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MICROCRACK EVALUATION USING LASER BACKSCATTERING

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Abstract: This paper describes the characteristics of the laser backscattering pattern of the microcrack on the ultra-fine finished surface of brittle material. The relation between the periodic backscattering pattern and the depth of the microcrack is made clear by employing the Boundary Element Method (BEM) simulations of electromagnetic wave scattering. The backscattering patterns are measured for the indentation microcracks with the depth of less than a hundred micrometer on the smooth glass surface. Experimental results show that the measured laser backscattering patterns agree with the simulation results and our method has a possibility to evaluate the depth of the microcrack quantitatively.
Keywords: Laser Back Scattering, Microcrack, Ultra-fine Finished Surface

1 INTRODUCTION

Recently, various kinds of brittle materials, for example, optical glass, crystal, Zerodur, ceramics, Si single crystal, etc., have been utilized as functional materials for electronic devices and optical parts and structural materials for precise measuring instruments. Ultra-precision ductile mode cutting and grinding enable to work these materials with high accuracy [1]. However, it is difficult to avoid generating a microcrack with depth of less than a hundred micrometer in process perfectly. For the sake of effective quality control, this problem must be overcome by establishing nondestructive microcracks evaluation method in process.

In this paper, we propose a new measurement method of a microcrack, whose principle is based on the laser backscattering. Electromagnetic wave scattering simulations make it clear that the mean period of laser backscattering pattern has the quantitative relation to the depth of a microcrack. This relation is proved by experiments to measure laser backscattering patterns of indentation microcracks on glass plates. Experimental results show that our method has a possibility to evaluate depth of microcrack quantitatively.

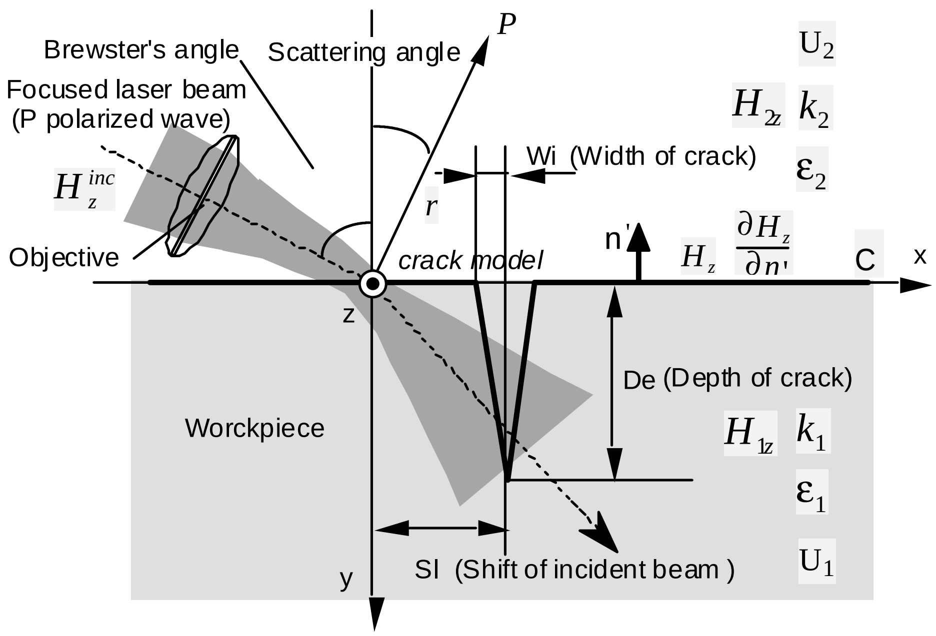


Figure 1. Simulation model and parameters

2 COMPUTER SIMULATIONS ON LIGHT SCATTERING

To investigate complicated laser light scattering from a microcrack, rigorous electromagnetic wave scattering simulations are carried out. The relation between the depth of a microcrack and backscattering pattern is made clear.

