A FRACTURE MECHANICS ANALYSES OF BURIED DEFECTS IN TURBINE DISCS

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SUMMARY

Since sub-surface defects are difficult to detect by NDT techniques, the possibility exists of missing a sub-surface defect which will eventually grow to failure. This paper uses simple linear elastic fracture mechanics (LEFM) theory to consider the implications of sub-surface defects of dimensions relevant to the operating conditions of gas turbine discs. It concludes with a more general discussion of the applicability of LEFM to real defects.

STRESS INTENSITY FACTORS (SIF) FOR NEAR-SURFACE DEFECTS

Very few solutions exist for the SIFs of cracks approaching a free surface, but all indicate that the crack tip nearer the free surface has a higher SIF than the 'buried' end. As an extreme case consider a sub-surface defect which breaks out to the free surface on the first application of a cyclic load. It will immediately be longer than a surface defect of the same original length (depth of penetration into the load bearing area) as the sub-surface defect. It will thus require fewer cycles of fatigue loading to reach instability at the internal end of the crack, and thus establishes a prima facie case for examining the problem in more detail.

It is clear from examination of available SIF solutions that a general analytic solution to the problem of a crack near the base of a turbine disc is impossible, but examination of the parameters of interest allows us to make approximations as follows:

For a turbine disc, the highest stress is the hoop stress, σ_θ, which

decreases radially, Fig. 1, but since the defects we are concerned with are much smaller than the wall thickness, we can use the SIF for a crack near a free surface subjected to a uniform stress [1], typically $\sim$ 800 MPa. In reality the defect will probably be irregular, of finite root radius perpendicular to σ_θ and definitely not a through crack. We assume the worst situation of a sharp through defect normal to the hoop stress which propagates immediately, thus making the following analysis unrealistic as <u>life prediction</u> but not as <u>comparison</u>. Typical defects of interest are in the order of 0.25 - 0.75 mm in length, a_i, with their centres at depth, b, equal to their overall length, see Fig. 1. From [1], for cracks with $a_i/2b = 0.33$, $K_A/K_B = 1.036/1.027$, i.e. the SIF at the end A nearer the free surface is only 1% greater than the SIF at the buried end B. Thus for these defects $K_A \cong K_B \cong 1.03\ \sigma \sqrt{\pi(a_i/2)}$.

TYPICAL MATERIAL PROPERTIES

For a typical gas turbine disc material typical property values are: fracture toughness $K_{IC} \approx 130$ MPa$\sqrt{m}$, and the crack growth threshold range $\Delta K_{TH} \approx 10$ MPa$\sqrt{m}$. Calculation of K_A, K_B using $\sigma_\theta = 800$ MPa yields 16.4 MPa$\sqrt{m}$ for the 0.25 mm long defect and 28.3 MPa$\sqrt{m}$ for the 0.75 mm long defect, the range of values being considerably above the threshold, yet below K_{IC}, thus indicating potential for fatigue crack growth if a fatigue cycle from zero to maximum is assumed (e.g. flight cycle loading of zero to max). Since calculations of this type should check the validity of LEFM, we can calculate the biggest reversed plastic zone at end A from $0.6\ (K_A/\sigma_y)^2$ where σ_y is typically 1,100 MPa, to be $\sim$ 0.4 mm. This is a considerable fraction of the remaining ligament, 0.75 mm, to the free surface, but nevertheless, considerable fatigue growth will still occur before plastic breakthrough.

FATIGUE CRACK GROWTH

Now consider the propagation of a surface crack of length, a_s, and the internal crack of length, a_i, remembering that the internal crack grows from both ends, i.e. its effective length is $a_i/2$. At either end of the internal crack $K_i = 1.03\ \sigma_\theta \sqrt{\pi(a_i/2)}$ and for the surface crack

