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FRETTING FATIGUE OF DEEP ROLLED SHRINK FITTED SAMPLES

C. Santus

University of Pisa, Department of Civil and Industrial Engineering, Italy

Abstract: The shrink fitted shaft to hub connection, loaded under bending, experiences Fretting Fatigue at the end of the contact where both stress concentration and microslip are acting. Shrink fitted testing is not standard and common as the bridge type test, however, the round geometry implies no edge effect, the shrinkage and the bending loads can be carefully controlled with strain gages, and the stress distribution easily calculated with finite element analyses. Though the shrink fit compressive state, the cyclic bending introduces tensile stresses, hence the introduction of compressive residual stresses can play a significant role to prevent the initiation and the propagation of the fretting fatigue cracks. Experimental results are reported in the paper where the fretting fatigue strength was remarkably improved after a deep rolling treatment. Numerical analyses even predicted the complete mode I closure of potential fretting fatigue cracks by taking into account the compressive residual stresses. SEM investigation showed how the crack pattern was significantly different with deep rolling, having multiple crack initiation sites and then either coalescence or crack branching. From the modelling point of view, the paper shows that the self-arrest theory cannot be used to assess the fretting fatigue strength, for deep rolled specimens, where the crack remains closed. A better prediction can be obtained with a critical plane multiaxial fatigue criterion, based on the shear stress amplitude, which under a compressive stress state can be more effectively assumed as the driving force of the crack. Consistently the orientation of the plane experiencing the maximum shear stress amplitude was found in agreement with the observed initial crack direction.

Keywords: Fretting fatigue; Deep rolling; Residual stresses; Crack initiation direction

1 INTRODUCTION

The Fretting Fatigue (FF) damage can be experienced in several applications, typically the dovetail interface of turbomachinery [1,2] and also the so called shrink-fitted (tubular or cylindrical) connection [3,4]. Experimental fretting fatigue testing approaches can be categorized as [5,6]: (1) full/small scale simulation of the real fretting problem and (2) idealized fretting fatigue testing where the contact conditions are properly controlled. Fretting tests are well summarized in the book by Hills and Nowell [5], and usually are according to the “bridge” type testing, where bridge means a two sided contact pad indenter. Many examples of this kind of testing are reported in the literature, e.g. the book by Attia and Waterhouse [7] and many other papers. A main limitation of the of the bridge type testing is that the displacement can never be equal at the two sides of the contact, in turn leading to different actual local fretting configurations. This problem can be solved by fixing one side of the contact bridge to the rigid part of the testing frame. This solution is reported in several contributions, e.g. Rossino et al. [8]. The contact configuration in bridge type testing usually is “Hertzian” contact, i.e. cylindrical-to-flat or sphere-to-flat contacts. The “flat and rounded contact” edge problem was tested, under the bridge configuration, by Namjoshi et al. [9]. The lateral edge contact effect was investigated by Kim and Mall [10] along with the issue of plane strain at mid width and plane stress at the sides. Another problem is the misalignment, a tilting angle can cause edge stress concentrations. Moreover the flat contact (either rounded or not) can experience tilting during the load thus producing a not well controlled stress distribution at the contact region. This latter problem is not the case with Hertzian contact, having a rounded geometry, but can be not well controlled in flat and rounded contact. The round geometry proposed in the present paper has no edges and the tilt due to the bending is well considered in the related FE model. The present paper shows fretting tests with a specific shrink-fitted assembly that resembles a tubular connection component, it is also based on the half bridge concept, and it eliminates geometry misalignments and any other edge effects.

The most common approaches to fretting are the analogies either with a crack or a notch [11] and the approach according to Kitagawa-Takahashi (KT) diagram, where the short crack arrest can be evaluated and the size effect is inherently considered [12]. This approach naturally assumes that the fretting is a tensile driven fatigue fracture since small crack propagation is caused by mode I. Another approach is multiaxial fatigue critical plane as reported by Araújo et al. [13] and others, where the shear stress amplitude is predominant. The test results presented in this paper are critically considered with the available approaches and a discussion provided specifically about the initiation crack direction.