2.1 Mathematical model based on BEM

The mathematical model for simulating electromagnetic wave scattering from a microcrack is based on Helmholtz equation derived from Maxwell's equations. Scattered field is obtained as the numerical solution of Helmholtz equation with satisfying boundary conditions given by microcrack model. Figure 1 shows the simulation model and parameters for analyzing of scattered field. We consider a situation that p-polarized Gaussian laser beam is focused on a dielectric surface with a microcrack, where the profile is assumed to be uniform in z direction. The incident position of the focused laser beam is distant Sl from the microcrack position and width Wi and depth De give microcrack size. Brewster angle as the incident angle is denoted by ϕ_b and scattering angle by Ψ. Let ε and k be dielectric constant and wave number respectively and quantities which refer to the dielectrics in the domain U_1 will be denoted by superscript 1, those referring to free space in the domain U_2 by superscript 2. Applying Green's theorem to Helmholtz equation, we obtain integral equations for the z-component of magnetic field H_{z1} and H_{z2} [2],

$$H_{z1} = -\frac{j}{4}\int_c \left\{ g\,\frac{\partial H_{2z}}{\partial n'} - H_{2z}\frac{\partial}{\partial n'} \right\} H_0^{(2)}(k_1 R)dl' \quad (1)$$

$$H_{z2} = H_z^{inc} + \frac{j}{4}\int_c \left\{ \frac{\partial H_{2z}}{\partial n'} - H_{2z}\frac{\partial}{\partial n'} \right\} H_0^{(2)}(k_2 R)dl' \quad (2)$$

where j denotes the imaginary unit, $\mathbf{n}'$ is unit normal pointing from dielectrics into free space, H_z^{inc} is the z-component of incident field, $H_0^{(2)}$ is the Hankel function of the second kind and zero order and $\gamma=\varepsilon_1/\varepsilon_2$. Moreover, $R=|\mathbf{r}-\mathbf{r}'|$ when $\mathbf{r}$ is a position vector pointing from the origin to an observation point P and $\mathbf{r}'$ is a position vector pointing from the origin to an integration point on the boundary C.

Taking limit of these equations as $\mathbf{r}$ approaches the points on the boundary C, eq. (1) and (2) then go over into following integral equations for obtaining the magnetic field H_z on the boundary and it's derivative with respect to normal direction $\partial H_z/\partial n'$.

$$\frac{1}{2}H_z = -\frac{j}{4}\int_c \left\{ g\,\frac{\partial H_z}{\partial n'} - H_z\frac{\partial}{\partial n'} \right\} H_0^{(2)}(k_1 R)dl' \quad (3)$$

$$\frac{1}{2}H_z = H_z^{inc} + \frac{j}{4}\int_c \left\{ \frac{\partial H_z}{\partial n'} - H_z\frac{\partial}{\partial n'} \right\} H_0^{(2)}(k_2 R)dl' \quad (4)$$

These integral equations are solved numerically by means of the boundary element method (BEM). Using H_z and $\partial H_z/\partial n'$ as the solution of these integral equations, far field of scattered light can be obtained from eq. (2). Finally, scattered light intensity distribution $P(\psi)$ is determined by following relation.

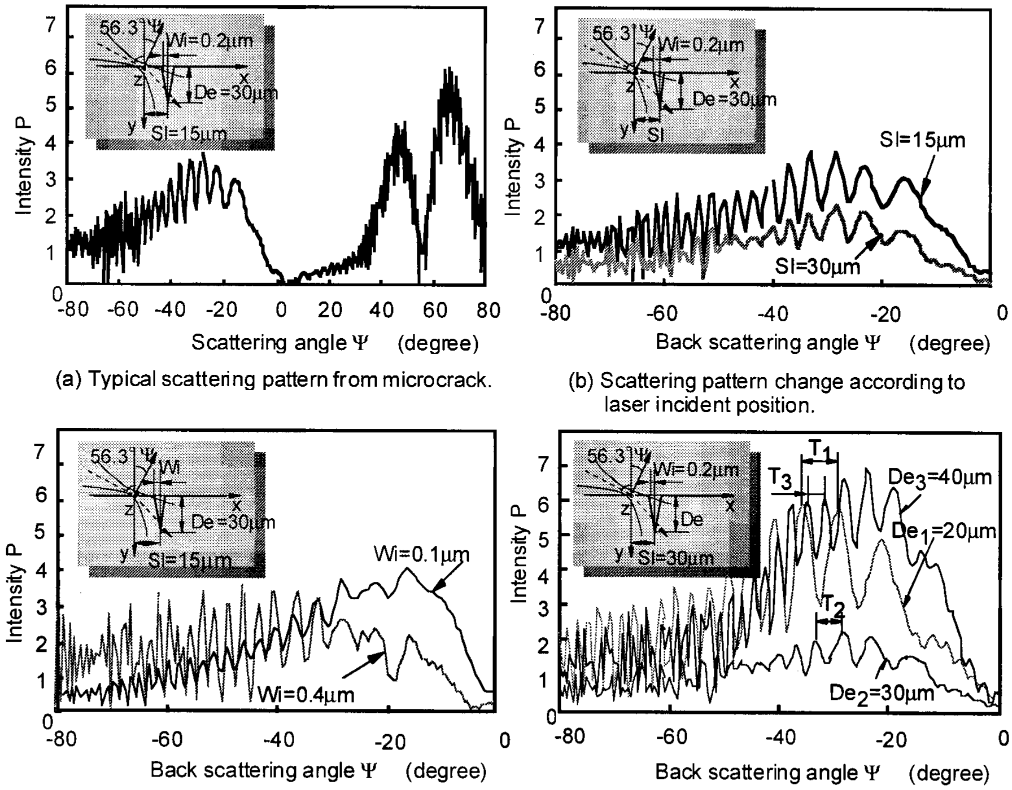
$$P(\Psi) = \left| \frac{j}{4}\int_c \left\{ \frac{\partial H_z}{\partial n'} - jk_2 H_z \cos(\Psi - \Psi'_n) \right\} \exp\left(jk_2 |r'| \cos(\Psi - \Psi')\right) dl' \right| \quad (5)$$

