17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Influence of Inclusion on Crack Tip in Rotating Disc by Photoelasticity and Caustic Method

Sasaki SYUUTEI [1]*, Hagiwara KEIICH [1]* and Ezumi TSUTOMU [2]*

[1]*Shibaura Institute of Technology, Applied Dynamics Laboratory,

3-7-5 Toyosu, Koto-ku, Tokyo 135-8548 Japan

Tel:+80-3-5859-8063 bch14940@nifty.com

[2]* Shibaura Institute of Technology, Applied Dynamics laboratory,

3-7-5 Toyosu, Koto-ku, Tokyo 135-8548 Japan

Tel:+80-3-5859-8063 ezumi@sic.shibaura-it.ac.jp

Abstract.

Fatigue and fractures such as blades and discs, which originate in the centrifugal force caused in the rotor, become factors that often cause serious accidents. The enlargement of machine and structure improves the possibility that do the latency of minute cracks and inclusion in materials in manufacturing processes. Severe working conditions also promote the propagation of the crack while operating. Thus, it is very important for the improvement in the safety of materials to analyze the interference problem of inclusion and crack. In this study, an inclusion in the rotating disc and the interference problem of the crack were examined. The influence of the mechanical property of the inclusion and the distance to the crack tip was examined. The stress intensity factor was determined by using photoelasticity and method of caustics. As a result, the stress intensity factor was decreased when Young's modulus of inclusion increased. Moreover, the stress intensity factor decreased as the distance from the crack tip to the inclusion boundary became longer. The stress intensity factor of the crack on the rotation center side increased more than the cracks on the circumference side of the inclusion.

Key Words: Experimental Stress Analysis, Stress intensity factor, Fracture Mechanics, Photoelasticity, Caustics Method, Rotating Disc, Inclusion

1. Introduction

The kind of rotary machines, such as a turbine rotor, a compressor rotor and a flywheel, is widely used from manufacturing industry to transportation to domestic life. Therefore, the fatigue and fracture of blades and disks caused by the centrifugal force generated from revolving part of machine often lead to serious accidents. However, it is difficult to control fractures even if optimal safety factors for various conditions are applied to the design. Therefore, the studies on material strength against various fracture morphologies in revolving part of machine have become increasingly important for safety design, and the knowledge obtained from the studies relating to the problems of cracks in revolving part of machine has been fully applied to safety design [1-4].

However, there are many material defects in engineering materials and the occurrences of some cracks and defects cannot be avoided during the manufacturing process of machines and structures, so interference problems on cracks are very important in the study of material fracture phenomena. Although the data obtained from theoretical and experimental analyses have been effectively used against the interference on crack and the interference between crack and inclusion [5], the studies relating to revolving part of machine are comparatively low.

In this study, assuming that cracks occurred near inclusions in a revolving disk, an experimental analysis was conducted relating to the effect of inclusions on stress intensity factor of crack tips, and the experimental results were comparatively reviewed. A photoelasticity and a method of caustics were used for the calculation of stress intensity factor [6-8]. As a result, the higher Young's modulus of inclusion in revolving disk becomes, the more the stress intensity factor decreases, and the shorter the distance between crack tip and inclusion boundary becomes, the more the stress intensity factor tends to increase.

2. Test Specimen and Experimental Method

Although there are several calculation methods of stress intensity factor by photoelasticity, a method of Smith et al. was applied in this study. Diverging light was injected to a specimen with stress frozen cracks and its image was taken from behind a screen. Fig.1 shows the test specimen's shape used in this experiment. The base material of test specimen is a rectangular board of epoxy resin in the market. In order to be fixed with a rotation axis of revolution loading equipment with a bolt, a hole of 20mm diameter was cut in the center of a rectangular test specimen, and processed with lathe to make its outer diameter 220mm. When processed, the test specimen was put between reinforcing plates on both sides to avoid residual stress coming in the test specimen. After that, on the pitch circle of 132mm in diameter (the position of 60% of the diameter of test specimen), round holes of 20mm in diameter were processed with upright drilling machine to insert inclusions. An extra fine saw blade of width of 0.15mm was used to produce cracks, holes of 1.3mm in diameter were made with a small size drilling machine, and cracks of 2α=10mm in length were inserted 5mm each toward radius. Cracks were inserted toward radius to make the distances from inclusions to crack tips 2,4, 6mm, and no crack near inclusions was kept for comparison. Inclusion models were produced by putting columns of epoxy resin with weight ratio of 100:20, 100:25, and 100:40 between the araldite Band the hardening agent. For a casting mold, silicone rubber was used, which was produced by mixing the main material and hardening agents at weight ratio of 100:1. Annealing was performed to release thermal stress of the casting from columns for which the casting was completed. To bond inclusions to test specimens, the mixture of araldite, epoxy adhesive of normal-temperature hardening type and hardening agent at weight ratio of 100:25 was used. Table 1 shows Young's modulus of disk of base material and each inclusion at room temperature (24℃). An ultrasonic testing machine was used to measure Young's modulus.

