A SHORT CRACK MODEL FOR FATIGUE LIMIT OF PRESS-FITTINGS IN RAILWAY AXLES

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ABSTRACT

There is an increasing demand for modern fatigue assessment methods to be applied to railway axles especially in high speed train applications, where high strength steel are used. In this paper we develop a fretting analysis based on facture mechanics to axle press-fittings by incorporating the 'short crack effect'. The analytical results have been compared with a series of fatigue tests obtained on small scale specimens.

1 INTRODUCTION

The press fitting zone in railway axles is critical from the fatigue resistance point of view, due to the combined action of contact stresses and wear phenomena, generally called fretting condition [1,2,3]. Under fretting conditions, short cracks nucleate because of cyclic contact shear stresses superimposed onto the fatigue stresses. Giannakopoulos, Lindley e Suresh [4] suggested an approach to fretting based on contact singular stress field, defining an analytical model (*Crack Analogue*) for SIF'determination. Another approach is that suggested by Kondo [5], which is based on the maximum local stress at the contact edge (Hot-Spot stress).

In this paper the fretting problem in press-fittings made of high strength steels is analysed from the fracture mechanics point of view, considering the short crack effect. In fact it has been shown that the scale affects in fatigue strength, which are typical for high strength axles, can be assessed in terms of fatigue threshold for short cracks [6]: it appears therefore important to analize the fretting in terms of short cracks. The research has addressed in particular an experimental investigation and a numerical analysis where FE calculations together with WF have allowed us to determine the SIF at the tip of prospective cracks in the press-fitting. Fatigue limit was then estimated as the threshold condition of the prospective cracks.

2 MATERIAL AND EXPERIMENTAL DETAILS

2.1 3D fretting fatigue tests

Fatigue tests were carried out on small scale specimens (fig. 1) with a press fitting. The diameter of the press fitting is 11mm. Specimens were made of a 30NiCrMoV12 steel (ultimate tensile strength 1050 MPa, yield strength $R_{p0,2}$=995 MPa, cyclic yield strength 730 MPa [6]). A cylinder in R7T steel which simulates the press fitted wheel was mounted onto the specimens. To obtain the desired value of pressure which is about 50-75 MPa, specimens and cylinders were machined to have an interference of 0.0121-0.0184 mm.

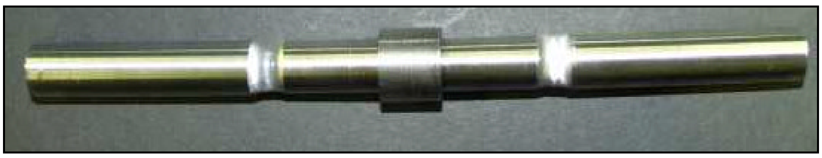


Fig.1: The small scale specimen with a press-fitted cylinder.

Fatigue tests were carried out under rotating bending on a four point machine (capacity 35Nm) at the speed of 1500 rpm. The experimental S-N diagram for 3D specimens at R=-1 obtained with an average contact pressure of 70MPa, is shown in fig.2. The fatigue limit is approx. 200 MPa.

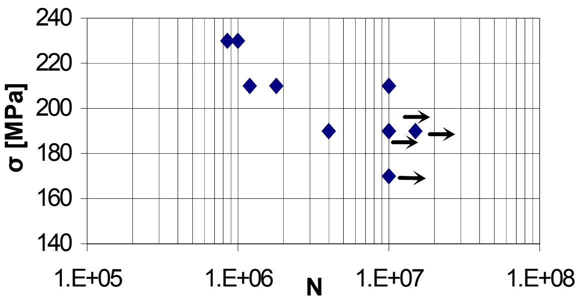


Fig.2: S-N diagram for 3D fretting specimens..

3 EXPERIMENTAL EVIDENCES

3.1 Fractographic evidences

Fractographic analysis shows how the failure zone due to fretting is not located at the end of the contact, but the distance from the contact edge is in the range 0.5-1.2 mm. This is because, even though the tangential stress responsible of fretting failure is concentrated at the contact edge, the stress due to the constant bending is nearly zero.