2 EXPERIMENTAL ACTIVITY

2.1 Bending setup of fretting fatigue tests

Fig. 1 illustrates the setup of the proposed fretting fatigue testing. The specimen, at the fretting interface, is conical in order to allow a calibration of the shrinkage imposed by means of an adjusting nut. The fretting load is applied according to a bending scheme with of a controlled hydraulic actuator. Two strain gages were used. One strain gage is on the shaft, with axial direction, at a certain distance with respect to the fretting point, for monitoring the actual bending load applied during the test. The other strain gage is applied at the outer periphery of the hub component, along the hoop direction, and it is used to calibrate the interference generated during the nut tightening before starting the fatigue loading.

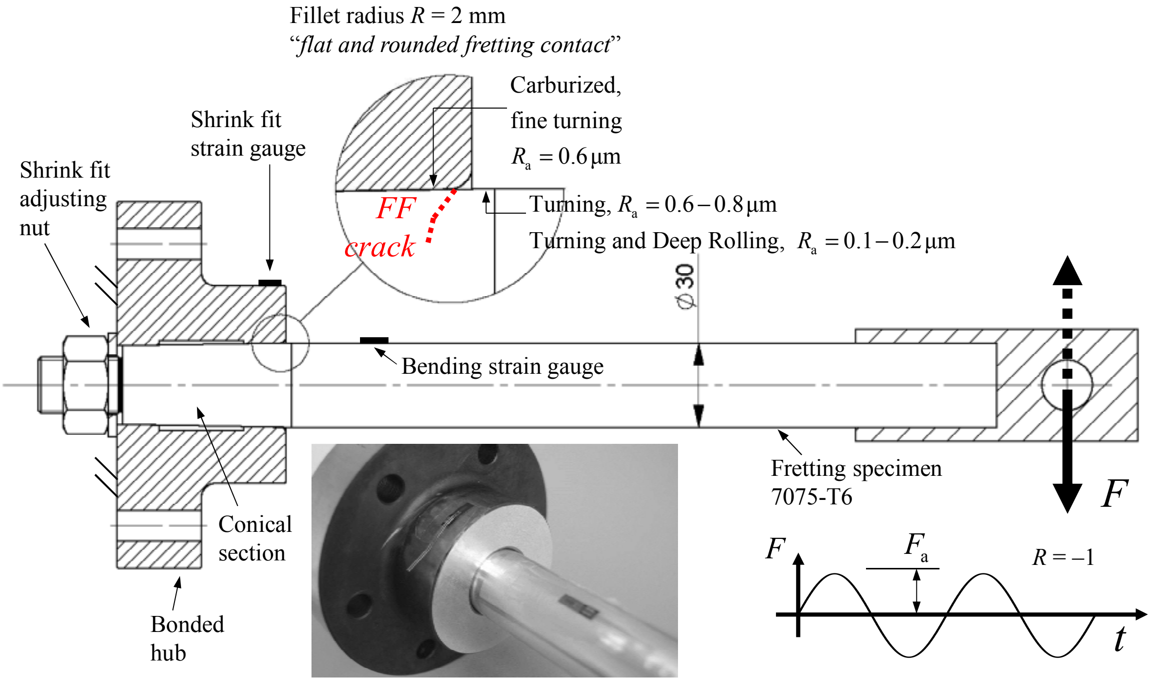
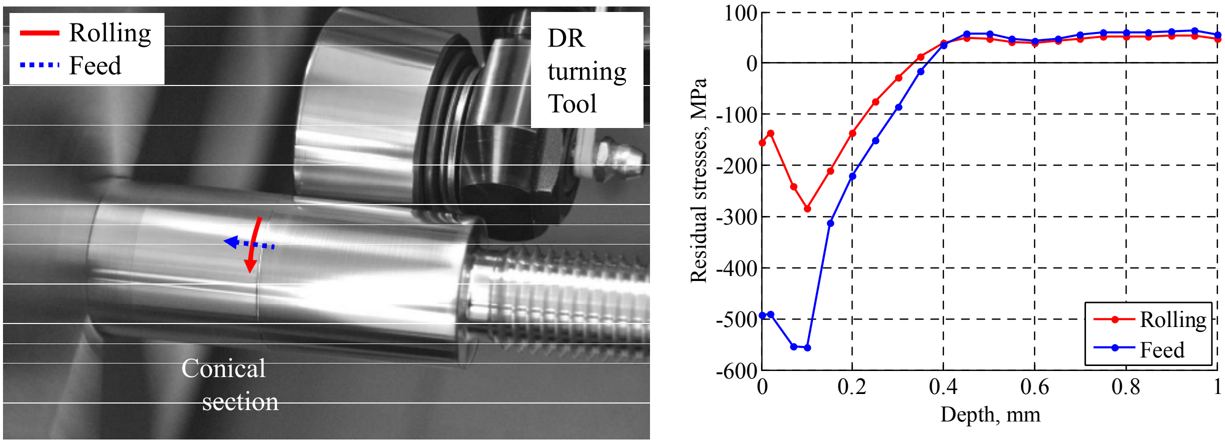