From the preliminary experiment, the revolution speed was 1600rpm to make the fringe order appropriate for analysis. An analysis by stress freezing was conducted in this experiment. After the images of isochromatic fringe and caustic patterns were taken, each of negative films was scanned to a PC by a film scanner. Then,γ_m,θ_m of isochromatic fringe loop and D of caustic pattern were measured, and stress intensity factors were calculated. Assuming the value of the calculated stress intensity factor on the side of rotation is K_{Ia} and the value of that on the side of circumference is K_{Ib} the cracks which occurred on the inner side of inclusions were categorized as “inside” and those on the outer side as “outside”.

3. Distribution of principal stress near inclusion and crack tip

Fig.2 shows whole images of isochromatic fringes of test specimens on which stress freezing was performed. In this figure, Young’s modulus of inclusions are: (a) 3.86Gpa, (b) 3.93Gpa and (c) 4.26Gpa.These images,starting at the top and going clockwise,there is an Inclusion with no cracks, distance of inclusion and cracks are 2mm, 4mm, 6mm. These images are when revolution speed was at 1600rpm, and the isochromatic fringe order near crack tips 13 fringes in

Table 1 Young’s modulus of inserts and rotating disc

Weight ratio	100:20	100:25	100:40	disc
Young’s modulus E [GPa]	3.86	3.93	4.26	3.67

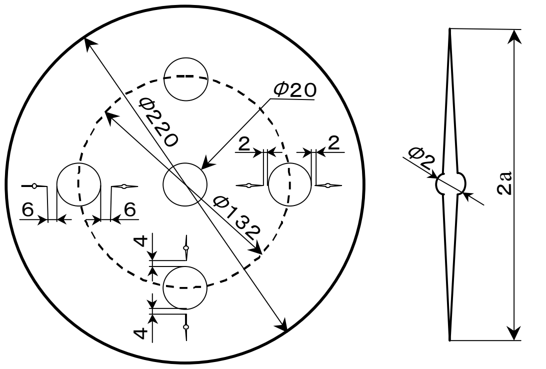
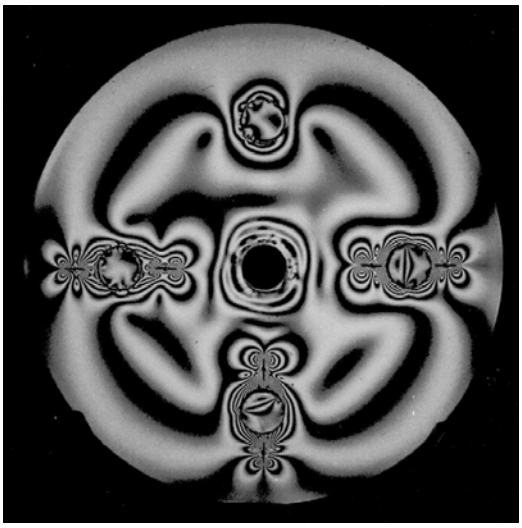


Fig.1 Dimension and shape of specimen

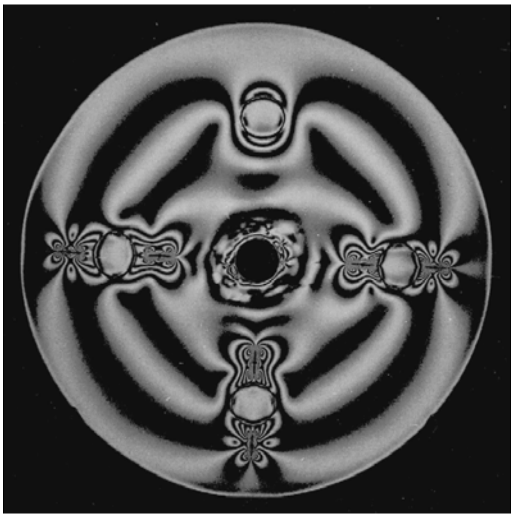
maximum. Figure 3 shows the isochromatic fringe loops and caustic patterns around crack tips of each test specimen. In this figure, (a) is the case that there is no crack and (b), (c) and (d) are the case that the distances from inclusion to crack tip are 2mm, 4mm and 6mm, respectively. Isochromatic fringe loops appeared as fringes symmetrically against cracks. All caustic patterns were approximately perfectly round, although when the distances from crack tips to inclusions were comparatively short, they were a little vague because the patterns were overlapped by the images coming from inclusions like the image shown in each specimen (b). From the above, all test specimens are not affected by mode Ⅱ, Accordingly, in this experiment, K_{I} only was researched on.

