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Correlation of Fracture Toughness Determined by Spin Burst Testing and Deep Notch Test†

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Abstract

For the estimation of the fracture toughness of the turbine generator rotor forgings by means of the fracture mechanics, the Spin burst testing which simulates the loading condition in the rotating rotor and the Deep Notch test which was proposed by H. Kihara and K. Ikeda to estimate the brittle fracture initiation characteristics were carried out.

The obtained test results are as follows.

1) *A good correlation of the fracture toughness determined by the Spin burst testing and the Deep Notch test was obtained.*
2) *The effect of the thickness on the fracture toughness of the turbine generator rotor forgings was recognized.*
3) *The dependency of the fracture foughness of the turbine generator rotor forgings upon the temperature was assumed the Arrhenius type dependency in the temperature range tested.*

1. Introduction

The rapid increase in size and rating of the turbine generators has been accompanied by a correspondingly increase in the stress of the turbine generator rotor due to the rotation.

Particularly, during a routine overspeed-trip test, the stress close to the yield strength of the rotor forgings generates in the neighbourhood of the bore hole of the rotors.

In many applications, high strength materials have been employed to limit the ratio of the design stress to the strength of the material.

In general, high strength materials trend to suffer from high ratio of the yield strength to the tensile strength and are liable to initiate the brittle fracture. Accordingly, higher strength materials used for the turbine generator rotor forgings are required higher "fracture toughness" to avoid the brittle fracture initiation.

Concerning the fracture toughness of the turbine generator rotor forgings, there are some reports written by A. J. Brothers et. al.[1], I. Katsura et. al.[2] and H. D. Greenberg et. al.[3]

Recently the making processes of large rotor forgings are developed greatly and also the fracture mechanics is applied to evaluated the significance of the defects in the industry.

In this paper, according to the fracture mechanics, the fracture toughness of the large turbine generator rotor forgings has been evaluated by the use of two testing methods. One is the Spin burst testing which simulates the loading condition in the rotating rotor and the other is the Deep Notch test which was proposed by H. Kihara and K. Ikeda to estimate the brittle fracture initiation characteristics.[4]

2. Material and specimen preparation

The seven types of materials were used for this investigations. The general description of these materials are shown in **Table 1.**

The heat-treatment of the seven types of materials is indicated in **Table 1** also, and the chemical composition and the mechanical properties of the materials are given in **Table 2, 3** respectively.

Four types of steel forgings A, B, C and D were removed from the large steel forgings.

3. Test specimens

The test specimens employed for the measurements of the fracture toughness of the turbine generator rotor forgings are as follows.

3.1 Spin burst testing specimen

Spin burst testing of notched-disks was conducted to evaluate the brittle fracture initiation characteristics of the turbine generator rotor forgings under the loading condition which simulates the actual rotor forgings.

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Table 1 Heat-treatment of tested materials.

Symbol	Material	Hcat Treatment	Remarks	
A	Steel forgings	A	SF55 (JIS G 3201)	Carbon steel forgings
B		Q & T	Ni-Cr-Mo-V steel forging	tempering at 450°C FATT is lower-grade than Material C
C				general
D				re-Q & T affer maching disks
E	rolled steel	N	low alloy steel	HT 60
F		Q & T		
G				HT 80

A — Annealing
Q & T — Quenehing and Tempering
N — Normalized
FATT — Fracture Appearance Transition Temperature

Table 2 Chemical compositions of the tested materials.

Symbol	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	Al	V	B
A	0.37	0.33	0.72	0.013	0.01	0.22	0.17	0.24	0.06	0.002		
B												
C	0.27	0.06	0.29	0.009	0.015	3.75	1.66	0.15	0.45	0.004	0.11	
D												
E	0.17	0.53	1.24	0.013	0.011	0.11	0.14	0.22				
F	0.15	0.40	1.28	0.025					0.26		0.06	
G	0.13	0.30	0.90	0.011	0.005	0.82	0.55	0.23	0.48		0.052	0.003

Table 3 Mechanical properties of the tested materials at room temperature.