Fig. 1 Test setup, bending load and machining details at the fretting interface.

2.2 Deep rolling surface treatment

Some specimens were Deep Rolled, at the fretting interface (the conical section) to provide a comparison with the untreated specimens. Fig. 2 illustrates the deep rolling process and the residual stresses along the principal directions. More details can be retrieved in Ref. [14] describing both the parameter dependencies and the residual stresses measurements, preliminarily performed on flat samples and then on the shafts.



(a) (b)

Fig. 2 Deep Rolling treatment on the shaft specimen: (a) process, (b) residual stress distribution.

A conical edge contact roller was used and the treatment was performed just by means of a CNC turning machine tool. The treatment is not isotropic, indeed along the shaft axis direction the (compressive) residual stress is quite higher than the other direction, and it is approximately equal to the material yield stress, so introducing the maximum possible beneficial effect.

2.3 Test results

The Fretting Fatigue test results are reported in Fig. 3. Four test series were performed combining both the application of the deep rolling and a lubrication to be initially applied before the interference preload. The test trends are evident and according to as expected: the lubrication reduced the local stresses (the friction shear component) and the residual stresses also increased the strength by hindering the crack initiation and propagation, as usual under fatigue. The highest strength was therefore obtained with both lubrication and deep rolling (series C). Some of the deep rolled tests reported failure outside the expected fretting 'hotspot' since the failure was at the deep rolling edge where the indenter tool was removed. All other tests reported a fretting fatigue crack initiated at the edge of the contact, either at the upper or the lower sides that nominally experienced the same local load, indeed the bending load was reversal. A few tests showed fretting crack both sides, however, just a single crack among the two was predominant and propagated up to the specimen final fracture.

