Fatigue Crack Initiation and Propagation under Circumstances of Residual Stress Produced by Shot Peening

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ABSTRACT. *Fatigue strength and fracture mode of shot peened materials depend on the conditions of the shot peening treatment. As for the fracture mode, internal fracture was recognized frequently, where fish eye pattern was observed on the fracture surface. Residual compressive stress underneath the surface of the material plays an important role to these phenomena. Fatigue tests were carried out for shot peened specimens under various conditions of shot peening treatments. The site of the origin of fish eye has a good correlation with the depth of crossing point from the specimen surface where residual stress changes from compressive stress to tensile one. The shape of fish eye was influenced by residual stress strongly. The scatter band of S-N plots has a tendency to become narrow when stress amplitudes at the sites of origin of fish eye are used as the stress amplitude of S-N plots.*

INTRODUCTION

Shot peening is one of the most important treatments for machine parts such as springs, gears and so on. Residual compressive stress underneath the surface of the machine parts produced by shot peening is effective to increase fatigue strength and/or fatigue life under cyclic loading. But what type of residual stress distribution is the most effective against the fatigue strength, and the relationship between such residual stress distribution and shot peening conditions such as shot size, shot hardness, shot speed and so on have not been clarified.

When fatigue tests were carried out for shot peened specimens, it has been recognized [1] frequently that fatigue crack initiated underneath the specimen surface and then fish eye pattern was formed on the fracture surface. Therefore, it is necessary to clarify the formation of fish eye, that means crack initiation and propagation under circumstances of residual stress for understanding the effect of shot peening treatments on fatigue strength.

In this study, rotating bending fatigue tests were carried out for shot peened specimens under various shot conditions and configurations of fish eye on fracture surfaces were observed in detail. Crack initiation and propagation processes under residual stress conditions for formation of fish eye were discussed.

EXPERIMENTAL

The material used was a Si-Cr spring steel. The cantilever type rotating bending fatigue testing machine was used under a frequency of 50Hz. The profile of the specimen is shown in Fig.1. Heat treatments of quenching and tempering were carried out for specimens machined roughly. After final machining shot peening treatments were performed.

Table 1 shows conditions and results of shot peening treatments. The size and hardness of shot and peening velocity were selected as parameters of the shot peening conditions. As the results different types of residual stress distributions were obtained. The compressive residual stress at specimen surface decreased and the depth of crossing point increased for specimens A and D, where large shots in diameter under high peening velocity, compared with for specimens B and C, where the treatments were performed using small shots under low peening velocity.

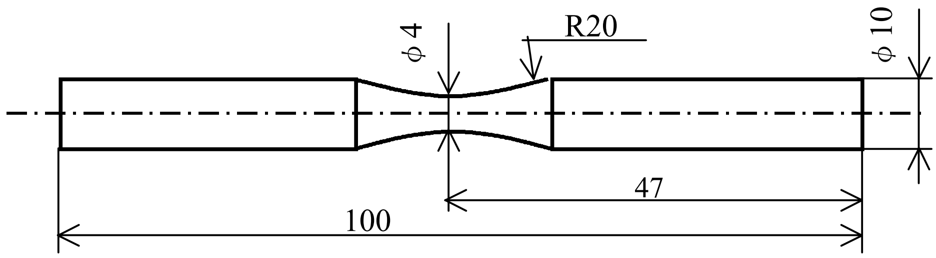


Figure 1. Profile of fatigue test specimen (in mm).

Table 1. Shot peening conditions and results of shot peening treatments.

Symbol and name of specimen		○ :A	□ :B	△ :C	◇ :D
Shot peening conditions	Shot diameter (mm)	0.6	0.3	0.3	0.6
	Shot hardness (HV)	550	700	550	700
	Peening velocity (m/s)	80	40	40	80
Results of shot peening treatments	Surface roughness (μ m)	11.3	4.8	4.2	15.6
	Residual stress at surface (MPa)	-600	-875	-700	-600
	Depth of crossing point (μ m)	220	90	100	260

RESULTS AND DISCUSSION

S-N Plots and Fracture Modes

Figure 2 shows S-N plots for all specimens those symbols correspond with those in Table 1. Fatigue strength at 10^7 cycles, for example, depends on conditions of shot peening. There is a difference of about 200MPa in fatigue strengths between specimen B, which is the highest of all, and specimen A, which is the lowest. It is a reasonable result that high compressive residual stress and low roughness at specimen surface are effective against fatigue strength.

