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Authors: **L. Bertini, C. Santus, A. Merlo, M. Bandini**

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# A fretting fatigue setup for testing shrink-fit connections and experimental evidence of the strength enhancement induced by deep rolling

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**L. Bertini, C. Santus\***

*University of Pisa, DICI - Department of Civil and Industrial Engineering, Italy*

**A. Merlo**

*ENI SpA, Italy*

**M. Bandini**

*Peen Service Srl, Italy*

## Abstract

Fretting tests are usually performed on flat specimens with lateral contacting pads. The shrink-fitted connection, which experiences fretting at the edge of the contact, prompted the alternative use of a round-shaped specimen. This simplified the equipment and provided an accurate alignment between the fretting specimen and the external hub which plays the role of the pad. The deep rolling treatment can also be efficiently applied to a round shape, which would otherwise be difficult on the flat specimen geometry. After introducing this solution for fretting testing, the paper shows an experimental campaign on three shrink-fitted connections with different sizes and material combinations. There was a significant improvement in fretting fatigue strength, induced by the deep rolling, for all three specimen types. Finally, SEM analyses provided insights into the fretting fatigue nucleation mechanisms both for untreated and deep rolled specimens.

## Keywords

Fretting fatigue, shrink-fit connection, deep rolling, residual stresses, SEM analysis

## 1. Introduction

Fretting is a specific kind of fatigue associated with micro-scale slip and stress concentration at the edge of the contact [1]. Examples of structural applications that tackle fretting damage are the dovetail fixture [2, 3], and the shrink-fit connection [4–9]. Since many issues play a role in the fretting problem, fretting testing is crucial both for the connection design and verification of predictive models. An interesting review of possible test rigs in the literature was proposed by De Pauw

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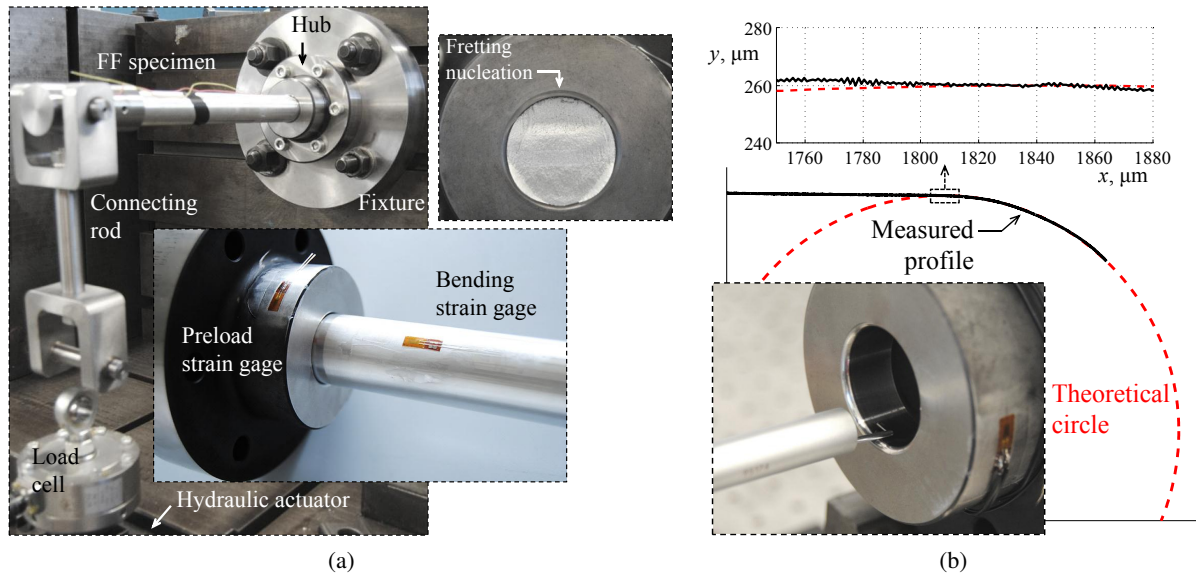
\* Corresponding author; e-mail: [ciro.santus@ing.unipi.it](mailto:ciro.santus@ing.unipi.it)

et al. [10] where the main classification was Full scale vs. Coupon scale test rigs. Full scale test rigs involve specific applications and they are aimed at allowable stresses for designing, while coupon rigs focus on the local fretting contact phenomenon itself. The books by Attia and Waterhouse, Hoepfner and Chandrasekaran and Mutoh et al. [11–13] report several examples of coupon test rigs and many others have been proposed more recently. The book by Hills and Nowell [14] clearly defines the “Bridge-type” test, where a flat specimen experiences the contact of two bridges at the opposite lateral sides, and each bridge has two contacting pads. The main drawback is that each bridge has free displacement which lead to different stick/slip conditions among the four pads. A significant evolution was to fix one side of the bridge to a large stiff part of the testing frame. Many examples of this kind of testing can be found in the literature [15–18]. However, the flat specimen with lateral contact can still experience various experimental issues mainly involving the lateral edge contact and the mount tilting of the pad. The finite contact width issue was initially investigated by Kim and Mall [19]. Later Liu and Hill [20] proposed a rounded lateral edge specimen to prevent asymptotic stress singularities at the boundaries of the contact width. The shrink-fit connection usually features the “flat and rounded contact” at the edge of the interface, where the fretting fatigue nucleates. At this position the contact stress distribution is the merging result of two stress asymptotes sometimes referred to “outer” and “inner”. The outer asymptote is a power law singularity, as with the complete contact problem, while the latter is a local Hertzian contact pressure distribution [21, 22]. Experimental fretting testing on the flat and rounded contact has seldom been proposed, for example by Namjoshi [23] and Kim and Mall [19], while others have reported flat complete contact [24–26]. The fretting setup proposed in this paper allows either complete or flat and rounded contact to be tested without any alignment or tilting issue, however, only flat and rounded tests have been carried out to date. A comparative experimental analysis was performed on specimens with different size ratios and material combinations. Untreated specimens were tested along with deep rolled specimens and the fretting fatigue strength enhancement was clearly evident. Finally, an SEM investigation was performed on the runout specimens in order to gain insight into the mechanics of fretting nucleation.