where ψ, ψ' and ψ_n' denotes the angle formed by vector $\mathbf{r}$ and x axis, $\mathbf{r}'$ and x axis, unit normal $\mathbf{n}$ on the boundary and x axis, respectively. Relation between scattering angle Ψ and ψ is given by $\Psi=\pi/2-\psi$.

2.2 Simulation results

We investigate laser light scattering from a microcrack propagating under a glass plate surface in air. As the parameters for the simulated model, refractive index of the glass plate 1.5 and air 1.0, wavelength of Ar laser light 0.488 μm, focal length of the objective 5.0 mm and numerical aperture (N.A.) 0.4 are set. Brewster angle 56.3 degree is determined from the refractive index of glass. These parameters are much the same as conditions for experiments using glass plates with indentation cracks.

Figure 2 shows simulation results. Typical scattering pattern from a microcrack with Wi=0.2 μm and De= 30 μm under the light incident condition of Sl=15 μm is indicated in Figure 2 (a). The intensity distribution has both forwardscattering pattern distributing around scattering angle of 56.3 degree and backscattering pattern distributing around –56.3 degree. The forwardscattering pattern is almost consistent with specular reflection of the incident focused Gaussian beam. However, we have few intensity at just 56.3 degree. This proves that particular reflection for the Brewster angle incident together with p-polarization is effectively simulated. On the other hand, the backscattering pattern emerges with just existing of a microcrack. This suggests that detecting backscattering light makes it possible to find a microcrack. Figure 2 (b) (c) and (d) shows the relation between backscattering pattern with periodic structure and parameters such as Sl, Wi and De. Although the mean period of backscattering pattern is considered to be almost independent of illuminating point and width of crack, it remarkably changes with depth of crack. Comparing T_1, T_2 and T_3 corresponding to each depth of 20, 30, 40 μm shown in Figure 2 (d), we found that the more deeply crack is induced, the shorter the mean period of backscattering pattern becomes. Therefore, it is possible to evaluate depth of crack by measuring period of backscattering pattern.



(a) Typical scattering pattern from microcrack.

(b) Scattering pattern change according to laser incident position.

(c) Scattering pattern change according to the width of crack.

(d) Scattering pattern change according to the depth of crack.

Figure 2. Simulation results of laser scattering from microcrack

3 DEPTH ESTIMATION OF INDENTATION CRACK

Since it is difficult to measure depth of microcrack directly, we can only estimate the depth of a microcrack generated by means of well-known process. In this case, the characteristic of microcrack is made clear enough to estimate depth based on its propagation feature. Thus radial crack generated by using indentation is investigated here.

3.1 Radial crack propagation model

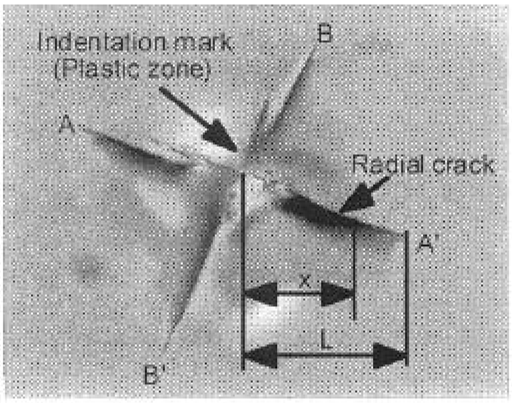
Radial crack on a glass plate induced by indentation is available for estimating its depth. Figure 3 shows the method to estimate depth of microcrack based on radial crack propagation feature. Length L of radial crack and a distance x from a center of indentation mark to a position where the depth is estimated are measurable by microscopic observation. Figure 3 (a) shows an example of microscopic image of a glass surface with indentation mark and radial crack. Referring to the radial crack propagation model as shown in Figure 3 (b), geometrical feature of the cross section A - A' and B - B' can be expressed by a semicircle approximately. Using the geometrical relations, depth De of radial crack is given by.