In Fig.2 solid and open marks mean that fatigue crack initiates at the surface and at the interior of specimen, respectively. For specimen A fatigue cracks initiated mostly from specimen surface. On the other hand, internal fracture with fish eye pattern on the fracture surface was dominant for specimen B.

Figure 3 shows examples of fish eyes. There was a non-metallic inclusion at the origin of fish eye, from which fatigue crack was initiated. In general, one fish eye was formed on fracture surface, but sometime multiple fish eyes could be observed on a fracture surface. The example is shown in Fig.4, where two fish eyes were recognized. The fish eye shown in Fig.4(b) is considered as one which brought final fracture. For another fish eye shown in Fig.4(c), there is a partial ring area surrounding the fish eye. Why such ring area was formed is very interesting and is discussed in later.

For indicating the configuration of fish eye which suggests the behaviours of crack propagation for radial and circumferential directions of the specimen from the origin of fish eye, three parameters d_0, a and b were measured as shown in Fig.5, where d_0

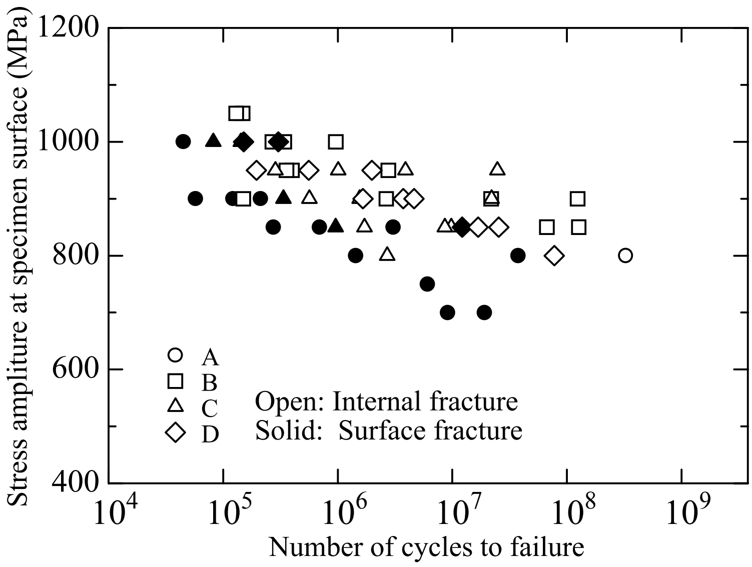
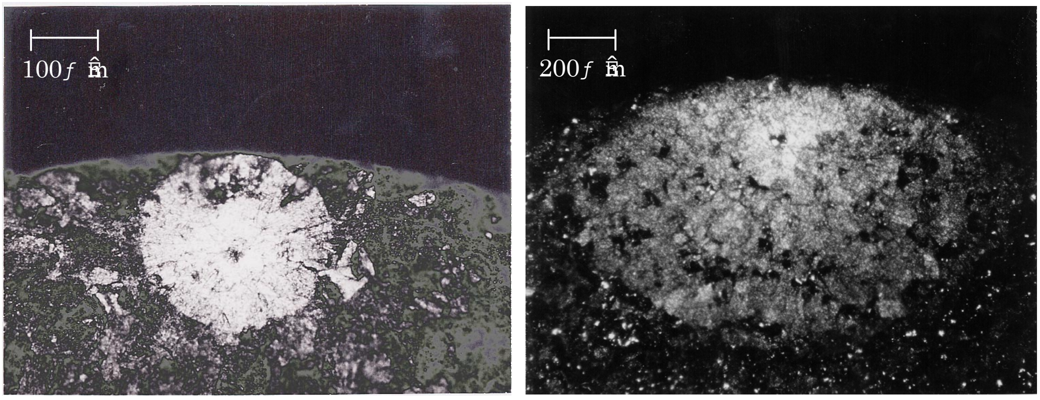


Figure 2. S-N plots where stress amplitude indicates one at specimen surface.

