).

Figure 7 Temper coloured crack surface of a shot-peened specimen

Figure 8 shows that the data of crack growth rate do not obey Paris law. Crack growth rate was calculated by differentiation of cubic equation which smoothed a part of the crack growth curve using each of five experimental points.

Figure 8 Effect of shot-peening on crack growth rate



The growth rate in a shot-peened specimen was lower than in an unpeened one when the crack depth was smaller than about 1.3 mm, and a little bit higher beyond the depth. In the case of $\sigma_a \geqslant 280$ MPa, the decrease of growth rate by shot-peening was kept for a deeper depth.

Non-LEFM behaviour at notch clearly appeared in shot-peening specimens under $\sigma_a = 200$ MPa.

Stress intensity factor due to compressive residual stress at the deepest point can be estimated by the following equation

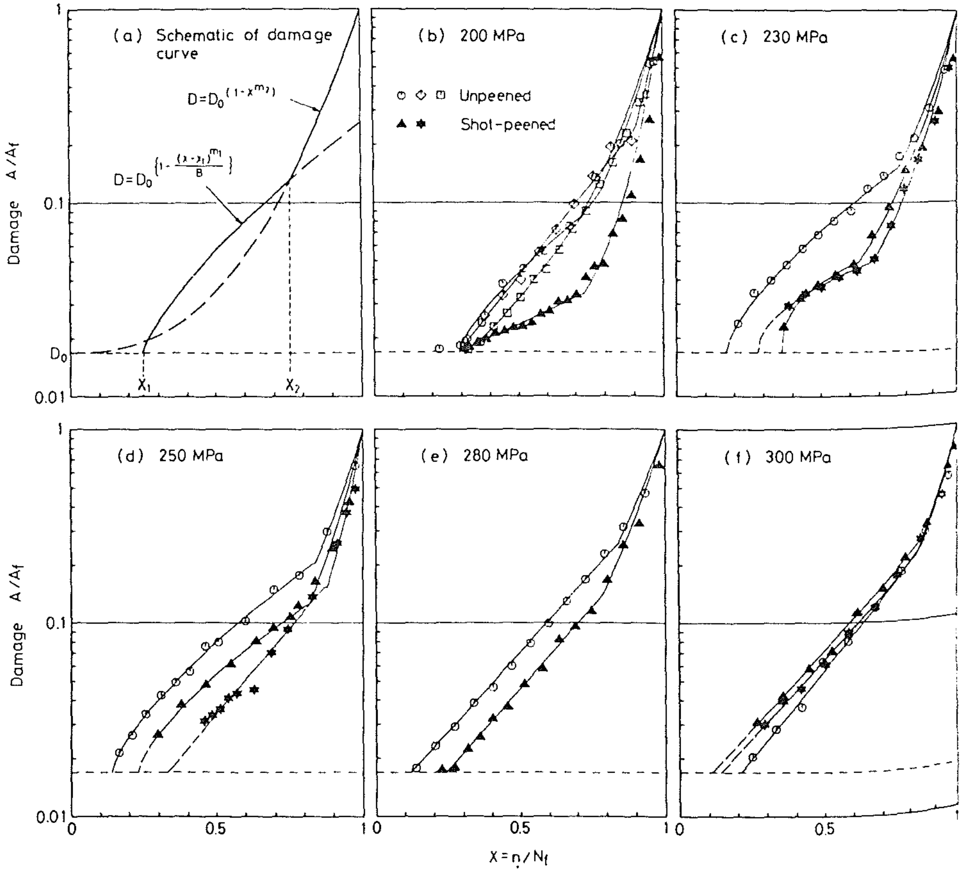
$$K_r = 1.12 \cdot 2\sqrt{\frac{a}{\pi}} \int_0^a \frac{\sigma_r(x)}{\sqrt{a^2 - x^2}} \mathrm{d}x \tag{10}$$

The depth when K_r equals zero may be 1.3 mm, but this figure is large in comparison with the thickness of hardened layer 0.3 mm. Redistribution of residual stress due to cyclic stress would be important.