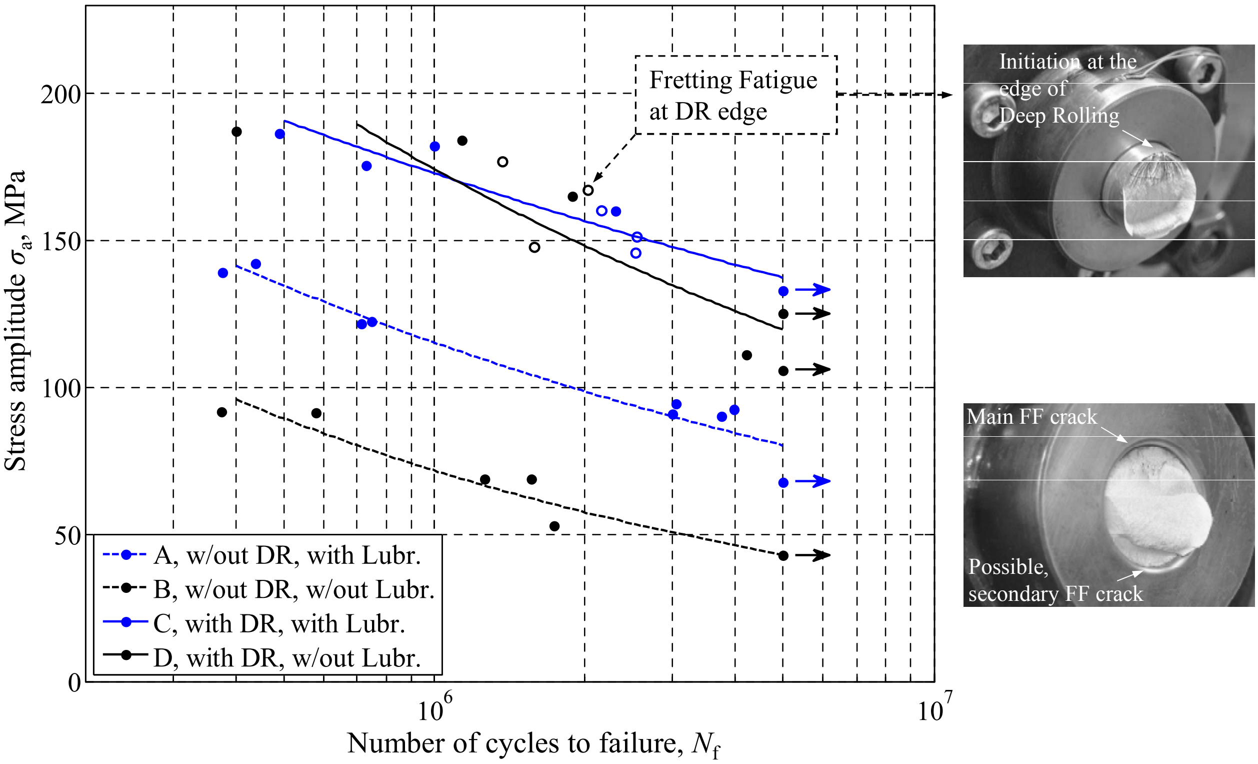


Fig. 3 Test results and fretting fatigue fracture sections.

2.4 SEM investigation of the fretting fatigue crack

After the fretting tests, SEM investigation were performed on the runouts. Fig. 4 illustrates the crack formation for each series. Multiple cracks were observed especially about the deep rolled specimens. The main evidence is that these cracks show a shallow angle with respect to the horizontal line. Obviously the leading crack would continue following a path more perpendicular to the specimen axis (mode I) but this happened only after a quite large size of the crack, in the order of 1 mm. Among the four series, those without lubrication (B and D), showed a preliminary very shallow path and then a slightly deviated path, while the others were more inclined to remain shallow or at least branch. This shallow direction is usual under fretting, and many literature examples can be cited. The general understanding of the problem is that a crack initiates along a shallow path which is consistent with the direction of the maximum shear stress amplitude, and then the crack kinks into the direction where the tangential stress is at a maximum in the mixed mode stress field, as Mutoh and Xu reports [15]. Alternatively the crack path can be immediately of mode I if the normal stress is prevailing as recently stated by Giner et al. [16].