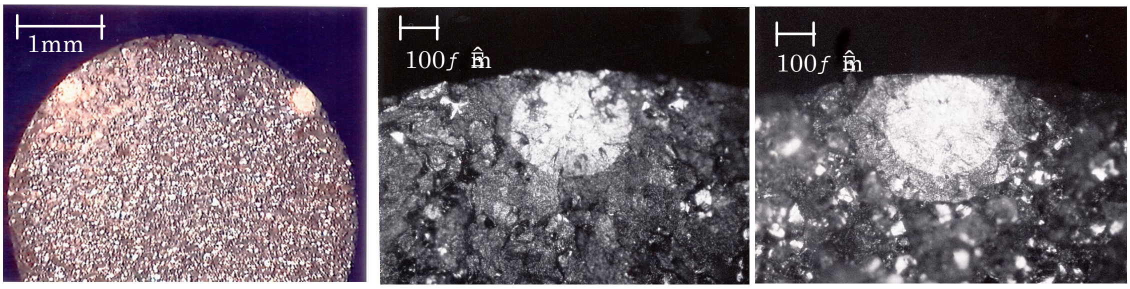
means the depth of the origin from the surface and a and b mean the widths of fish eye for radial and circumferential directions, respectively.



(a) Specimen C
σ_a = 900 MPa, N_f = 1.55×10^7

(b) Specimen D
σ_a = 800 MPa, N_f = 7.78×10^7

Figure 3. Examples of fish eye patterns observed on fracture surfaces.



(a) Macroscopic feature

(b) Fish eye bringing final fracture (Left one)

(c) Fish eye growing at another site (Right one)

Specimen B, σ_a = 1050 MPa, N_f = 1.32×10^5

Figure 4. Multiple fish eyes observed on a fracture surface.

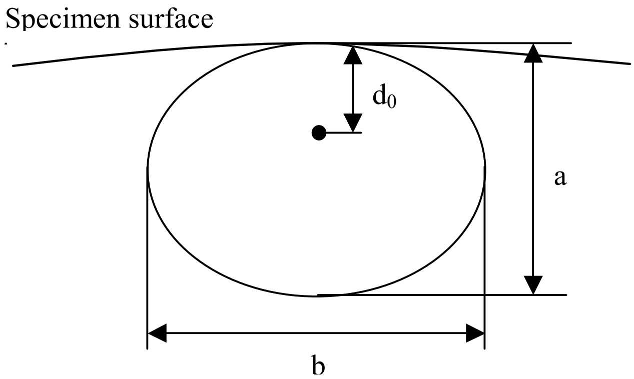


Figure 5. Definitions of parameters d_0, a and b indicating the configuration of fish eye.

Position of Crack Initiation Site and Crack Propagation for Radial Directions to Form Fish Eye

The configuration of fish eye and the depth of the origin of fish eye from specimen surface depend on conditions of shot peening treatment. The depth relates to the depth of crossing point. Figure 6 shows the relationship between d_0/d_{cp} and $2d_0/a$. The abscissa d_0/d_{cp} means the depth of the origin of fish eye normalized by the depth of crossing point d_{cp}. The ordinate means the ratio d_0 to a half of the width of fish eye in radial direction a/2.

The relationship between d_0/d_{cp} and $2d_0/a$ has a unique tendency independent of conditions of shot peening treatments. The values d_0/d_{cp} distributes between about 0.85 and 3. This result can be understood from Fig.7, where stress distribution of bending specimen with compressive residual stress at surface is shown. Fatigue crack initiated from a non-metallic inclusion under high stress field as a result of superposing residual stress on applied stress.

The values of $2d_0/a$ were mostly less than unity for a range of small values of d_0/d_{cp}. When the value of $2d_0/a$ is less than unity, it means that the position of the origin of fish eye has a tendency to be located in surface side of specimen against the centre of the fish eye. Under a condition of rotating bending, there is a stress gradient in a specimen and stress at the surface is the highest. Therefore when a crack initiates from an internal inclusion, it must propagate more rapidly for the surface than for the centre in radial directions and the value of $2d_0/a$ must be larger than unity. This tendency has been recognized [2] in fish eyes formed under rotating bending fatigue tests for high strength steels without any surface treatments. Contradictory result obtained for present specimens is considered as a result of compressive residual stress existing underneath the specimen surface. As is shown in Fig.7, distribution of tensile stress range is severe for the centre than for the surface in radial directions by residual stress to a certain position deeper than crossing point.

