EFFECT OF SURFACE CRACK GEOMETRY ON THE FATIGUE LIFE OF HIGH STRENGTH LOW ALLOY STEEL

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ABSTRACT

A study has been made concerning the effect of surface crack geometry on the fatigue life of a high strength low alloy steel connecting rod of a high power diesel motor. Connecting rods are usually designed to have "infinite" fatigue life but they may suffer premature failure in the presence of surface cracks which can be nucleated due, for example, to poor maintenance practice. Finite element calculations were carried out to determine the stress levels developed in the rod during its operational cycle. Using the mechanics of surface cracks, a design curve depicting the relationship between the length and depth for nonpropagating cracks was established. The results have indicated that semicircular cracks as small as 1.8mm in length (i.e. 0.9mm radius) are in fact capable of propagating and that fatigue life would drop by about an order of magnitude as the initial crack length was increased from 2 to 8mm. On the other hand, an 8mm long semielliptical crack was shown to be able to propagate only if it had an initial depth of at least 0.3mm. Increasing that initial depth from 0.3 to 2mm the fatigue life would drop by more than two orders of magnitude.

KEYWORDS

Fatigue limit, Semielliptical cracks, nonpropagating cracks, crack propagation, fatigue life.

INTRODUCTION

Fatigue fracture can occur in high strength low alloy steel motor connecting rods due to poor maintenance practice. Such practice can promote the nucleation of surface cracks, which may then propagate, leading to fatigue failure of these rods. As they are usually designed to work at stress levels below the materials endurance limit and therefore expected to last "indefinitely", their premature failure could have serious implications. Accordingly, the prediction of fatigue life in the presence of surface cracks should represent an important task that is closely related to economic as well as safety considerations. Primarily, fatigue life is determined by crack growth kinetics, which for a given loading condition, depends on the initial geometry and dimensions of the propagating crack.

In the present work, finite element calculations were performed to determine in-service stress levels developed in a steel connecting rod of a high power diesel motor used for offshore oil well perforation. As surface cracks were found to be present, apparently due to inadequate maintenance, eventual failure of the rod by fatigue was considered to be a real possibility. With this in mind, the mechanics of surface cracks proposed by Newman and Raju [1] was adopted and a design curve depicting the relationship between the length and depth for nonpropagating semielliptical cracks was established. Using the same mechanics, growth kinetics and hence fatigue life were estimated for propagating semielliptical as well as semicircular cracks of different initial dimensions.

FATIGUE LIMIT

The connecting rod under consideration was made of a BS 818M40 high strength low alloy forged steel, with a yield stress, σ_Y, and ultimate strength, σ_u, of 710 and 880MPa, respectively. As to the fatigue limit, this was estimated from [2,3]

$$\sigma_e = k_a k_b k_c k_d \sigma_u /2 \tag{1}$$

k_a, k_b, k_c and k_d in the above equation are factors which take into account the effect, on the fatigue limit, of the degree of surface finish, size of the component, confidence limit and service conditions. For normal surface finish and ambient service conditions, it is proposed [2,3] that the factors k_a and k_d be taken as 0.9 and 1, respectively. The size factor k_b which corresponds to the cross sectional dimensions (12 x 42mm) of the rod was estimated following [2] as 0.77. Finally, for a survival probability of 0.99, a confidence limit k_c of 0.814 was adopted [2] and Eqn. 1 was then used to deliver a value of 248MPa for the fatigue limit of the rod. This value should be viewed as only a rough estimate of the steel's endurance limit, given the empirical nature of Eqn. 1. One may also add that Eqn. 1 is, in fact, valid for rotational (fully reversed) bending.

STRESS CALCULATION

The forces acting on the connecting rod during the operational cycle of the motor were estimated from appropriate data referring to both operational and dimensional aspects of the motor's components. The inertia force, driving force and frictional force were taken into account and were assumed to be uniformly distributed over the areas on which they respectively act. The connecting rod was then modeled in the X-Y plane by a number of finite elements (Figure 1), with their third dimension (along the Z axis) corresponding to the rod thickness. An ANSYS 5.1 ED software was used and stresses were calculated for various positions of the rod during its operational cycle. The results obtained have indicated that the region between the holes in the above figure is the most highly stressed area and that stresses there vary between a minimum of zero (no load) and a maximum of about 300MPa. This gives rise to a cyclic loading of stress amplitude, σ_a, and a mean stress σ_m of 150MPa.

