FAILURE ANALYSIS OF A GENERATOR ROTOR WITH A DEEP CRACK: FRACTOGRAPHY AND FRACTURE MECHANICS APPROACH

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A generator rotor was retired from service due to a large transverse crack. It was clarified that the crack started at a surface defect placed at the root of a tooth, critical under the anomalous high flexural stresses induced by particular problems typically occurring at the beginning of rotor life. During the following years, the crack grew mainly during transients and not during operation; that was the reason why the crack could not be detected by on-line vibration monitoring for most of the time.

INTRODUCTION

This paper deals with an activity of failure analysis performed by CISE and ENEL on a generator rotor, which was retired from service after approximately 131000 operating hours and 400 start-ups, due to a remarkable increase in the amplitude of vibrations during rotation. A campaign of in-situ ultrasonic inspections, carried out with winding installed, revealed the presence of a large crack inside the component, located close to the driven end-face; such findings were confirmed by the results of an analytical simulation study of the dynamic behaviour of the rotor, accounting for a hypothetical defect. After dismantling the coils, a large transverse crack became actually visible, extending on the external surface of the rotor for more than 180°. A large transverse section, containing the defect, was cut from the rotor and subjected to additional non-distructive inspections (US and magnetic particle inspection); on the basis of such indications, further machining was performed, in order to obtain the thinnest possible slick containing the whole crack, which extended through approximately 60% of the cross sectional area. The slick was broken open by high-cycle fatigue in CISE Materials Laboratory, by means of a servo-hydraulic test machine with 250 ton capacity and using low loads in order to avoid serious disturbances to the original crack tip. A sketch of the rotor transverse section with the crack is shown in Fig.1.

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FAILURE ANALYSIS

The general aspect of the fracture surface is shown in Fig.1. The elliptical shape of the beach marks indicates clearly that the crack started at the root of the first tooth near to the magnetic pole. At the starting site, a big forging defect is emerging at the root of the tooth (Fig.2). Fractographic analyses in a scanning electron microscope and metallography on a section demonstrated the defect to be a lap, about 3 mm long at the surface along the tooth root and almost 20 millimeters in depth. The sketch in Fig. 3 shows the two projections of the defect on the circumferential and transverse plane of the rotor (in both cases a semielliptical shape was chosen to approximate the actual shape).

From the lap a circumferential crack originated (possibly due to radial load cycles associated to start-ups); but the crack after some millimeters changed its direction gradually towards a transverse plane, indicating that since the beginning flexural longitudinal loads gave a contribution.

The ΔK values at the initial defect were estimated using the stress values obtained in radial and in longitudinal direction by finite element calculations made by the constructor. Under such loads, the Newman-Raju (1) formulas for semielliptical surface defects were applied to the two projected defects of Fig.3, obtaining $\Delta K = 18$ MPa$\sqrt{}$m for radial stresses applied to the circumferential projection of the defect (Fig.3a) and $\Delta K = 1.8$ MPa$\sqrt{}$m for longitudinal stresses in normal operating conditions. At the beginning of its working life, during some of the first start-ups, some problems of oil film instability (due to particular design of main bearings) induced anomalous resonant vibrations at 1,000 rpm, for several minutes; from vibration monitoring and calculations, a load peak of $\sigma_{max} = 120$ MPa was evaluated for these fatigue cycles at $R = -1$. In this condition, $\Delta K = 10$ MPa$\sqrt{}$m was calculated at the projection defect of Fig. 3b. As described in the following section, these ΔK values were compared with threshold ΔK values and the defect resulted to be critical for fatigue crack growth. The number of cycles estimated from on-line vibration monitoring during that anomalous behaviour was large enough (about 45000 cycles) to allow consistent crack propagation. Actually the first beach mark, corresponding to the beginning of normal operation is at 15 mm on one side, 50 mm on the opposite, 30 mm in radial direction (all these are distances from the defect location).

The crack propagation phase is clearly due to high cycle fatigue induced by flexural longitudinal loads, typical of both service conditions and vibrations at critical frequencies during transients. A good correlation was found between the history of the rotor and the sequence of the beach marks (B.M.) on the fracture surface, until the previously described first beach mark near the crack origin. In particular a crack stop along half of the crack front was recognized at about half depth and resulted to be due to a revision, with realignment.

The estimation of crack growth rates, by evaluating the ratio between the B.M. interspacings and the number of cycles associated to the corresponding operating periods, yields values lower than 10^{-9} m/s, i.e. in the threshold region, (indicating $\Delta K \approx \Delta K_{th}$ values during operating periods); only during the last service period (when the crack size was enormous) a crack growth of some millimeters was found; only during this last period a big increment in vibration amplitude was detected. On the contrary, the da/dN estimated by the ratio between crack increments between B.M. and the number of cycles at higher loads due to vibrations of the rotor at the critical frequencies (some thousands during each transient) resulted to be higher than threshold. This allows to conclude that during the rotor history the crack grew significantly mainly during transients, precisely while the component was rotating at its characteristic frequencies and not during normal operation.