Symbol	distance from the center of rotors mm	0.2 % off set strength $\sigma_{0.2}$ kg/mm^2	tensile strength σ_B kg/mm^2	elongation δ %	reduction of area φ %	FATT (V-notch Charpy) °C	FATT (pressed notch Charpy) °C	hardness Hv (10 kg)
A	300	28.9	55.6	27.1	42.6	90	87.5	—
B	300	59.4	86.7	22.0	62.1	11	16	288.3
C	300	68.9	87.0	22.3	61.2	−40	−37	281.8
D	300	59.1	78.1	24.1	63.3	−105	−107	—
E	—	38.6	63.5	31.0	—	45	—	—
F	—	53.0	65.0	18.0	—	−20	0	—
G	—	85.0	88.0	35.0	—	−85	−90	—

The notched-disks are spun at steadily increasing speed in vacuum heavy-walled pit until fracture occurs.

Views of notched-disk specimen set up ready for testing and the driving facilities for the Spin burst testing are shown in **Fig. 1.**

The notched-disks have outer diameter 500 mm, inner diameter 70 mm, thickness 20 mm and 50 mm and the machined notches at the bore hole symmetry with respect to the rotating axis. The notch has a sharp tip of 0.1 mm radius, 0.2 mm wide and 2 mm long. The location and the general geometry of the notched-disk are shown in **Fig. 2.**

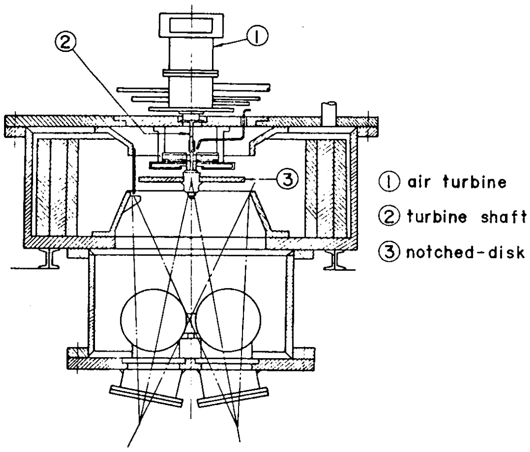
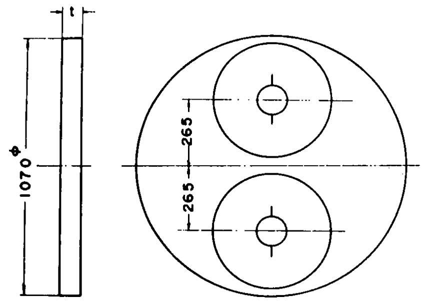
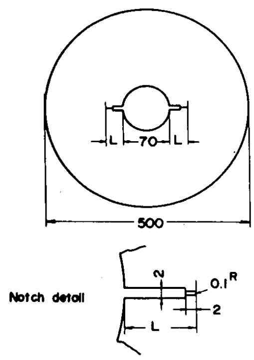


Fig. 1. Driving facilities for the Spin burst testing.





Specimen symbol	Thickness t mm	Notch length L mm
A-1	20	40
A-2	20	20
A-3	20	40
A-4	20	5
A-5	50	40
A-6	50	40
B	20	40
C-1	20	40
C-2	20	40
D-1	20	115
D-2	20	40
E	20	40
F	20	40
G	20	115

Fig. 2. Location and geometry of notched-disk.

3.2 Deep Notch test specimen

The Deep Notch test was conducted in order to estimate the brittle fracture initiation characteristics of the turbine generator rotor forgings. The specimen location in the rotor forging and its configuration are shown in **Fig. 3.**

The specimen has a size of 500 mm×400 mm, and the notch length is 120 mm. The notch has a sharp tip of 0.1 mm radius, 0.2 mm wide, which proves that the radius is equivalent to a natural crack from the view of the brittle fracture initiation characteristics.

In order to estimate the effect of the specimen thickness on the brittle fracture initiation characteristics, the specimen 20, 50 and 100 mm thickness were tested.

