FITNESS FOR PURPOSE QUALIFICATION OF A STEAM TURBINE ROTOR

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A dispute about the effect of a central zone, rich in US indications, on the fitness for purpose of a LP turine rotor for 350 MW electric power plant is described.The attempt of dispute settlement by an analytical procedure for fitness for purpose qualification of rotor based on the fracture mechanics methods is analyzed.

INTRODUCTION

The problem of the rotor quality arose during forging of an LP rotor for 350 MW fossil fuel power plant. The rotor is made of 1.75CrNiMo steel. The routine US inspection after forging revealed a zone rich in US indications in the end part of the rotor, Fig. 1. The total volume of the zone amounts to 0,111 m^3. The US indications are supposed as being non-metallic inclusions. The US indications were quantitatively assessed by number and size at 18 places distributed equidistantly along the central contaminated zone. The total of 396 US indications at all 18 places were recorded. Their average and maximum size range from 0.2 to 0.5 mm and from 0.3 to 1.3 mm respectively. The forge master reported nonconformity to the turbine manufacturer. The rotor manufacturer declared the US indications innocuous and asked a written concession for further rotor processing from the purchaser. The purchaser refused to give the concession and insisted on delivery of a new, nonconformity-free rotor, or alternatively at least on the convincing results of a fitness for purpose qualification of the disputed rotor.

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The manufacturer agreed and selected an analytical procedure based on fracture mechanics methods. The first step in the procedure was to calculate the number of loading cycles needed for fatigue crack to grow to a critical size from US indications as initiation sites. The next step was to calculate the critical crack size for brittle fracture.

In determining the number of loading cycles Paris equation was used. In order to ensure a conservative estimate the following assumptions were made. All recorded US indications at one place were taken as being cracks of the maximum size recorded there. The crack growth of 0.1 mm was taken as critical. The spacing between two neighbouring indications was calculated assuming a uniform volume distribution of indications. Taking into account the flaw size underestimate by US testing the maximum size of US indications was doubled for calculation purposes. The results of the calculation are given in table 1. Determination of the critical crack size for brittle fracture was based on K_{Ic} = 150 MPa$\sqrt{m}$. The critical crack size of 0.72 m was calculated for brittle fracture to occur.

TABLE 1 Calculated number of cycles for fatigue crack growth 0.1 mm*

Location	Maximum operating stress (MPa)	Maximum stress intensity ΔK (MPa$\sqrt{m}$)	Initial crack size ao (m×10-3)	Half distance b (m×10-3)	Calculated number of cycles for crack growth 0.1 mm
Torsional load					
B	140	9.06	2.0	5.0	2.9×10exp4
L	58	2.84	1.3	2.6	4.6×10exp5
O	49	1.70	0.8	3.8	2.2×10exp6
Centrifugal load					
B	75	2.86	1.1	5.0	4.6×10exp5
L	58	2.84	1.4	2.6	4.6×10exp5
O	58	2.02	0.9	3.8	13.0×10exp5

* Calculations are based on the expression: da/dN=10exp-11×ΔKexp3

The purchaser's answer to the results of analytical procedure was negative. He felt the current quality assurance standards were violated by the presence of the extensive US indications zone. Moreover, the purchaser considered the results of the analytical procedure as not convincing enough. The obtained results were taken as too optimistic and highly questionable, in view of the well known detrimental effect of non-metallic inclusions on fatigue resistance and fracture toughness. The purchaser declared readiness to accept the manufacturers conclusions only if the results of the analytical procedure could be confirmed by the experimental determinations on the samples taken from the US indications rich zone. The manufacturer however, refuse any additional rotor testing, which made a further course and final issue of the dispute uncertain. The reason to discuss the dispute in more detail here is a more general significance of relevance of steel cleanness for rotor quality assurance.

DISCUSSION

The most important question to be answered regarding the analytical method used is whether a conservative enough assessment is ensured.

The fatigue crack growth rate curve used for the determination of the number of cycles for 0.1 mm crack propagation, together with the calculated crack rates form are shown in Fig.2. It is seen that only one out of six crack rates, calculated separately for centrifugal and torsional loads, lies on the straight Paris segment of the fatigue crack growth curve. The remaining five calculated crack propagation rates lie on the Paris line extrapolated below the stress intensity threshold. The extrapolation is partly justified by the presence of flaws which by size can be classified as natural short cracks, or alternatively, as their initiation sites. In the presence of short cracks the threshold can be shifted to the lower stress intensity values. This is shown by dotted curves A and B in Fig. 2. Curve C represents the usual dependence of propagation rates of the so called natural short cracks on ΔK. It is seen that only in the case A the extrapolated fatigue growth rate has a conservative value. In the other two cases, (B and C) the extrapolated fatigue crack growth rates are non-conservative. However, for the correct determination of crack growth rates experimentally determined curves B and C should be available. Unfortunately they are not, and all tree curves (A, B and C) in Fig. 2 are drawn arbitrarily just for illustrative purposes.