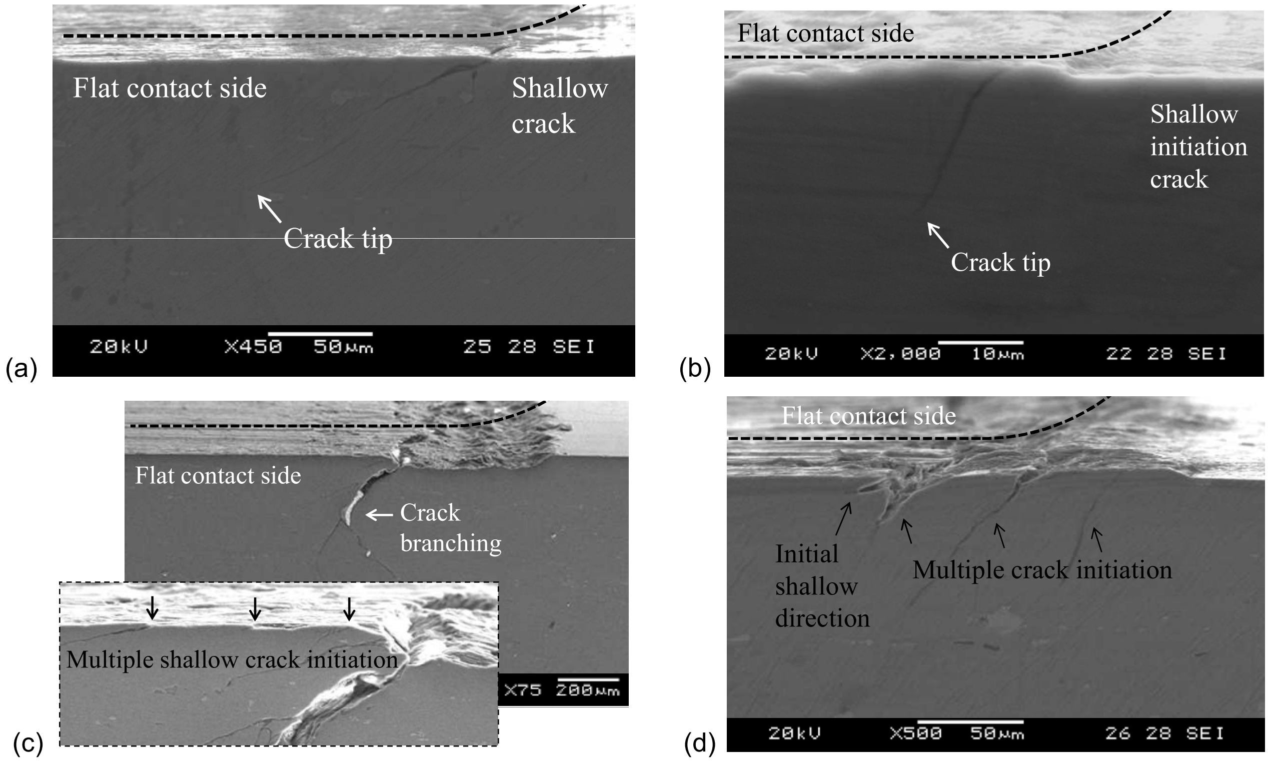


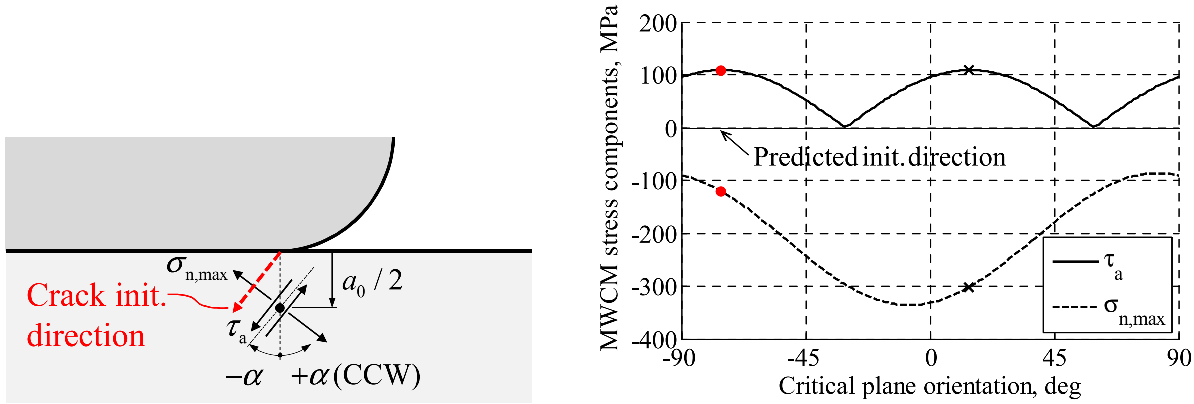
Fig. 4 SEM investigations on fretting fatigue cracks: (a), (b), (c), (d) for A, B, C, D series respectively.

3 NUMERICAL RESULTS

3.1 Direction of crack initiation

Numerical analysis allowed obtaining the local stress distribution at the fretting region. The first investigation was then devoted to the crack initiation angle prediction. The shear stress amplitude was calculated at the half the material size a_0 along with the maximum normal stress, Fig. 5.