Damage curves are shown in Figure 9. In this test, $A_0 = 1.12$ mm², $A_f = 0.5\pi R^2 = 66.4$ mm², $A_0/A_f = 0.0169$.

Solid lines are fitting curves by equation (5) and (3) which show good agreement with experimental data. Based on their features, three regimes are considered in the fatigue damage process (Fong, 1982), as follows (see Figure 9(a)).

Figure 9 Effect of shot-peening on damage curve



Regime 1 ($0 \leqslant x < x_1$): damage incubation period (there may be microcracks, but the cracks which leads to final fracture do not appear yet)

$$D = D_0 \tag{11}$$

Regime 2 ($x_1 < x < x_2$): damage sharing period (sudden appearance and steady growth or hesitation under the influence of notch and so on)

$$D = D_0^{\left\{1 - \frac{(x - x_1)^{m_1}}{B}\right\}}, \left(1 - \frac{A_0}{A}\right) = 1 - e^{-\left(\frac{x - x_1}{\beta_1}\right)^{m_1}} \tag{12}$$

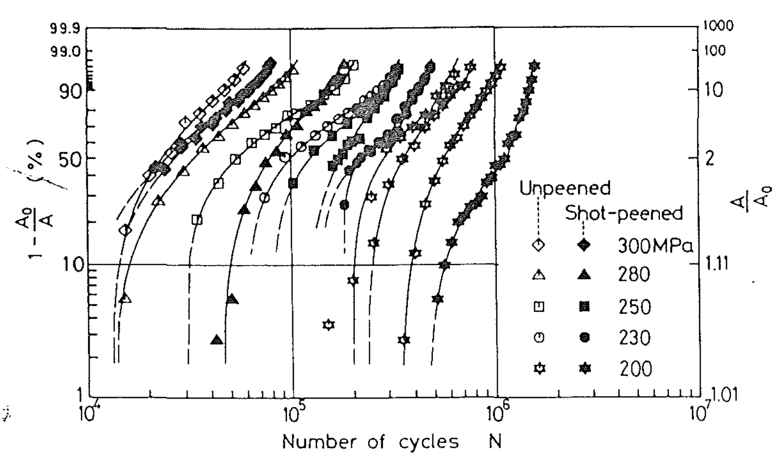
Regime 3 ($x_1 < x \leqslant 1$): damage run-away period (sure final fracture with steady acceleration)

$$D = D_0^{\left(1 - x^{m_2}\right)}, \quad \left(1 - \frac{A_0}{A}\right) = 1 - e^{-\left(\frac{x}{\beta_2}\right)^{m_2}} \tag{13}$$

Repressed growth behaviour in regimes 2 and 3 is clearly seen in Figure 9(b).

Figure 10 shows crack area growth curves expressed by Weibull function of equations (12) and (13). Table 4 gives the numerical value of the parameters in equations (12) and (13).

Figure 10 Crack area growth curves expressed by compound Weibull function



About the relations between stress amplitude and parameters, as shown in Figure 11, x_1, B and m_2 have some stress dependency, but m_1 and x_2 have not.

The fatigue life, N_f, of a blunt notch specimen can be subdivided into two phases, such that

$$N_f = N_i + N_p = x_1 N_f + (1 - x_1) N_f \tag{14}$$

Figure 12 shows the relation between stress amplitude and ΔN_i and ΔN_p which are the increments of N_i and N_p by shot-peening, and that shot-peening increases the