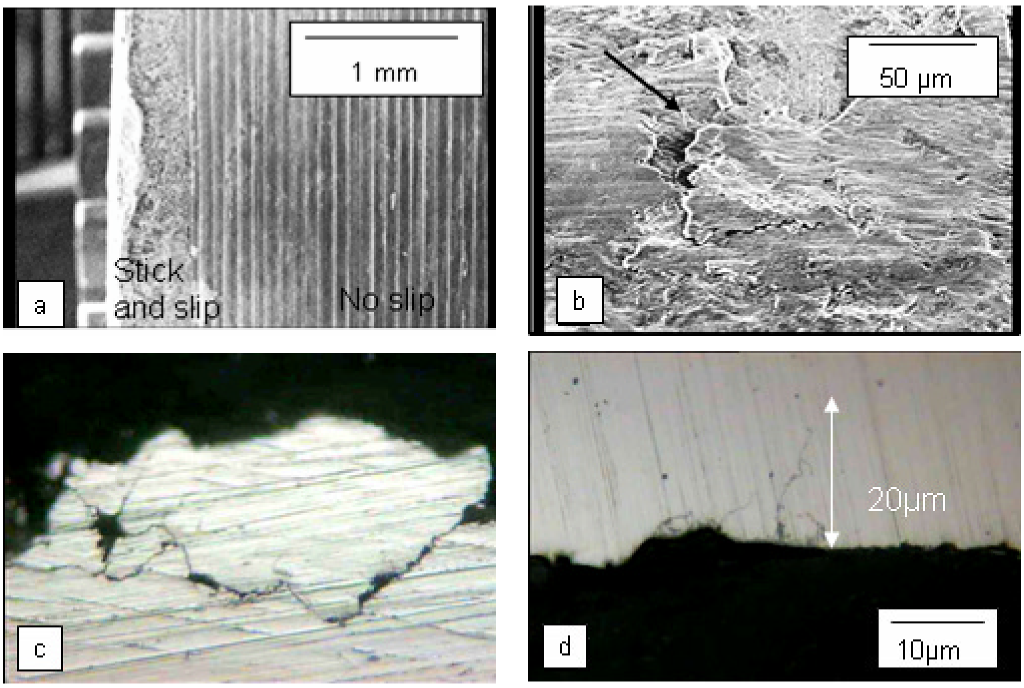


Fig.3: Fractographic observations: a) surface damage near fracture surface; b) fretting scars; c and d) non propagating cracks observed on polished sections.

In fig.3.a it is possible to note the difference between the no-slip zone and the partial slip zone, characteristic of fretting condition, where micro displacements takes place. In fig.3.b the presence of fretting scars is underlined. In fig.3.c and fig3.d several non propagating cracks are observed on polished sections of run-out specimens. In particular, two kind of cracks can be noticed: the first type inclined about 45° from the surface normal. These micro-fractures then can self-arrest or deviate to the second type, which is almost perpendicular to the surface.

4 FRACTURE MECHANICS APPROACH TO FRETTING

4.1 Stress intensity factors

Observed the presence of numerous short not-propagating cracks of a few microns, it is possible to justify the experimental results in terms of fracture mechanics, and then to determine a relation between applied limit fatigue stress and ΔK threshold so justifying this great reduction in fatigue resistance in components working in fretting conditions.

The purpose of the analytical model is to find the trend of the SIF along the crack. Known the contact stresses and consequently the stress field inside the material, K_I and K_{II} are determined using the weight function method: for a surface crack perpendicular to the surface the weight functions used are common in literature, whereas for an inclined surface crack those suggested by Rooke [7] are preferred.

The contact stresses due to press-fitting can be calculated developing a finite element model for each specimen. Denoting σ(x) and τ(x) the normal and the tangential component of the nominal stress along the crack (0≤x≤a) calculated according to a local coordinate system (xOy), the expression for an inclined crack (θ respect to the normal to the surface) is:

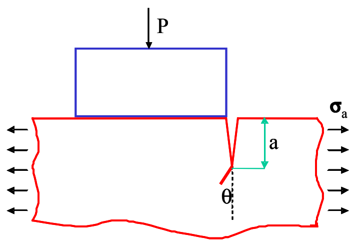


Fig. 4: Schematization of the problem.

$$\begin{pmatrix} K_I(a,\vartheta) \\ K_{II}(a,\vartheta) \end{pmatrix} = \frac{1}{\sqrt{\pi a}} \int_0^a \begin{pmatrix} g_I^p(x,a,\vartheta) & g_I^q(x,a,\vartheta) \\ g_{II}^p(x,a,\vartheta) & g_{II}^q(x,a,\vartheta) \end{pmatrix} \cdot \begin{pmatrix} \sigma(x,\vartheta) \\ \tau(x,\vartheta) \end{pmatrix} dx \qquad (1)$$

where g are the weight functions suggested by Rooke [7].