$$De = \sqrt{L^2 - X^2} \qquad (6)$$

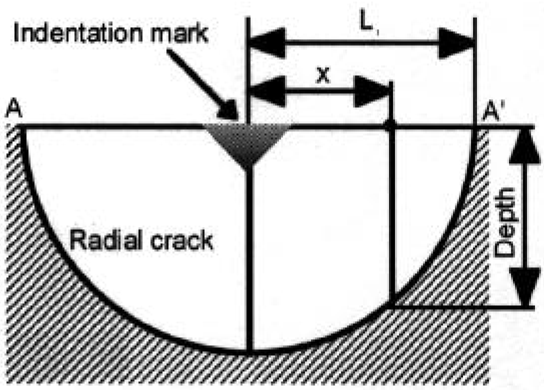
Therefore, depth at arbitrary point on radial crack can be estimated from measurements of L and x based on radial crack propagation feature.

3.2 Depth estimation using microscopic image

To obtain cracks with different depth, indentation microcracks are generated by load from 200 gf to 1000 gf in 10 second using Vickers indenter. As workpiece, slide glasses for microscope with surface roughness of 0.005 μm Ra and refractive index of 1.5 are used in these experiments. Figure 4 (a), (b) and (c) show microscopic images of a indentation mark and indentation cracks by load of 200 gf, 500 gf and 1000 gf. Crack propagation length on the glass plate surface measures 25 μm long for load of 200 gf using the microscopic image and in the same manner 60 μm long for 500 gf, 85 μm long for 1000 gf. Figure 5 shows crack depth estimation at the position x where laser light illuminates and backscattering is measured. Crack depth is estimated from measurement of L and x with using eq. (6). The range of estimated depth from 19.2 to 60.2 μm is wide enough to check the change of backscattering with depth suggested by simulation results.

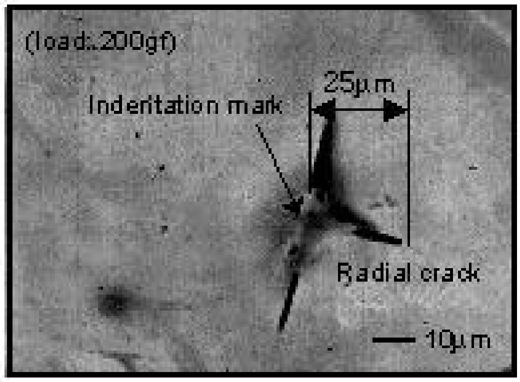


(a) Measurement of x and L based on microscopic image of identation

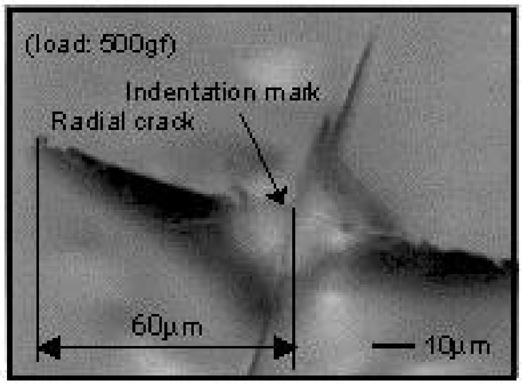


(b) Depth estimation based on radial crack propagation feature

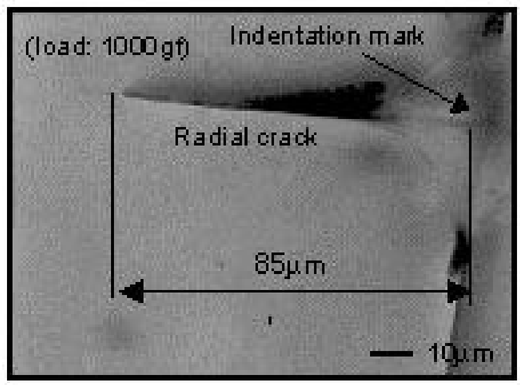
Figure 3. Schematic diagram of depth estimation From microscopic image