Table 4 Experimental parameters

Stress (MPa)	*Shot or not*	*Regime 2* x_1	B	m_1	β_1	*Regime 3* x_2	m_2	β_2
200		0.31	0.88	1.2	0.278	0.789	3.19	0.643
		0.29	1.35	0.75	0.229	0.720	2.84	0.609
		0.29	0.95	1.0	0.233	0.907	4.41	0.727
	Shot	0.29	2.6	1.0	0.637	0.727	5.60	0.778
230		0.17	1.3	0.7	0.195	0.779	2.44	0.562
	Shot	0.36	2.25	0.4	0.225	0.629	2.89	0.615
	Shot	0.28	2.4	0.5	0.346	0.676	3.42	0.663
250		0.14	1.26	0.72	0.195	0.843	2.84	0.609
	Shot	0.23	1.4	0.7	0.217	0.822	3.60	0.676
	Shot	0.33	1.0	1.0	0.245	0.885	4.83	0.747
280		0.12	1.08	1.0	0.265	0.841	2.34	0.548
	Shot	0.24	1.06	1.0	0.260	0.788	2.77	0.602
300		0.21	0.98	1.0	0.240	0.857	2.69	0.593
	Shot	0.14	1.1	1.0	0.269	0.833	2.53	0.573
	Shot	0.11	1.1	1.0	0.269	0.861	2.53	0.573

Figure 11 Variations of the parameters in equation (12) and (13) with stress amplitude σ_a

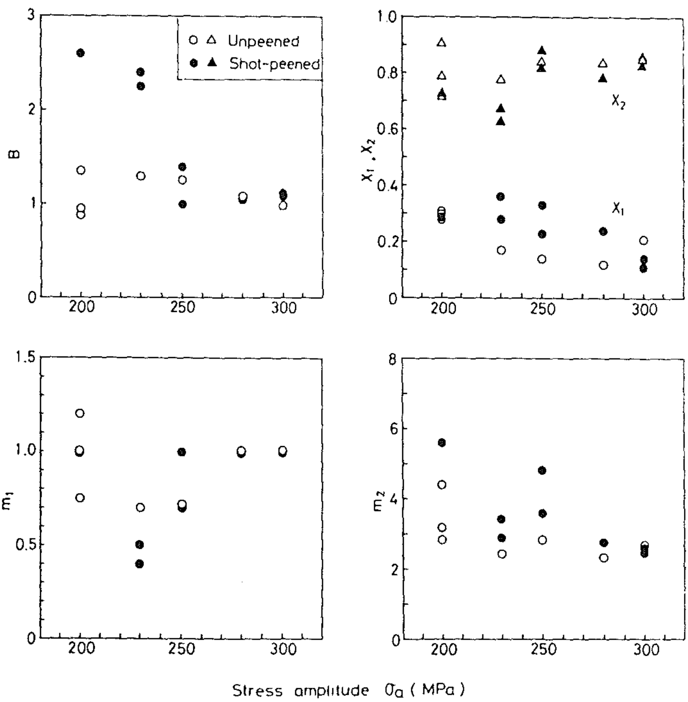
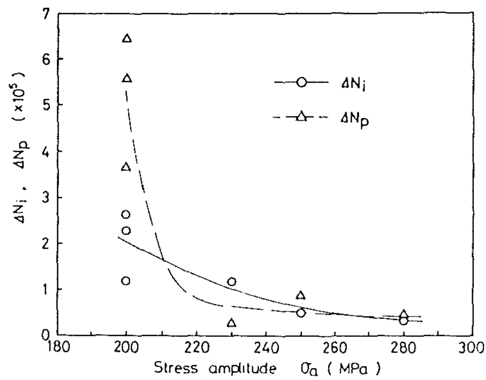


Figure 12 Increment of crack initiation and propagation period by shot-peening



propagation period more effectively than the initiation period under lower stress level. Increase of this fatigue life was given by small crack growth less than 1.3 mm depth.

5 Conclusions

Under the cyclic rotating bending condition (constant load), the fatigue damage quantified by cracked area is expressed by the compound power exponential function which is identical with Weibull function, that is, the crack growth process also can be expressed by Weibull function. Crack growth characteristics represented by three parameters in Weibull function and the effect of shot-peening on it were clarified.

Shot-peening delays crack initiation at the notch and decreases the crack growth rate only when the crack is small. In the case of a lower stress level, the increment of fatigue life by shot-peening is mainly got by the increment of crack propagation life.

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