The equivalent stress amplitude (σ_{ar}) for a completely reversed loading can be calculated from [3]

$$\sigma_{ar} = \sigma_a / (1 - \sigma_m/\sigma_u) \tag{2}$$

resulting in a value of approximately 180MPa, which is less than the fatigue limit, σ_e, estimated earlier. One may thus conclude that the connecting rod was in fact appropriately designed. However, the presence of surface cracks capable of propagating under the cyclic stress state acting in the rod can lead to its failure and the prediction of fatigue life in this case becomes a necessary undertaking. Establishing a size criterion for nonpropagating cracks, though, should precede such an undertaking.

NON PROPAGATING CRACKS

A crack present in the connecting rod will remain stationary as long as the interval of the acting stress intensity factor, ΔK, is kept below the threshold level ΔK_{th} (taken as $7MPa\sqrt{m}$ for the steel in question [4]). For semielliptical surface cracks (Figure 2), ΔK can be calculated from [1]

$$\Delta K = \Delta\sigma \sqrt{\frac{\pi a}{Q}}\, fgh \qquad (3)$$

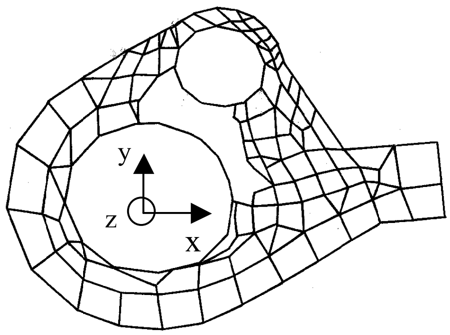

Figure 1: Finite element modeling of the connecting rod head.

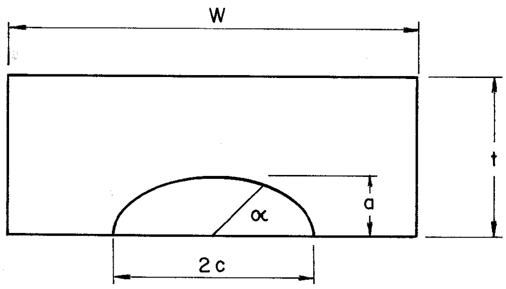

Figure 2: Geometric parameters of semielliptical cracks.

where $\Delta\sigma$ is the stress interval and Q, f, g and h are functions of a, c, t and W, and are given elsewhere [1,5,6]. As shown in Figure 2, the crack depth and crack length are represented by a and 2c, respectively. The angle α defines the angular position of the point on the crack tip where ΔK is to be calculated and t refers to the thickness. For a surface crack, which lies in the highly stressed area along the line of closest approach between the circular holes (Figure 1), W was taken as 52mm, which corresponds to the distance of closest approach measured along that line.

For a given crack depth a, one can determine the largest length such that the crack will not be able to propagate, a condition that is satisfied for $\Delta K = \Delta K_{th}$. Possible combinations of a and c for nonpropagating cracks can thus be obtained and are presented in Figure 3. An important conclusion that can be drawn from this figure refers to the strong influence of the crack depth on the maximum permissible length for values of a around 0.3mm.

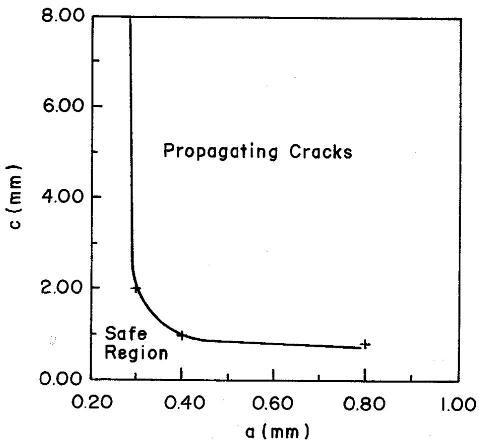

Figure 3: Limiting dimensions for nonpropagating cracks.

CRACK GROWTH KINETICS

Inspections have detected the presence of an 8mm long surface crack in the highly stressed region of the connecting rod. According to Figure 3, semielliptical cracks of that length would be expected to propagate under the cyclic stress acting in that region if they have a depth of at least 0.3mm. The crack propagation rate at the point on the crack front defined by $\alpha = \pi/2$ can be expressed as [4,7]

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{4}$$

where N is the number of cycles and ΔK is given by Eqn. 3 for $\alpha = \pi/2$. The constants C and m for the steel in question were taken as 1.67×10^{-9} mm/cycle and 2.25, respectively, for ΔK in MPa [4].