Whereas for a normal crack the normal stress contributes only for the mode I and the tangential stress only for the mode II, in case of inclined crack both of the stresses contribute to the mode I and mode II of crack propagation.

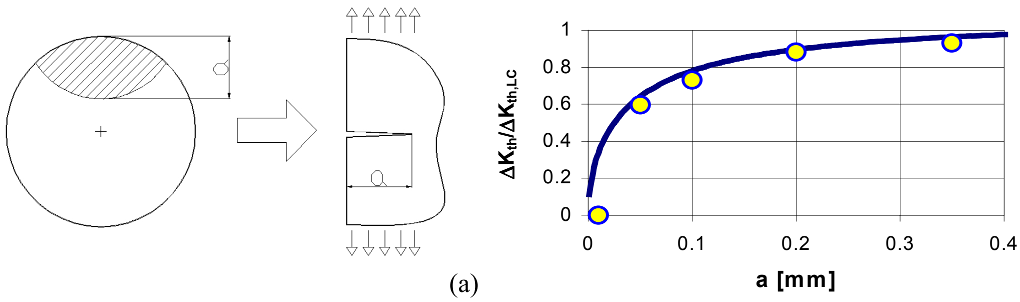
It is observed that the fretting cracks frequently start inclined of an angle θ respect the normal to the surface so that they will propagate below the contact zone, and then they deviates to reach the direction normal to the surface. The first stage for short crack, called "stage I" is principally due to the action of shear stress, whereas the second one, "stage II", is driven by the effect of the normal stresses. In presence of fretting condition, the stage I can be longer because of the high shear stress on the surface; the crack propagates for a few ten microns inclined of about 45° and then it can even stop, because of the high gradient of stress near the surface.

The criteria used to determine the crack growth direction are the MSS (Maximum Shear Stress) criterium for the stage I (mode II) and the MTS criterium for the stage II (mode I), for which the angle of propagation θ corresponds to the maximum K_θ.

4.2 Short crack effect

Threshold experiments for short cracks in 30NiCrMoV12 steel have been obtained with fatigue limit tests on micronotched specimens [6]. In particular data were interpolated with an El-Haddad model (fig.5) [8]:

$$\Delta K_{TH} = \Delta K_{TH,CL} \sqrt{\frac{a}{a + a_0}} \tag{3}$$



(a) (b)

Fig.5: Threshold for short cracks: a) equivalence between elliptical crack and surface crack; b) Kitagawa diagram for surface crack.

5 APPLICATION TO FRETTING

5.1 Stress analysis for the press-fitting

To obtain the stresses along the contact between specimen and cylinder under bending, a detailed FE analysis was carried out (Fig. 6a). Press-fitting was modelled as 'hard contact' with a friction

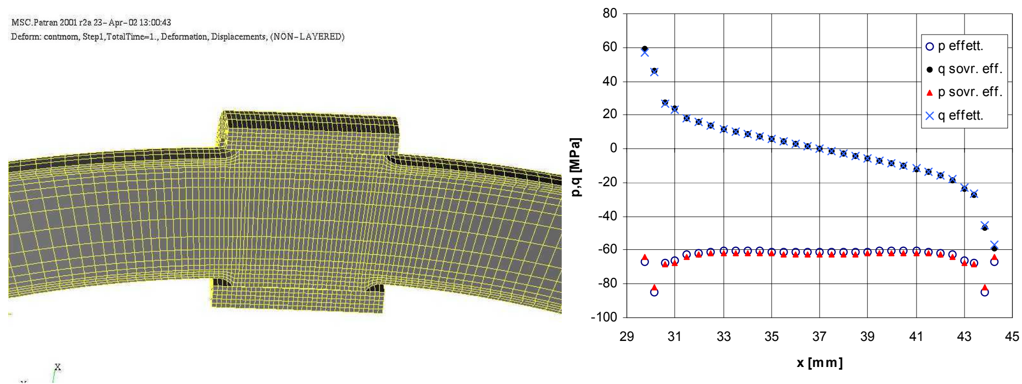


Fig.6: FE analysis: a) 3D specimen finite element model; b) surface contact stresses.

coefficient of 0.5-0.75, which leads to a slip zone at the end of the contact [9]. The stress distribution of contact stresses is shown in Fig. 6b.