As the on-line vibration monitoring apparatus is usually readjusted during each stop, it could not detect the crack presence for several years; only during the last (short) operating period, when the crack grew even during normal operation, the on-line vibration monitoring could reveal the crack.

FATIGUE THRESHOLDS

A stress analysis study by the rotor constructor indicated that at the defect position the radial cyclic (tension-compression) stresses during transients (resulting from centrifugal loads, and e.m. forces from electrical wiring) were always below material yield, with stress ratio (R) equal to -2.1 (i.e. mainly compressive fatigue). Moreover, the defect underwent longitudinal cyclic loads induced by the initial problems with $R = -1$. To clarify the possibility of the defect to propagate by fatigue, under such loads, tests were carried out on specimens taken from the rotor to determine ΔK_{th} threshold values. C(T) specimens were used in the more conventional tests with $R = 0$ carried out for reference, and Single Edge Notched Tension SEN(T) specimens when testing at negative R conditions (2). Evidence was found of a decrease of ΔK_{th} with stress ratio (from 10.5 MPa$\sqrt{m}$ at $R=0$ down to 6.4 MPa$\sqrt{m}$ at $R=-3$, Fig.4). Applying these results to the actual situation for the radial stress at the defect site in the rotor (σ_{max} = 250 MPa, and $R=-2.1$), it is found that ΔK_{th} = 6.4 MPa$\sqrt{m}$, leading to (for a semicircular surface crack idealisation) a critical defect length a_{cr} = 0.6 mm. This is well below the resolution level of non destructive techniques (NDT) typically applied at rotor delivering. However, this alarming result must not be emphasized. The actual number of such operational cycles is normally low during the typical life of a plant (about one thousand) and even if they are much above threshold, the total crack growth is expected to be less than one tenth of millimeter during a whole rotor life. In conclusion, fatigue cycling provided by centrifugal and e.m. forces (one cycle at each transient) cannot be held responsible for the cracking of this rotor. The flexural longitudinal bending forces, with R=-1 induce a much lower ΔK than threshold during normal rotor rotation, even with such a large defect. But considering the previously described anomalous resonant vibrations, happening for several minutes at 1,000 rpm, σ_{max} = 120 MPa and R=-1, one obtains from the actual FCG tests, with an approximate analysis considering that the projected crack shape is semicircular: ΔK_{th} = 8.7 MPa√m, and a_{cr} = 3.3 mm. As this size is below the initial defect size the initial defect could actually undergo fatigue propagation, under these anomalous cyclic conditions.

THE EFFECT OF COMPRESSION ON FATIGUE CRACK GROWTH

A reduction of the critical defect size and an increase of crack growth kinetics in the first propagation stage is given by the violation of the Principle of Correspondence of the Fracture Mechanics theory, under partly compression fatigue. There is some evidence in literature (3) that under compressive fatigue loading the fracture mechanics parameter ΔK loses its general capability of uniquely correlating crack growth rates, and the crack growth rate becomes dependent, for fixed values of ΔK, R and crack size a, on the value of σ_{max} (or σ_{min}); or equivalently, for fixed values of ΔK, R and σ_{max}, on the value of a. The values of ΔK_{th} measured in specimens with varying amounts of compressive stresses and final crack lengths indicate such a dependence, as shown in Fig.6. Consequently, once a defect has been detected by NDT, the evaluation whether it will be frozen or not, must take into account the decrease of ΔK_{th} values at decreasing defect sizes. As a general example for a NDT-revealed defect, 3 mm in size, semicircular, under fatigue with R = -1, the threshold condition can be roughly estimated from the two equations (the latter obtained by best-fitting test results):

$$\Delta K_{th} = 1.12 \, \frac{2}{\pi} \, \sigma_{max} \sqrt{\pi a} \tag{1}$$

$$\Delta K_{th} = 10.5 + 0.086 \, \sigma_{max} \tag{2}$$

the solution being: σ_{max} = 68 MPa and ΔK_{th} = 4.7 MPa√m. (It must be remarked that a maximum longitudinal stress of about 60 MPa can be evaluated at the tooth root, due to rotation cycles of this rotor at resonance frequencies during transients). In the traditional approach, not considering this violation of the correspondence principle of Fracture Mechanics at R < 0, one would simply use the threshold as determined from the classical tests involving large cracks: ΔK_{th} = 8.7 MPa√m in this case. The size-dependence of the threshold is a key effect, causing cracks to propagate that otherwise might be supposed frozen. Obviously a factor of ½ in stress intensity reduction means ¼ for the decrease of the critical crack size. Neglecting this fact would therefore provide a strong non-conservatism in integrity analysis involving $R < 0$ situations.