(a) Identitation crack under load of 200 gf

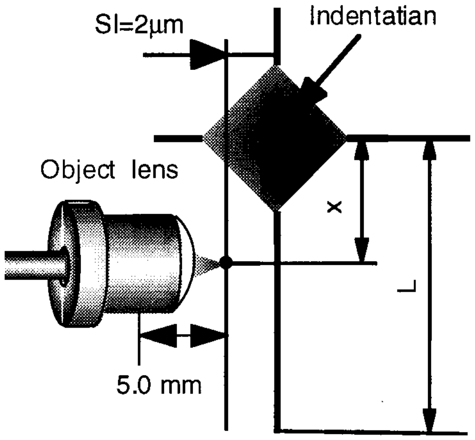


(b) Identitation crack under load of 500 gf



(c) Identitation crack under load of 1000 gf

Figure 4. Microscopic image of identitation Crack on the glass plate sureface



Load (gf)	L (µm)	x (µm)	Depth (µm)
200	25.0	12.5	19.2
		10.0	21.9
300	35.0	15.0	26.8
		12.5	28.7
400	50.0	35.0	35.7
		20.0	45.8
500	60.0	40.0	44.0
1000	85.0	65.0	54.8
		60.0	60.2

Figure 5. Measurement points and estimated depth of identitation crack

4 MEASUREMENTS OF LASER BACKSCATTERING

In order to confirm the relation between the mean period of backscattering pattern and depth of crack suggested by computer simulation results, measurements of backscattering pattern of indentation crack are performed.

4.1 Experimental setup

Schematic diagram of optical system for obtaining laser backscattering pattern is indicated in Figure 6. The Ar+ laser beam passes through a polarizer, a beam expander, a half mirror and an object lens, then focused to a workpiece surface by Brewster angle. Brewster angle is set to be 56.3 degree for the glass with the refractive index of 1.5. The backscattering light travels the same optical path again and deflected by the half mirror, then the backscattering pattern is detected by CCD areasensor after through relay lenses and a polarizer. Positioning of laser incident beam to a measurement point beside a crack is checked using microscope unit with CCD camera.

4.2 Experimental results

Backscattering patterns from microcracks induced in subsurface of glass plates can be successfully detected using the developed optical system. Focused Gaussian laser beam with p-polarization illuminates a microcrack on the surface under the conditions indicated in Figure 5 such as Sl = 2 µm and measurement position x corresponding to each estimated depth. Figure 7 (a), (b) and (c) shows typical backscattering pattern and the intensity distribution for microcracks having estimated depth of 19.2, 44.0 and 60.2 µm. Measurement angle of scattering is adjusted in backscattering domain from –

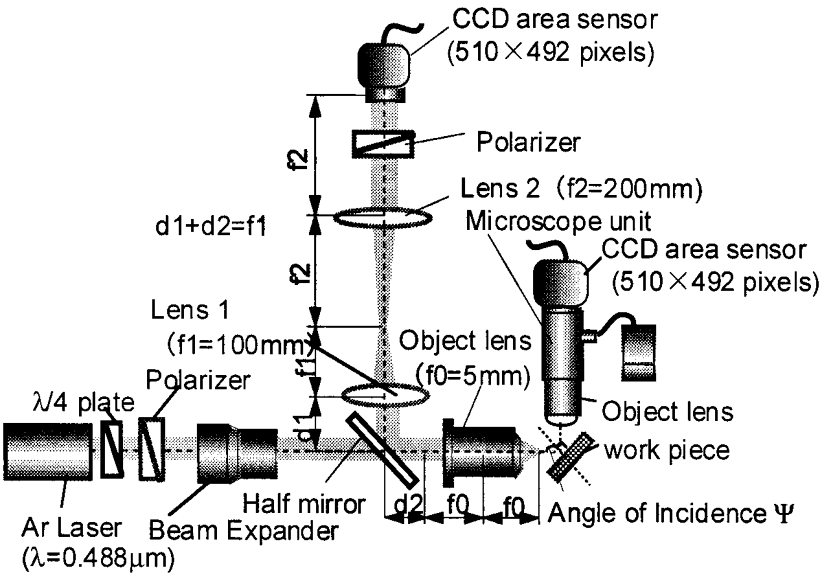
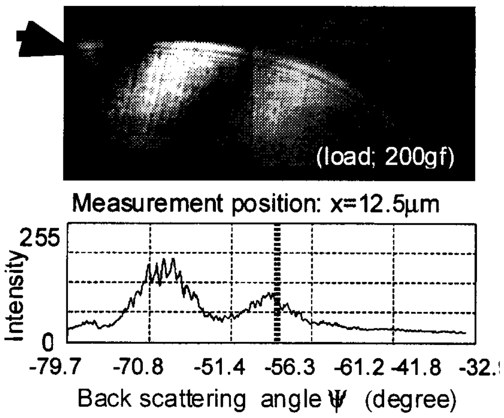
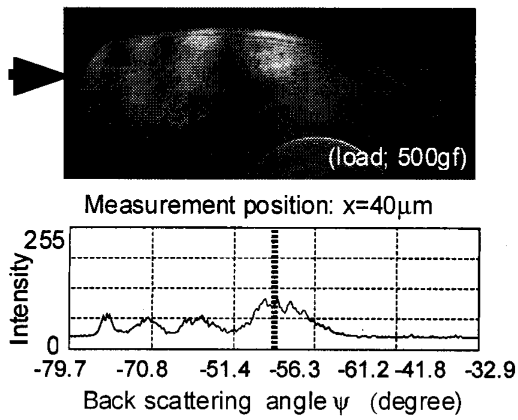