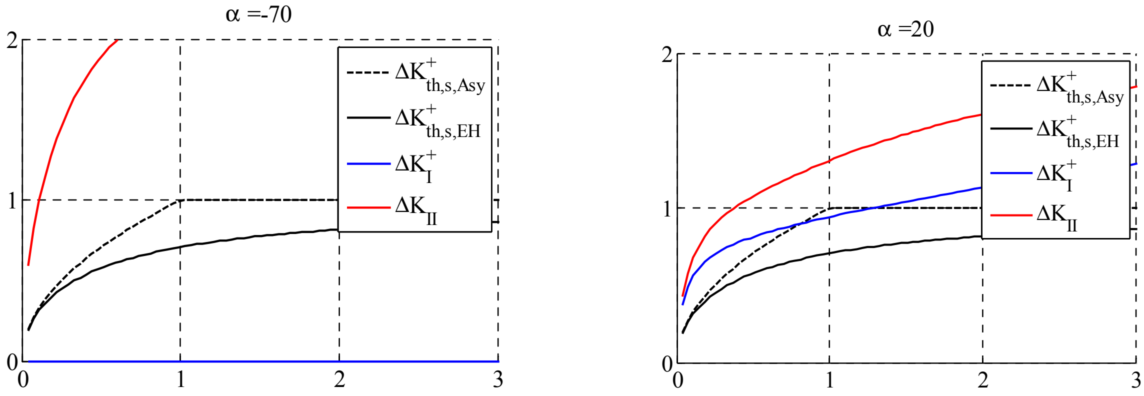
$$a_0 = \frac{1}{\pi}\left(\frac{\Delta K_{\mathrm{th}}}{\Delta \sigma_0}\right)^2 \tag{1}$$



(a) (b)

Fig. 5 Prediction of the initiation crack direction for the deep rolled specimens.

It is very important to mention that the shear stress amplitude is a 90° periodic function, indeed the shear is equal by comparing any two perpendicular directions [16,17]. Consequently, there are two shear amplitude maxima in the half plane range from -90° to 90°. Nevertheless, the maximum normal stress is a 180° periodic function, hence just one single plane direction is identified if the combined max shear stress amplitude and most tensile normal stress criteria are applied. By following this plane selection, a shallow negative angle is identified, that is coherent with the experimental evidence, Fig. 5. Actually, this consistent prediction just happened only for the deep rolled specimens (C and D series). Not rolled specimens showed a similar shear stress amplitude trend, but the most tensile plane was at the other max shear amplitude angle. The predicted direction was therefore to be corrected by considering a different combining parameter. Instead of the max normal stress, the mode II stress intensity factor range showed remarkably higher values within the a_0 range, Fig. 6. After introducing this correction, the initial shallow orientation was again captured. The direction toward the inner flat contact side was preferential despite the positive mode I stress intensity factor that would have experienced the crack along the complementary direction, Fig. 6.



(a) (b)

Fig. 6 Mode I and II stress int. factor ranges along the complementary directions, not rolled specimens.

3.2 Strength prediction based on a shear stress parameter

According to the appropriate crack direction, shear stress amplitude and maximum normal stresses were considered and a multiaxial parameter evaluated at the half the material length, according to Refs. [8, 13]:

$$\tau_{a,eq} = \tau_a + \kappa\left(\frac{\sigma_{n,max}}{\tau_a}\right),\ \tau_{a,eq}\ \text{to be compared to}\ \lambda \tag{2}$$

The results based on this equivalent shear stress amplitude are reported in Tab. 1. An accurate prediction is evident confirming the driving role of the shear stress for this specific configuration of fretting tests.

Table 1 Multiaxial fatigue criterion results, ratio $\tau_{a,eq}/\lambda$.

Series A	Series B	Series C	Series D
0.99	0.80	0.90	1.23

4 CONCLUSIONS

- A bending device for fretting has been presented along with four test series on aluminium alloy 7075-T6 combining different surface conditions: lubrication and deep rolling treatment.
- Fretting strength was increased both by the introduction of a lubricant, that reduced the coefficient of friction, and in turn the shear stresses at the fretting interface, and by the deep rolling that induced highly compressive residual stresses.
- The angle of the initial direction of the crack was found to be in accordance with the SEM experimental evidence for the deep rolled specimens, while for the untreated tests the normal stress suggested the complementary plane. The introduction of a further parameter as the mode II stress intensity factor range was required to retrieve the correct prediction.
- The critical plane multiaxial predictive stress, suggested in the literature, was found to be quite accurate for the tests presented in the paper, confirming the shear stress as the driving parameter.

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