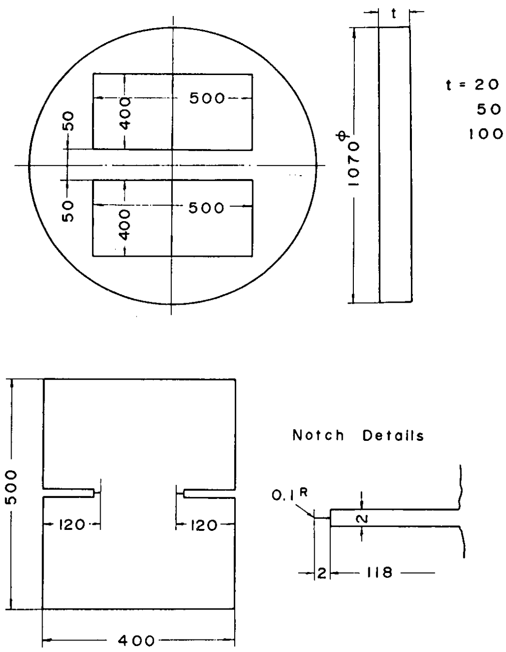


Fig. 3. The Deep Notch test specimen.

4. Test results

4.1 Spin burst testing results

In the case when the notched-disk is steadily turning at the constant angular speed ω (rad/sec), the net nominal stress for a notched-disk is given taking account of the area reduction due to the presence of the notches.

$$\sigma_{net} = \frac{\rho\omega^2}{3} \cdot \frac{R_2^3 - R_1^3}{R_2 - R_1 - L} \qquad (4.\ 1)$$

where, R_2 -outer diameter of the notched-disk

R_1 -inner diameter of the notched-disk

L -notch length

ρ -density of material

and also, the mechanical condition of the notched spin disk is represented by means of the stress intensity factor K which connects the local stress field around the crack tip of the notched spin disk to the centrifugal force due to the rotation.

For a notched spin disk in **Fig. 2,** Winne, D. H. and Wundt, B. H.[5] developed the stress-intensity factor K_I based on the results of the Bowie's analysis[6].

$$K_I = \sigma_{net}\,(\pi R_1)^{1/2} \cdot \frac{3(3+\nu)\,(1-X-X\lambda)}{8(1-X^3)\,F(\lambda)} \qquad (4.\ 2)$$

where, ν-Poisson's ratio, $X = \frac{R_1}{R_2}$, $\lambda = \frac{L}{R_1}$

and $F(\lambda)$ is a function of λ as shown in **Fig. 4.**

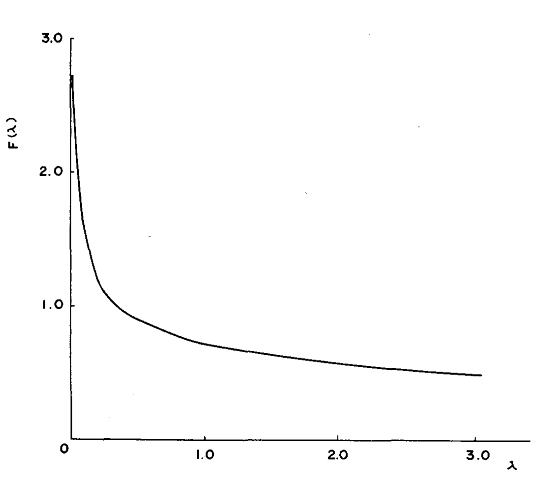


Fig. 4. Values of $F(\lambda)$ for K_I determination of notched Spin Disks.

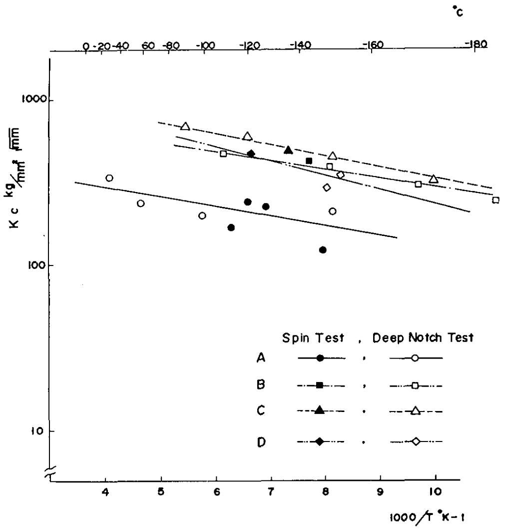


Fig. 5. The Spin burst testing and the Deep Notch test results.

Table 4 The spin burst testing results.