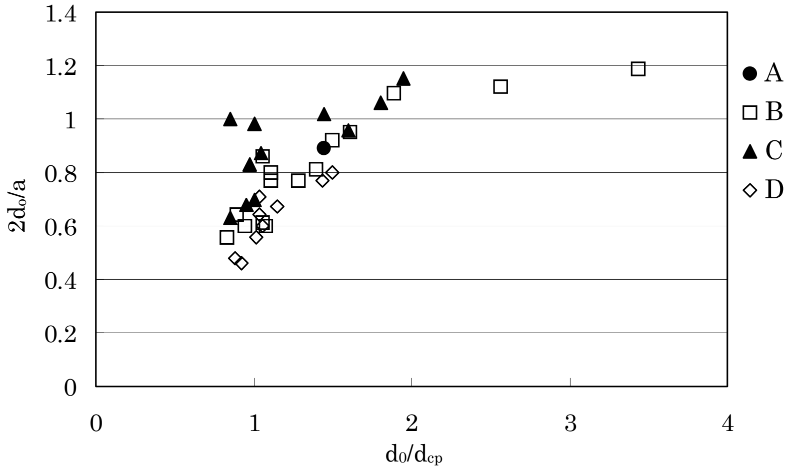


Figure 6. Relationship between d_0/d_{cp} and $2d_0/a$.

Crack Propagation for Circumferential Directions to Form Fish Eye

Figure 8 shows the relationship between $2d_0/a$ and eccentricity of fish eye defined by b/a. There is a unique tendency independent of conditions of shot peening treatments. The value of b/a was larger than unity and it increased with decreasing the value of $2d_0/a$. These results mean that under a condition for initiated crack from internal inclusion to propagate slowly for the surface direction compared with for the centre direction the crack can propagate more rapidly for circumferential directions than for radial directions. As one of the reasons, it can be pointed out that the same high tensile stress range acts uniformly for circumferential directions from the origin of fish eye as that acts at the origin.

It is considered for high strength steels, for example, that crack propagates rapidly to bring final fracture when the front of fish eye reaches to the specimen surface. The

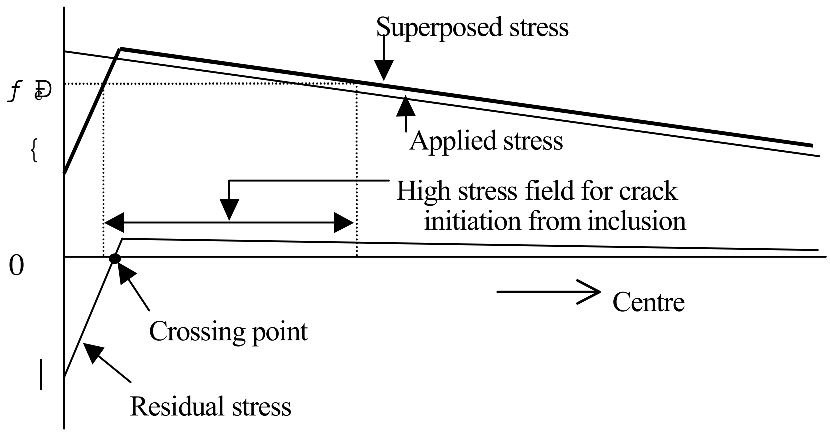


Figure 7. Stress distribution of bending specimen with compressive residual stress underneath the surface.

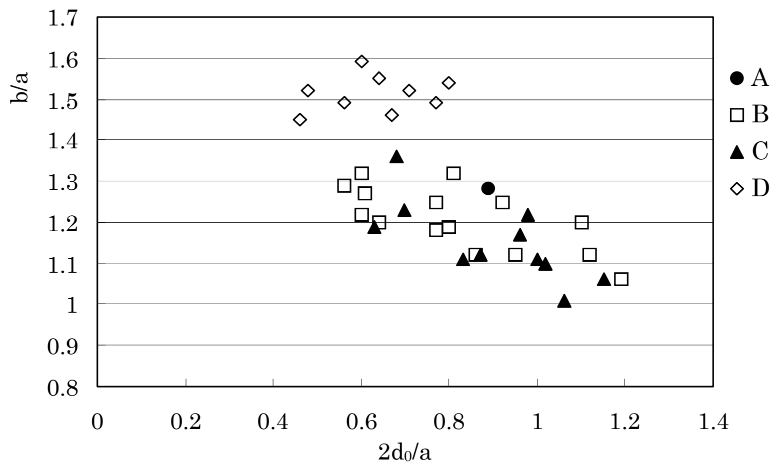


Figure 8. Relationship between $2d_0/a$ and eccentricity of fish eye b/a.

partial ring area surrounding the fish eye shown in Fig.4 (c) suggests that crack does not propagate rapidly to bring final fracture after the crack front of the fish eye reaches the specimen surface, but there is a period for crack to propagate concentrically around the origin of fish eye. At the specimen surface, crack propagation for circumferential direction was not accelerated particularly nevertheless severe applied stress condition. Compressive residual stress at the specimen surface plays an important role to delay crack propagation after formation of fish eye.