The segment of the rotor with US indications was cut from the bottom part of a 32 tones ingot. The assumption that the recorded US indications are the only non-metallic inclusions present could be justified only if they were exogenous. However the total number of the US indications recorded and presumable locations of the inclusions in the sedimentation cone of the ingot, rather point to their endogenous origin. In this case the recorded inclusions might be considered as representing the coarsest classes of the total endogenous inclusion population. The entire population of endogenous inclusions should actually comprise a continuous series of finer classes, which were not recorded because they lie by size below the sensitivity level of US testing method. A hypothetical continuous inclusion size distribution curve, with US revealed inclusions taken as coarse size classes and finer size classes calculated on the assumption of log normal size distribution is shown in Fig. 3.

If the US indications marked the presence of endogenous inclusions, then the real spacing between neighbouring inclusions is smaller than those used in the fatigue crack growth rate calculations. In the latter case a number of finer inclusions would additionally be present between two US recorded macroscopic inclusions. The use of higher than real spacings makes the calculated number of cycles increasingly non-conservative. With decreasing spacings the calculated number of cycles for 0.1mm crack growth decreases sharply and gets lower than the contracted number of starts during turbine life time.

The fracture toughness value K_{Ic} = 150 MPa√m used in a critical crack size determination the inception of brittle fracture actually lies on the lower bound for 1.75CrNiMo steel. This value was obtained for steels of higher cleanness level. In view of detrimental effect of non-metallic inclusions on notch impact and fracture toughness the validity of this value for US indication zone in the LP rotor is highly questionable. Consequently, the evaluated critical crack size of 0.72m may be taken as exaggeratedly optimistic.

A technical satisfactory alternative could be the removal of the whole center part of the rotor by making center bore hole. If it would be viable technically it could be proposed as a possible technical solution of the dispute.

CLOSURE

Rotor fatigue lifetime and fitness for failure free operation could not be reliably assessed by an analytical procedure based on fracture mechanics methods. The reason for it lies in the lack of data on natural short fatigue crack growth rates, on the effect on non-metallic inclusions on the fracture toughness of 1.75CrNiMo steel and on the total number and size distribution of non-metallic inclusions in the central US indications rich zone. Without this a satisfactory analytical procedure can not be conceived.

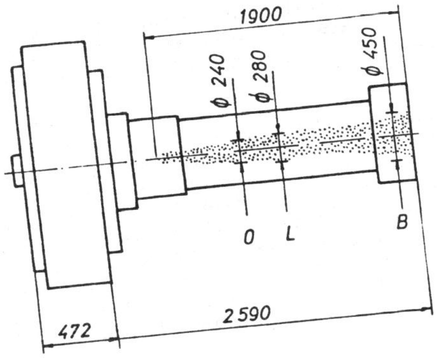

Fig. 1 Shaft end with US indication zone

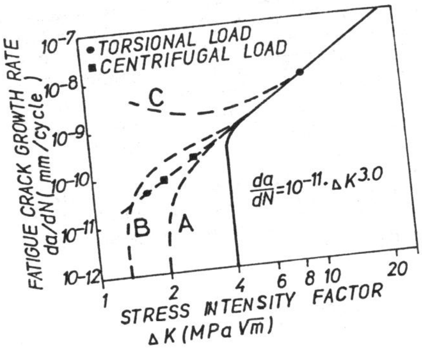

Fig. 2 Fatigue crack growth rate vs stress intensity factor

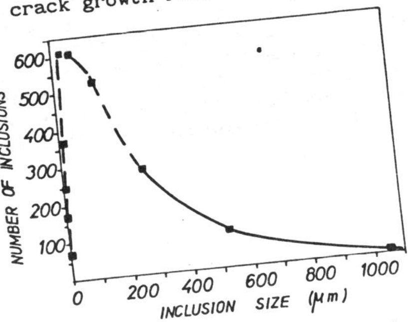

Fig. 3 Non-metallic inclusion size distribution curve