5.2 SIF for a prospective crack and fatigue limit

The superficial stresses in the contact zone obtained by the simulation are the sum of two contributions: the stresses due to the nominal bending and the stress due to the press-fitting interference. ΔK_I and ΔK_{II} can then be calculated using Eq. (1) for different crack positions and the driving force for a prospective kink can be calculated according to MSS and MTS criteria [10]. In particular analysis with MSS is able to describe the nucleation of cracks along 45° planes [9].

Fig. 8 shows the values of $\Delta K_{\theta\theta}$ in function of the distance from the contact edge for a 50 μm crack (perpendicular to the surface): $\Delta K_{\theta\theta}$ exhibits a maximum at 0.8mm from the edge, in agreement with the experimental observations. The propagation angle corresponding to $\Delta K_{\theta\theta,max}$ is about 15°, while polished sections show a direction more or less perpendicular to the surface.

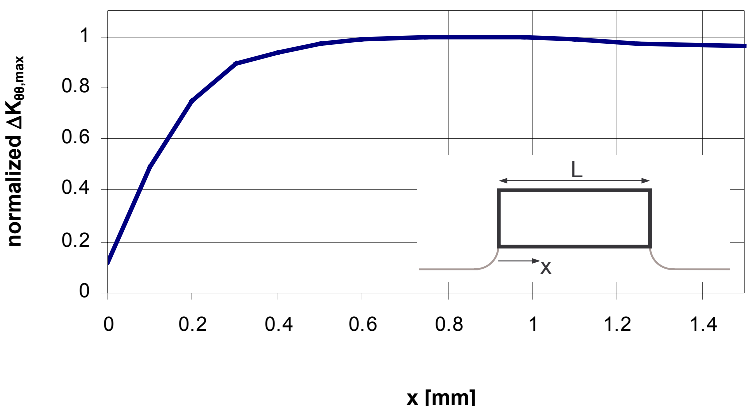


Fig.8: Calculation of $\Delta K_{\theta\theta,max}$ for a prospective crack along the contact edge.

Considering a crack at 0.8 mm from the contact edge with an angle of 15°, the fatigue limit can be expressed in terms of fracture mechanics: fatigue limit is the cyclic stress at which $\Delta K_{\theta\theta,max}$ is equal to ΔK_{th} for short cracks. Both parameters are a function of crack length (see Fig. 9): it can be estimated that the fatigue limit is in the interval from 190 to 210 MPa (the curve $\Delta K_{\theta}(a)$ becomes tangent to the curve $\Delta K_{th}(a)$ as in *'R method'* analysis). However, it should be also observed that the predicted length of non propagating cracks is approx. 25 μm, a value bigger than the depth of the material effectively damaged observed on run-out specimens.

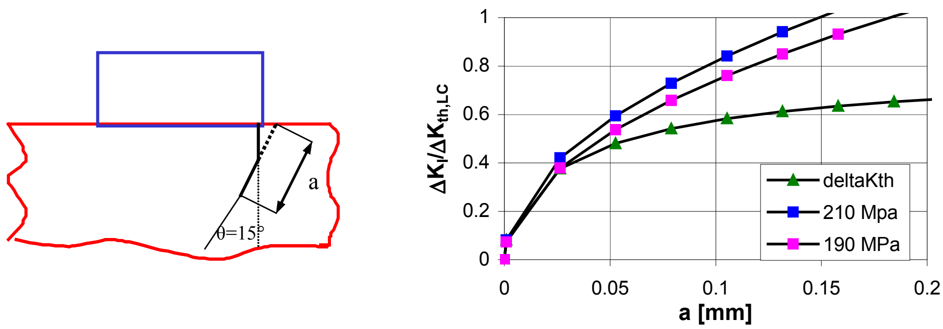


Fig.9: Determination of fatigue limit for 3D specimen.

6 CONCLUSIONS

Fretting of press-fittings is one of the major fatigue problems of axles and new methods need to be developed for assessing the structural integrity of these parts. In particular in this paper a fracture mechanics approach to fatigue strength is presence of fretting is discussed.

To apply the LEFM approach, the SIF's variation ΔK_I and ΔK_{II} along a inclined or not surface crack is calculated. It has been derived the value of ΔK_θ, which compared with the fatigue threshold ΔK_{th}, obtained following the short crack theory, leads to the fatigue limit prediction.. In particular, estimations are very close to experimental results on 3D small scale fretting specimens, even though the predicted length of non-propagating cracks is bigger than the observations.

This method, which leads to calculations similar to those of 'R curve', will also be applied to the estimation of fatigue strength of 'full-scale' press fittings.

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