4. Stress intensity factor of cracks on the inner side of inclusions (center side)

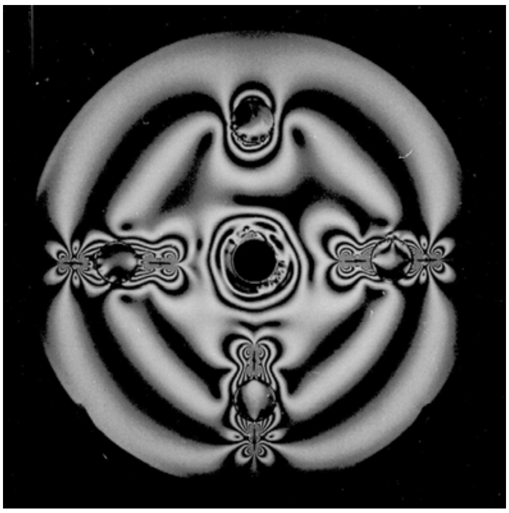
Fig.4 (a) and (b) shows the relation between the stress intensity factor KI obtained by photoelasticity and method of caustics and the distance from inclusion boundary to crack tip. Fig.4 (a) shows the stress intensity factor of cracks on the circumference side (inclusion side) and (b) shows the value on the center point side. It shows that when cracks are on the inner side of inclusions, the value of stress intensity factor KIa become larger. In particular, that trend appeared when Young’s modulus of inclusions were 3.86Gpa and 3.93Gpa. Similar trend also appeared when the stress intensity factor of crack on inclusion was KIb. The larger opening of crack on the side of inclusion, namely, the larger value of KIb is, the larger the value of KIa is. The deformation of crack was controlled by large Young’s modulus of inclusion against base material. When Young’s modulus of inclusion was



(a) 100:20

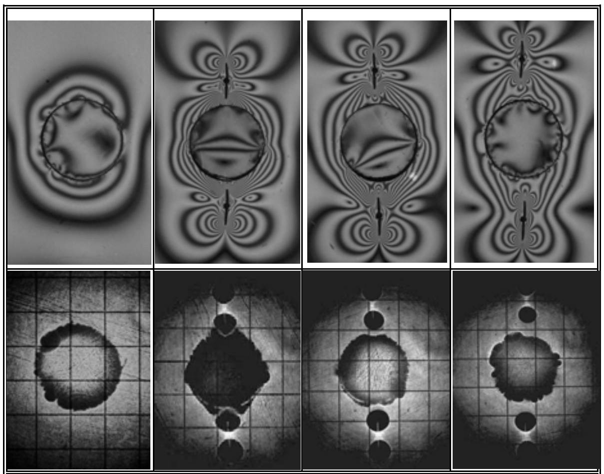


(b) 100:25

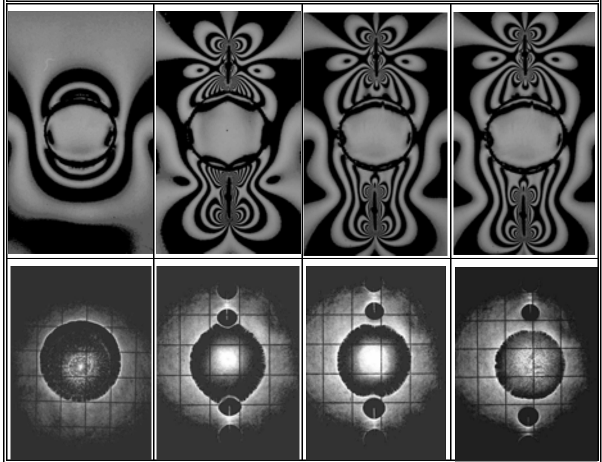


(c)100:40

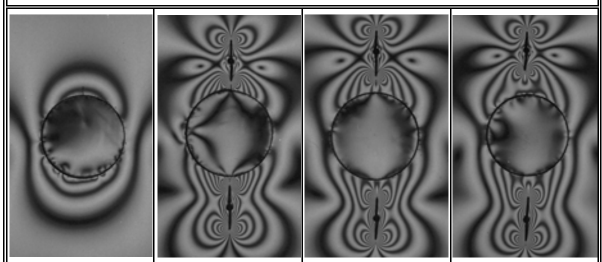
Fig.2 Full field isochromatic fringe pattern of rotating disc