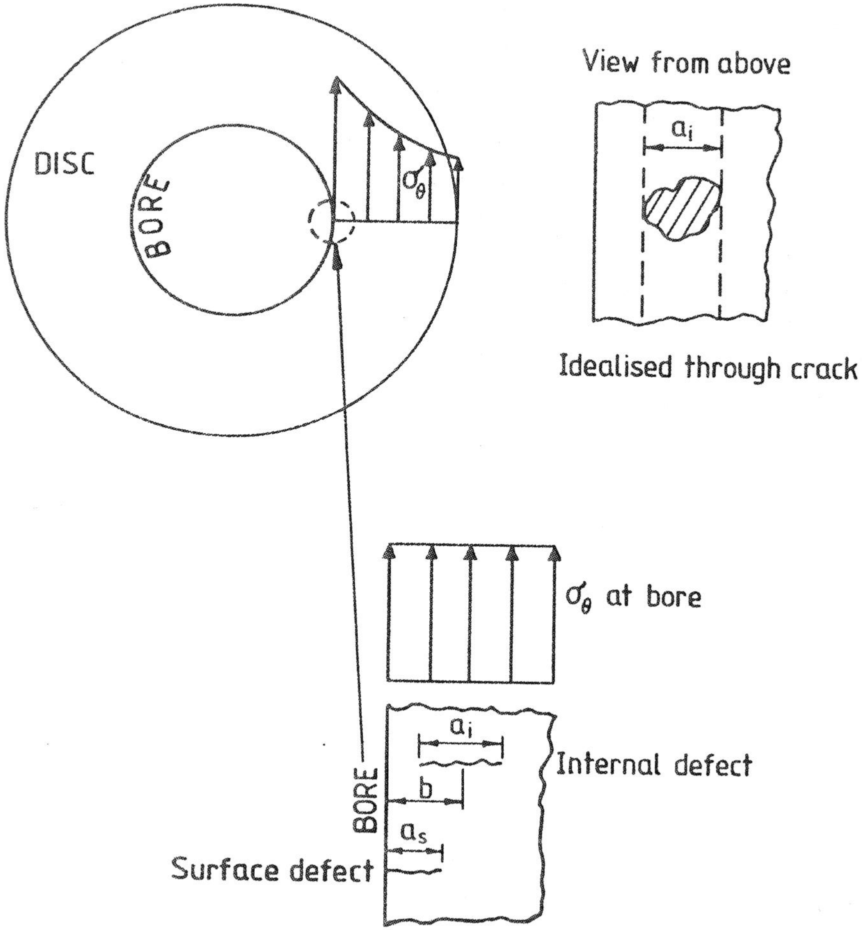

Fig. 1: Defects near the base of a gas turbine disc.

$K_s = 1.12\,\sigma_\theta\sqrt{\pi a_s}$. Now the fatigue life can be obtained by integrating a Paris type law between suitable limits, viz

$$\frac{da}{dN} = C\ (\Delta K)^n = C(\alpha\sigma\sqrt{\pi a})^n$$

$$\int_{a_1}^{a_2} \frac{da}{\alpha^n\, a^{n/2}} = C(\sigma^n\, \pi^{n/2})N_f$$

where a_2 and a_1 are the final and initial crack lengths. Assume α is not a strong function of crack length

$$N_f \propto \frac{1}{[(n/2)-1]\alpha^n}\left\{\frac{1}{a_1^{(n/2-1)}} - \frac{1}{a_2^{(n/2-1)}}\right\}$$

Because a large amount of growth is possible before breakthrough or failure, a_2, makes a negligible contribution, thus the ratio of life, N_s, due to the surface crack, to life due to the internal crack, N_i, can be approximated by

$$\frac{N_s}{N_i} = \left(\frac{1.03}{1.12}\right)^n \left(\frac{a_i/2}{a_s}\right)^{(n/2)-1} \qquad (1)$$

For n = 4,

$$\frac{N_s}{N_i} = 0.36\left(\frac{a_i}{a_s}\right)$$

Thus we can conclude, for the values of stresses and defect size appropriate to the turbine disc problem, that for a buried flaw located with its near edge at a depth equal to size, that

(1) the fatigue life is approximately 3 times longer than a surface defect of the same size,

(2) approximately equal fatigue lives would be obtained if the buried flaw was 3 times larger than the surface defect, and

(3) near surface defects are unlikely to cause worse fatigue problems than defects of the same size breaking the surface.

DISCUSSION

The assumption that the defects are crack-like and grow immediately cyclic stressing begins, is central to the problem of the conservatism of LEFM. It is probable that in many cases most of the useful life of a defected component occurs in sharpening the defect into a crack. Present NDT techniques are not effective in distinguishing between rounded defects and cracks. The acuity of a defect will be determined by the way in which it is produced. For wrought products, the degree of deoxidation and composition of the initial case determines the amount of porosity, segregation and distribution of inclusions prior to working. The shape of these defects will be modified by working, whilst machining, grinding and heat treatment can give rise to crack life defects at the surface. The manufacturing route may also lead to residual stresses in the disc which are difficult to quantify and have been neglected in this analysis. Clearly, service stressing can sharpen and cause the defects to grow, making the analysis of this paper more applicable to remaining life considerations, rather than initial life predictions. The defect v. crack debate is probably more significant than the approximations make is assessing a suitable SIF value. Even for a wide variety of crack shapes due to shrinkage in steel castings, Pook et al [2] found that, $K = \sigma\sqrt{\pi a}$, was a versatile approximation. The use of an index 4 in the Paris crack propagation law may be questioned. If the steeply rising portion of the crack growth curve connecting threshold to linear region is used leading to 'high cycle' fatigue lives, the index in Eqn. (1) becomes much greater than 4, say 9. This reinforces the conclusion about the surface defect having a shorter life, since the internal defect can be shown to have a life some 24 times longer than the surface defect. However, the ratio of crack sizes for the same lives remains largely unchanged.

Finally, the importance of notch acuity can be well appreciated in Fig. 2. The crack in this butt welded joint has chosen to avoid the gross obvious defects, and has initiated and grown from the small but sharp defect at the surface by the toe of the weld. Indeed fatigue lives for welded joints have been recently successfully predicted [3], by measuring the depth of such surface defect and integrating a growth law, without allowing any initiation period.

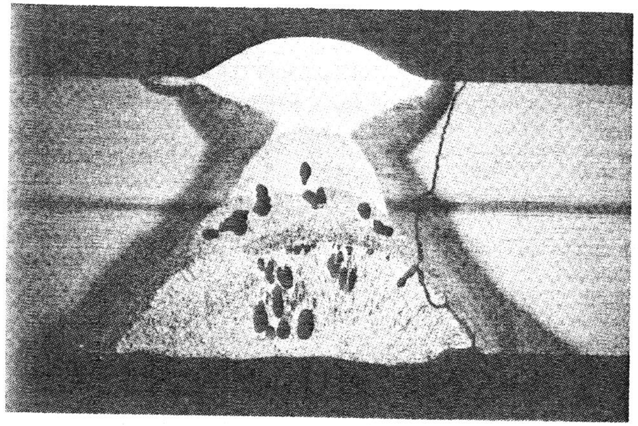

Fig. 2: Fatigue cracking at a defective butt welded joint. (Photograph courtesy of Welding Institute, UK.)

ACKNOWLEDGEMENT

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