Equation 4, which is not valid for near threshold crack propagation, is applicable (for ΔK levels far from ΔK_{th}) to all points on the crack front and dc/dN can therefore be obtained from the corresponding value of ΔK (calculated for $\alpha = 0$). One can thus obtain a and c as functions of N by simple integration and are presented in Figure 4 for an initial crack length of 8mm and three different initial crack depths. Notably, the number of cycles to failure was found to drop by two orders of magnitude as the initial value of a was increased from 0.3 to 1mm.

As ΔK varies along the crack tip, the propagation rate would do likewise. In fact the crack propagation is fastest for $\alpha = \pi/2$ and slowest for $\alpha = 0$. This leads to a situation where the crack front will eventually become semicircular (a = c) and the propagation rate will be the same in all directions. If one supposes that the initial crack is semicircular, similar calculations would show that the largest nonpropagating crack, for the cyclic stress under consideration, is of radius $a = c \approx$ 0,8mm. Cracks of larger size are obviously capable of propagating and the variation of crack radius with the number of cycles was determined for two different initial radii of 1 and 4mm (Figure 5). A decrease of about an order of magnitude in fatigue life is seen to be brought about as the crack radius was increased from 1 to 4.

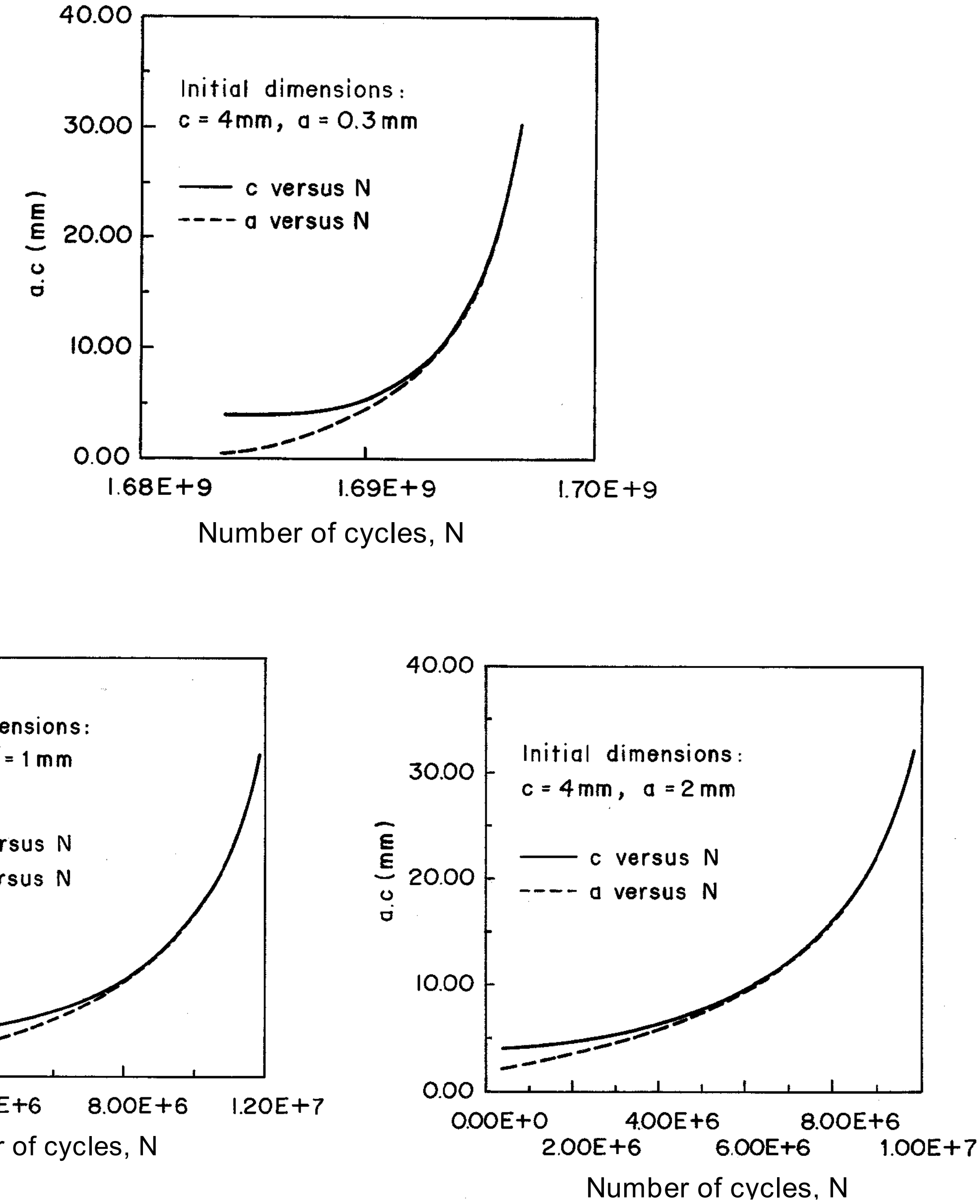