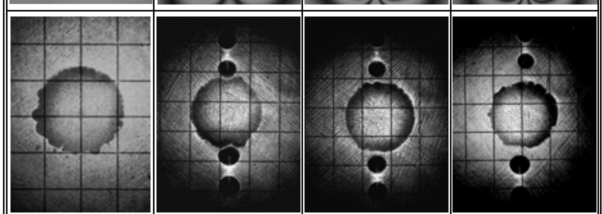


(a) Non crack	(b) 2 mm	(c) 4 mm	(d) 6 mm
E = 3.86 [GPa] (100:20)			



(a) Non crack	(b) 2 mm	(c) 4 mm	(d) 6 mm
E = 3.93 [GPa] (100:25)			



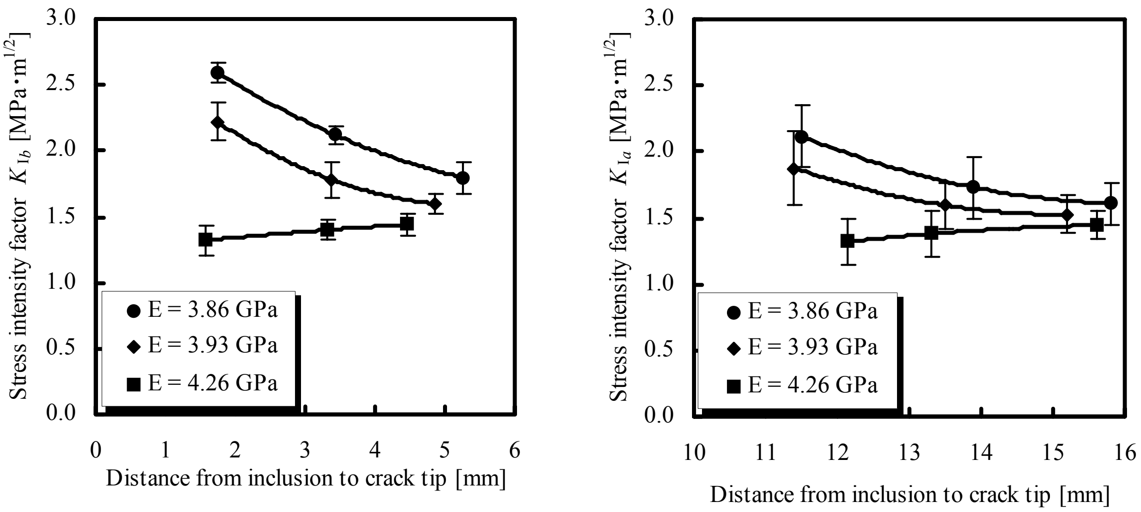


(a) Non crack	(b) 2 mm	(c) 4 mm	(d) 6 mm
E = 4.26 [GPa] (100:40)			

Fig.3 Isochromatic fringe and caustic patterns near crack tip in rotating disc

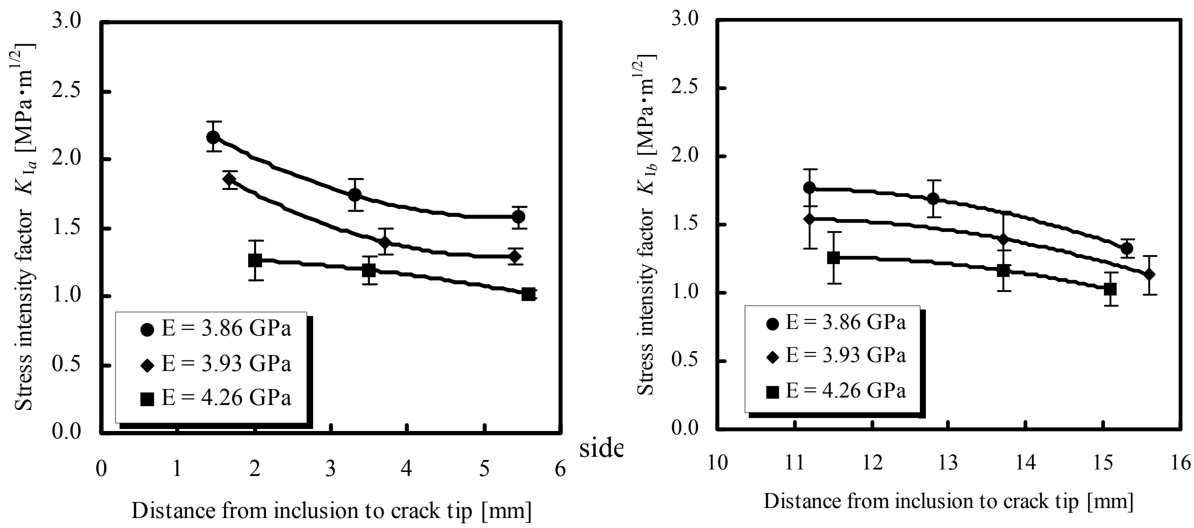
4.26Gpa , the effect of inclusion on deformation of crack was small, and the values of both K_{Ia} and K_{Ib} decreased because the more the crack tip on the side of inclusion come to inclusion, the larger the value K_{Ib} becomes. In the case that there is no inclusion in the revolving disk, there is a trend that the more a crack with a given length is separated from the revolving center, the more the value of stress intensity factor decreases. Furthermore, the stress intensity factor of crack on the side of circumference shows lower value than that on the side of revolving center. However, as clearly shown in this experiment, when inclusions lurk in a revolving disk .if a crack exists in the inner side of inclusion the stress intensity factor of crack on the side of inclusion becomes greater.