Symbols of notched disk	Fracture temperature °C	Fracture net stress σ_{net} kg/mm²	0.2 % Off-set strength $\sigma_{0.2}$ kg/mm²	Fracture toughness K_{IC} kg/mm²·$\sqrt{mm}$
A—20—40	−148	9.44	54	113.4
A—20—20	−129	20.21	47	230.1
A—20—40	−114	13.04	42	156.7
A—20—5	−122	32.56	45	243.3
A—50—40	−138	10.76	50	129.3
A—50—40	−139	8.65	51	103.9
B—20—40	−144	34.26	98	411.8
C—20—40	−142	26.60	96	319.7
C—20—40	−137	38.43	94	461.9
D—20—115	−135	38.81	85	417.9
(D—20—40)	−133	47.63	84	572.5
E—20—40	−118	23.29	60	281.1
F—20—40	−124	39.51	67	474.9
G—20—115	−129	49.62	59	534.3

Note; D—20—40 Did not fracture at the speed 13570 r. p. m.

Conducting the Spin burst testing, the fracture net nominal strength and the fracture toughness are obtained by the equations (4. 1) and (4. 2) respectively.

The test results are shown in **Table 4** and **Fig. 5.**

4.2 Deep Notch test results

In the case when the Deep Notch test specimen is statically loaded, the net nominal stress for this specimen is calculated ignoring the presence of the notches and its stress concentration effects.

$$\sigma_{net}=\frac{P}{2(b-a)t} \tag{4. 3}$$

where,

P-applied load

a-notch length

b-half width of the specimen

t-specimen thickness

and also, the mechanical condition of the Deep Notch test specimen is indicated by the stress intensity factor K as follows[6].

$$K=\sigma\sqrt{\pi a}\ f(\gamma) \tag{4. 4}$$

The modification coefficient $f(\gamma)$ is a function of ratio of notch length to half width of specimen-$\gamma=a/b$

$$f(\gamma)=\sqrt{\frac{2}{\pi\gamma}\left(\tan\frac{\pi\gamma}{2}+0.1\sin\pi\gamma\right)}$$

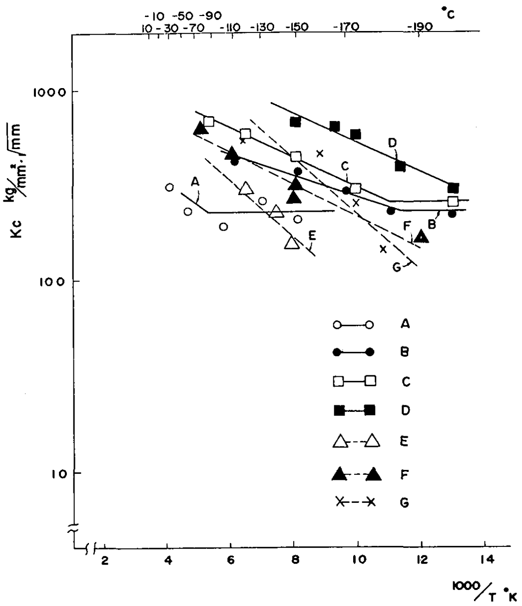


Fig. 6. Dependency of fracture toughness of tested materials on temperature; thickness-20 mm.

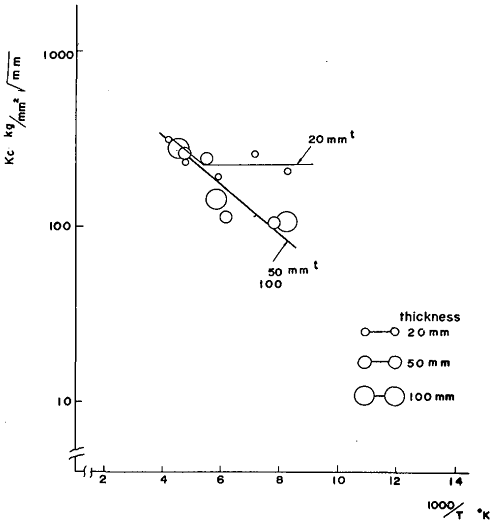


Fig. 7. The effect of thickness (Material A).