Figure 4: Variation of crack dimensions with N for nonpropagating cracks.

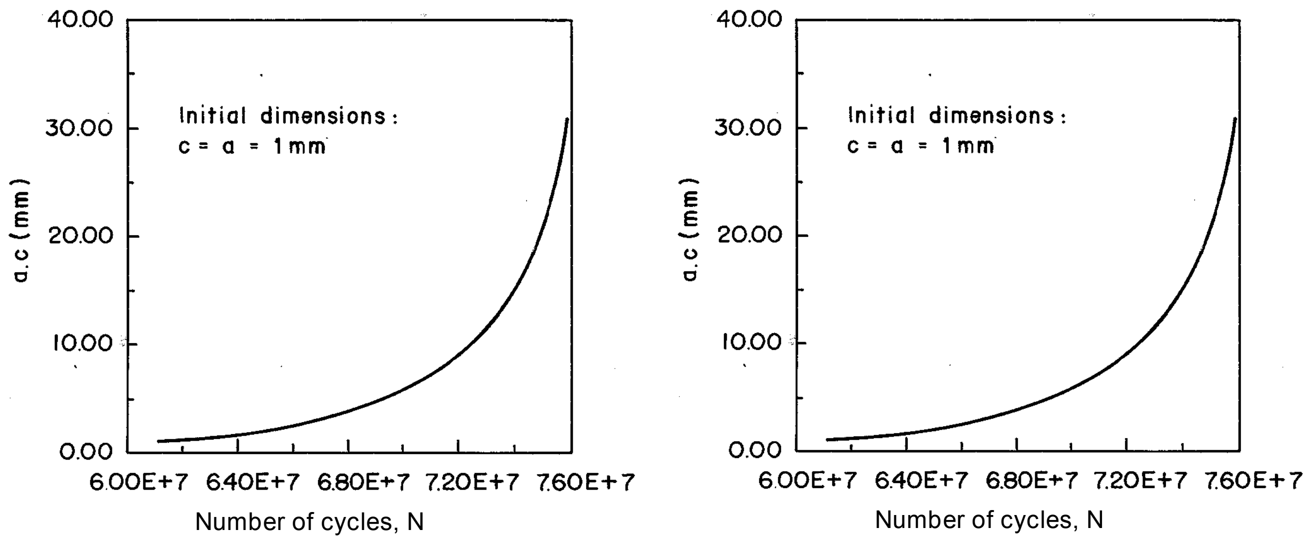

Figure 5: Variation of crack radii with the number of cycles for a semi circular crack of given initial radii.

CONCLUDING REMARKS

Based on the results presented above, the following conclusions can be drawn:

As the equivalent stress amplitude acting in the highly stressed region was found to be less than the steel's endurance limit, the connecting rod in question was considered to be appropriately designed. However irregular motor operation and/or poor maintenance practice can result in the nucleation of surface cracks and these may propagate leading to final failure after a limited number of cycles.

Semicircular cracks as small as 1.8mm in length were shown to be active, i.e., capable of propagating under the cyclic stresses acting in the rod. An 8mm long semielliptical crack would be active only if it has a depth of at least 0.3mm.

In the presence of active surface cracks, fatigue life was found to be strongly dependent on the initial crack geometry and dimensions. For the loading conditions in question, the number of cycles to failure was reduced by about an order of magnitude as the initial length of an existing semicircular crack was increased from 2 to 8mm. For an 8mm long semielliptical crack, fatigue life was found to drop by a factor close to 200 as a result of increasing the initial depth from 0.3mm to 2mm.

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