5. Stress Intensity Factor of Crack on the outer side of Inclusion (circumference side)



(a) Stress intensity factor values of inclusion side (b) Stress intensity factor values of center of rotation

Fig.4 Relation between stress intensity factor and distance from inclusion boundary to cracktip(inside)



(a) Stress intensity factor values of inclusion side (b) Stress intensity factor values of center of rotation

Fig.5 Relation between stress intensity factor and distance from inclusion to crack tip (outside)

Fig.5 (a) and (b) shows the result. Fig.5 (a) shows the value of inclusion, and (b) shows the value of circumference side. As shown in Fig.5 (a), the more the crack is separated from an inclusion, the more the stress intensity factor K_{Ia} decreases. In a similar way, it shows that the stress intensity factor K_{Ib} on circumference side decreases. It is considered because, although stress intensity factor on circumference side is affected by a crack deformation on the side of inclusion not a little, it is getting close to the trend when there is no inclusion. Furthermore, the larger Young's modulus of inclusion becomes, the more the stress intensity factor decreases. Similar trends were observed about every value. In other words, when there is a crack on the outer side of inclusion, the opening of a crack is controlled by the inclusion.

6. Conclusion

In this study, the behaviors of inclusions and crack tips in a revolving disk were analyzed by a photoelasticity and a method of caustics. As a result of the study about the effects of the mechanical property of inclusion and the distance from crack to inclusion boundary extended on a crack deformation, the following knowledge was obtain:

1) The longer the distance from inclusion boundary to crack tip is, the more the stress intensity factor tends to decrease.

2) The higher the Young's modulus of an inclusion near crack tip is, the more the stress intensity factor decrease.

3) The stress intensity factor of a crack on the center point side of inclusion shows a larger value than that on the circumference side.

References

［1］ M.Isida, Stress Intensity Factors of Rotating Disks with Internal Crack at Arbitrary Position ,Transactions of the Japan Society of Mechanical Engineers,47-414,A(1983),229-234.

［2］ J.G.Blauel, J.Beinert and M.Wenk., Fracture Mechanics Investigations of Cracks in Rotating Disks,Experimental Mechanics,3(1977),106-112.

［3］ T.Ezumi, and S.Takahashi, Stress Intensity Factors for the Mixed Mode in Rotating Disks (Determination by Photoelastic and Caustics Method), Transactions of the Japan Society of Mechanical Engineers,53-494,A(1987),1946-1952.

［4］ T.Ezumi. K.Suzuki and S.Takahashi.,Examination of Stress Intensity Factors of Rotating Elliptic Disks Having Outside Cracks, Proceedings of the Japan Society for Photoelasticity, 21-1(2000),15-20.

［5］ K.Fujimoto and Y.Hashimoto,Elasticity Analysis of Interference Problem of Circular Inclusion and Crack, Transactions of the Japan Society of Mechanical Engineers,61-581,A(1995),20-27.

［6］ C.W.Smith,Photoelasticity in Fracture Mechanics, Experimental Mechanics,20(1980),390-396.

［7］ P.S.Theocaris and E.E.Gdoutos, A Photoelastic Determination of Stress Intensity Factors, Engineering FractureMechanics, 7(1975),331-339.

［8］ H.Ito, K.Nishimura and T.Ezumi, Influence of Mechanical Properties of Inclusion on Deformation of Crack Tip in Rotating Disk (Experimental Examination by Photoelasticity and Method of Caustics), Transactions of the Japan Society of Mechanical Engineers,70-699,A(2004),1609-11615.