CONCLUSIONS

The crack started at a surface defect placed at the root of a tooth, mainly under the anomalous high flexural stresses induced by particular problems, typical of the configuration in which the rotor was introduced at the beginning of its life. It grew mainly during transients, when the component rotated for some minutes at its own characteristic frequencies. As the growth during normal operation was negligible for many years, on-line vibration monitoring was uneffective in revealing the crack, up to the final growth of the very large crack, when it began to grow even in normal operating conditions.

Fatigue threshold measurements indicated a size dependence of this parameter for negative R values. Due to this effect, the minimum defect size detectable by NDT cannot be guaranteed to be undercritical for fatigue growth.

For a safe operation of such components the following is recommended:
accurate periodical inspections during shut-downs, with a periodicity based on the elapsed number of transients (and not the operational time);
the use of intelligent and more sophisticated vibration monitoring systems, focusing the analysis also on transient periods, could give early indications of growing cracks, much before than in this case history.

REFERENCES

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(3) Yu, M.T., Hopper, T.H. and Au, P., "Fatigue 84", p.179-190.

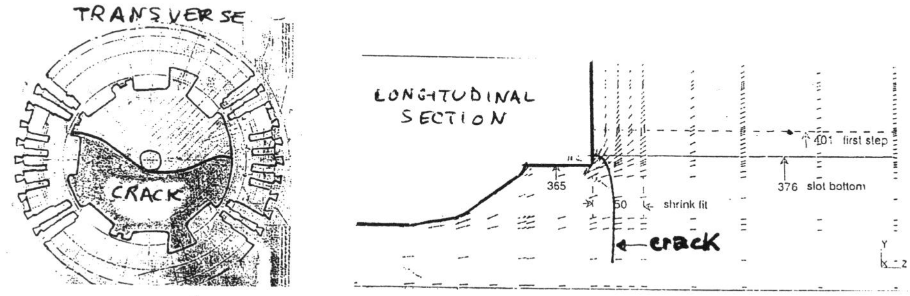

Fig. 1 Sketch of the crack in the rotor

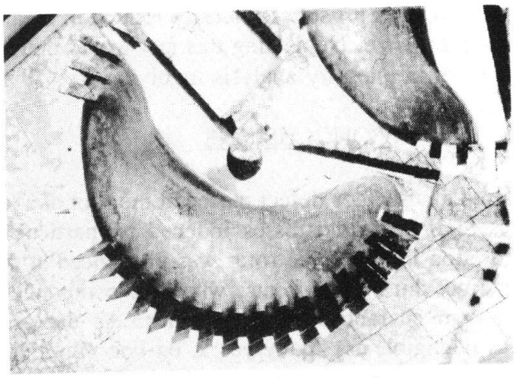

Fig. 2 Fracture surface of the fatigue crack

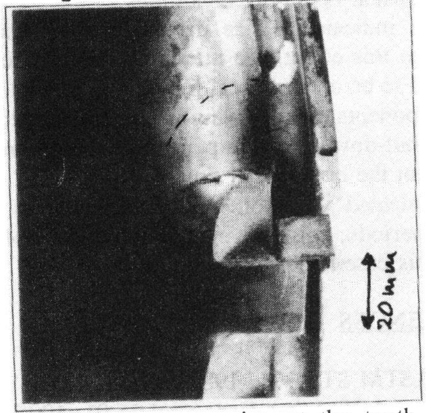

Fig. 3 Defect emerging at the tooth root and the first beach mark

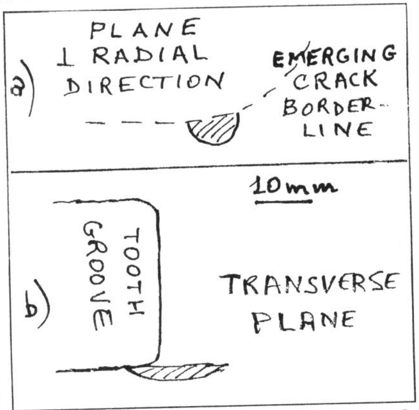

Fig. 4 Defect projections: a) circumf. plane; b) transverse plane.

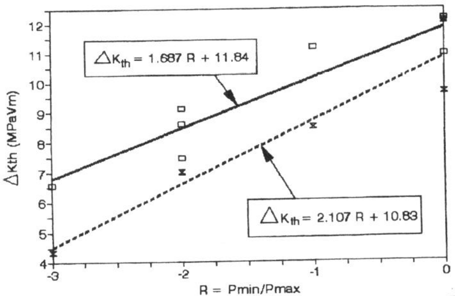

Fig. 5 ΔK_{th} vs stress ratio R

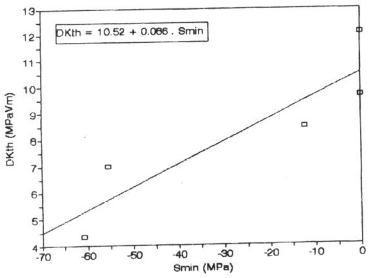

Fig. 6 ΔK_{th} vs σ_{min}