Figure 6. Schematic diagram of optical system for obtaining laser backscattering pattern

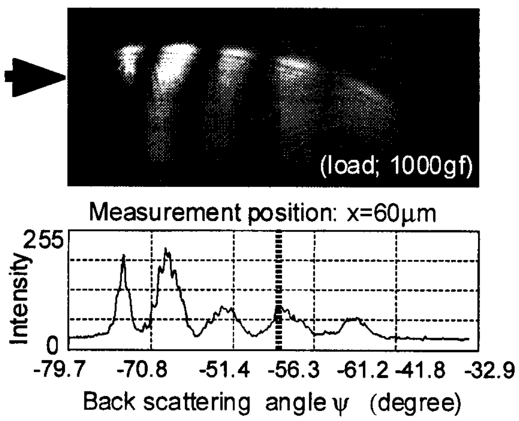
79.7 to –32.9 degree around Brewster angle. As shown in pictures, periodic fringe like pattern is detected and the mean period of backscattering pattern seems to be changing with depth of microcrack also. So, to investigate this tendency quantitatively the mean period is evaluated from intensity distribution of backscattering pattern. Figure 8 shows the plot of the mean period of backscattering pattern expressed by scattering angle versus the estimated depth of microcrack. These measurement results show that the mean period of backscattering pattern decreases with an increase in depth of crack. Especially, the change of the periodicity for the depth of less than about 30 μm is so dramatic that the backscattering method has the advantage for evaluating smaller depth of microcrack sensitively.



(a) Backscattering pattern for depth=19.2μm



(b) Backscattering pattern for depth=44.0μm.



(c) Backscattering pattern for depth=60.2μm.

Figure 7. Typical backscattering pattern changing with the depth of crack

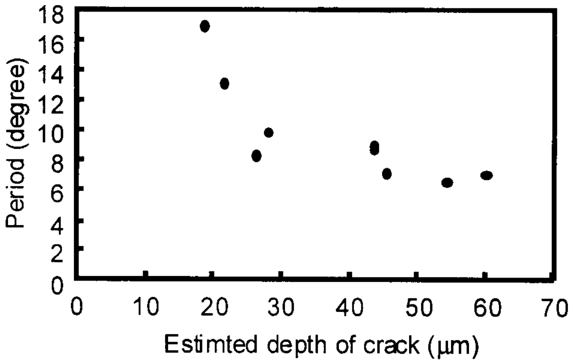


Figure 8. Relation between the period of backscattering pattern and the depth of microcrack

5 CONCLUSIONS

Computer simulation results based on BEM suggest that laser backscattering patterns for microcracks have periodic structure. The deeper crack is, the shorter the mean period of backscattering pattern becomes. Measurement results of backscattering patterns for indentation cracks agree with the computer simulation results. Measurements of backscattering patterns for the microcrack having various depths result that depth of crack in a hundred micrometer has quantitative relation to the mean period of laser backscattering pattern. Especially, the dramatic change of backscattering pattern for depth of less than about 30μm makes it possible to evaluate smaller depth of microcrack sensitively.

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