Factors Which Govern Fatigue Life and Fatigue Strength of Shot Peened Specimens

Internal fracture accompanying with fish eye is dominant in fatigue fracture for shot peened specimens. The positions of the origin of fish eye are almost located deeper from the specimen surface than crossing points. This result suggests that tensile stress range is important for crack to initiate from internal defects such as non-metallic inclusions as well as the size of the defect. As the first step of discussions, the relationship between stress amplitude applied at the origin of fish eye and the number of cycles to failure was checked. The relationship is shown in Fig.9. The scatter band of plots becomes narrower than that shown in Fig.2, but the scatter itself does not diminished.

As factors of the scatter in plots shown in Fig.9, the size of defect at origin of fish eye, position from the surface and the distribution of residual stress can be pointed out. The distance from the origin to edge of fish eye varied depending on the direction. In general, the distances for the circumferential directions are the maximum and one for the surface direction is the minimum. This tendency can be explained from the stress distribution by superposing residual stress on applied bending stress. The number of cycles for formation of fish eye after the period of initiation of fatigue crack at the origin of fish eye and the early stage of crack propagation to a certain distance can be obtained analytically but it has been reported [3], for example for tool steels, that the

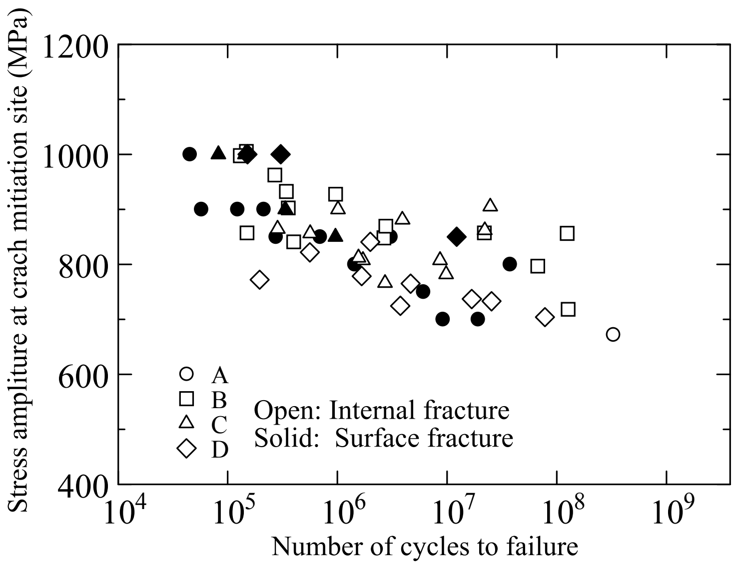


Figure 9. S-N plots where stress amplitude means one at crack initiation site.

cycles is not dominant in total fatigue life.

Recent result [4] indicates that the period of initiation of fatigue crack at the origin of fish eye and the early stage of crack propagation to a certain distance is dominant in fatigue life, where the size of defect of the origin of fish eye plays an important role. The information about the size of defects of the origin of fish eye has not been obtained yet for the present specimens. The details of those effects on fatigue lives and fatigue strength will be shown in near future.

CONCLUSIONS

Rotating bending fatigue tests were carried out for shot peened specimens to clarify the effects of shot peening conditions on fatigue behaviour. The results obtained are summarized as follows:

1. As for the fracture mode, internal fracture was recognized frequently, where fish eye pattern was observed on the fracture surface.
2. The relationship between d_0/d_{cp} and $2d_0/a$ had a unique tendency independent of conditions of shot peening treatments. The positions of the origin of fish eye are almost located deeper from the specimen surface than crossing points.
3. The shape of fish eye was influenced by distribution of residual stress strongly.
4. The scatter band of S-N plots has a tendency to become narrow when stress amplitudes at the sites of origin of fish eye are used as the stress amplitude of S-N plots.

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REFERENCES

1. Research Committee for Optimizing a Shot-Peening Process (2002) *Trans. Japan Soc. for Spring Research* **47**, 43-61.
2. Shiozawa, K., Tao, L. L. and Ishihara, S. (1999) *J. Soc. Mat. Sci., Japan* **48**, 1095-1100.
3. Abe, T. and Kanazawa, K. (1996) *J. Soc. Mat. Sci., Japan* **45**, 9-15.
4. Oguma, N. and Sakai, T. (2001) *J. Soc. Mat. Sci., Japan* **50**, 516-523.