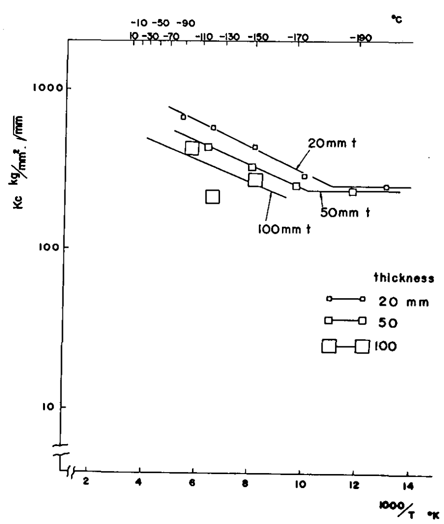


Fig. 8. The effect of thickness (Material C).

where, σ-uniform gross stress $(=P/2bt)$

Conducting the Deep Notch fracture test, the fracture net nominal strength and the fracture toughness is evaluated by the equations (4. 3) and (4. 4) respectivery.

The Deep Notch test results are shown in **Fig. 6.**

And the test results of the Spin burst testing and the Deep Notch test are plotted in the same coordinates of **Fig. 5.** The effect of the thickness on the brittle fracture initiation of the turbine generator rotor forgings is shown in **Fig. 7** (Material A) and **Fig. 8** (Material C).

5. Conclusions

The conclusions which were obtained from the Spin burst testing and the Deep Notch test results are as follows.

1) A good correlation of the fracture toughness determined by the Spin burst testing and the Deep Notch test was obtained (c. f. **Fig. 9**).

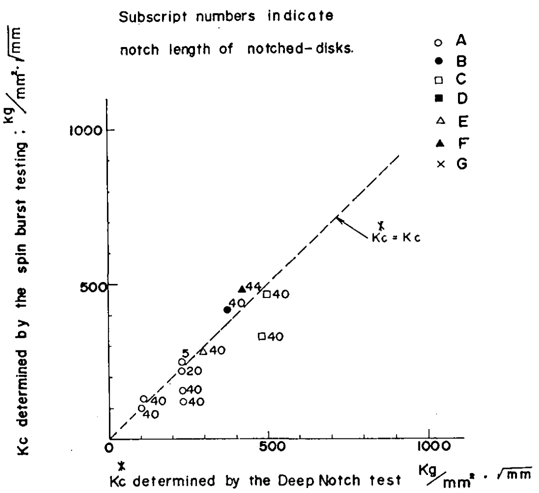


Fig. 9. Correlation of fraction toughness between Spin burst test and Deep Notch test.

2) The effect of the thickness on the fracture toughness of the turbine generator rotor forgings was recognized by the Deep Notch test, in the material A its effect disappeared more than 50 mm thickness but in the material C did not varnish up to 100 mm thickness.

   Therefore, in estimating the fracture toughness of the turbine generator rotor forgings by means of the fracture mechanics, the Deep Notch test specimen of at least 100 mm thickness must be used.

3) The dependency of the fracture toughness of the turbine generator rotor forgings upon the temperature was assumed the Arrhenius type dependency in the temperature range tested.

References

1) Brothers, A. J. Newhouse, D. L. and Wundt, B. M. "Results of Bursting Tests of Alloy Steel Disks and Their Applications to Design against Brittle Fracture" Paper No. 93. Presented at the ASTM Annual Meeting. ASTM, Philadelphia.

2) I. Katsura, K. Watabe, M. Katsuta and A. Takei; "Bursting Tests of Materials for Rotors of Large Turbine-Generators" Jour. of the J.S.M.E. Vol. 64, No. 507, April, 1961.

3) H. D. Greenberg, E. T. Wessel, W. G. Clark, Jr. and W. H. Pryle "Critical Flaw Sizes for Brittle Fracture of Large Turbine Generator Rotor Forgings" Scientific Paper 69-1D9-MEMTL-P2, Dec., 1969.

4) H. Kihara and K. Ikeda; "On Brittle Fracture Initiation (Second Report) -Brittle Fracture Initiation Characteristics- Jour. Soc. Naval Arch. Japan Vol. 120, P 207, 1963.

5) Winne, D. H. and Wundt, B. H.; "Application of the Griffith-Irwin Theory of Crack Propagation to the Bursting Behavior of Disks inching Analysis and Experimental Studies" Trans. A.S.M.E. 80, 8, Nov., 1958.

6) Paris, P. C. and Sih G.; Synposium on Fracture Toughness Testing and its Application ASTM STP 381, 1965.