## 2. Fretting test setup

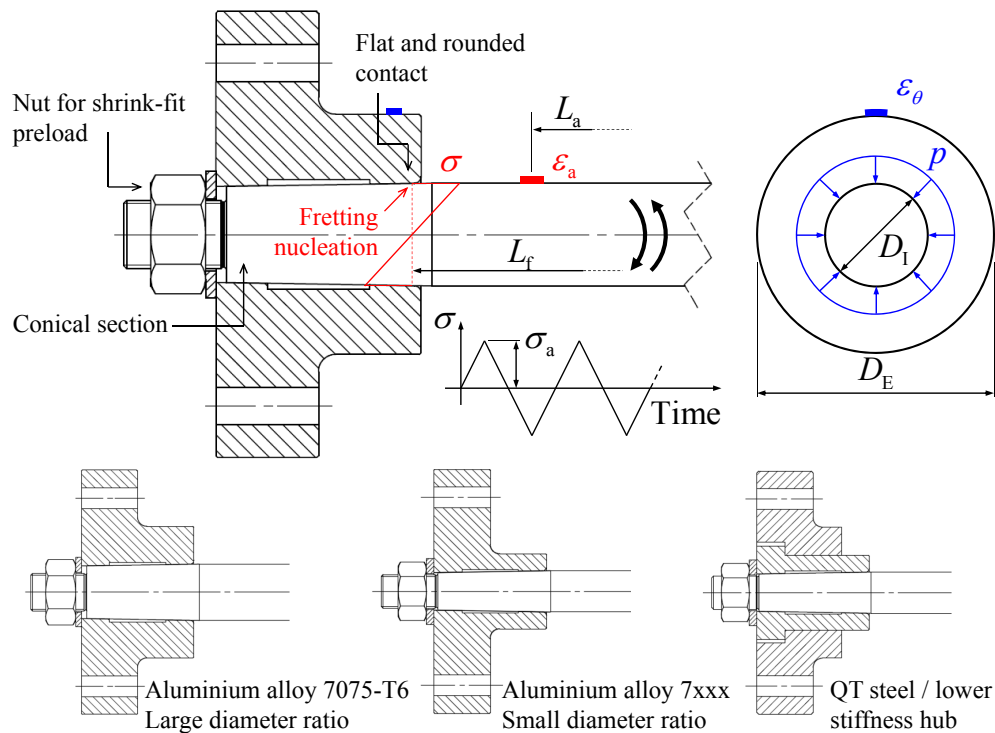
As an alternative to the common push-pull fretting testing configuration, the fatigue cyclic load can be induced from a bending scheme, as introduced in the pioneering work by Nishioka and Hirakawa [27] who investigated axle assemblies, and also more recently proposed by Juoksukangas et al. [28], Croccolo et al. [29] and Zalnezhad et al. [30]. The bending configuration allows high stress at the fretting point with a relatively low force, thus large-sized sections can also be easily tested. Figure 1 (a) shows the test rig setup introduced in this paper, which was initially proposed in a previous work by Santus et al. [31] and then developed. The specimen is a shaft which is shrink-fitted into an external hub, and the cyclic load was applied with of a controlled hydraulic actuator. The working frequency of the tests was limited at 10 Hz basically due to the cantilever beam large stroke. The fretting fatigue crack nucleated at the edge of the hub contact, and macroscopically propagated perpendicularly to the shaft axis up to the final fracture. The steel hub internal surface was turned, carburized for a higher surface hardness than the mating specimen, and again turned as finishing for a fine surface roughness and accurate shape. Grinding was avoided because the fillet geometry had to be obtained by imposing a continuous profile on a numerical control turning machine to have no dents or any other shape irregularity at the fretting point. The final surface quality was then verified to be similar to a grinding finishing, along with the accurate flat and rounded shape at the edge of the hub, as shown in Fig. 1 (b). The shaft testing region was also fine turned and the obtained finishing surface roughness was in the range  $R_a = 0.6 - 0.8 \text{ } \mu\text{m}$ . This surface roughness was then significantly reduced (approximately by a factor of five) after the deep rolling treatment.

The testing portion of the specimen was conical and the external hub accurately reproduced the same cone angle. In order to couple the specimen and the hub, precise diameter tolerances were not required because of the conical shape. The calibration of the shrinkage was easily controlled by means of an adjusting nut that introduced an interference between the



**Fig. 1.** (a) Test rig setup and fretting fatigue fracture obtained. (b) Profile measurement of the rounded edge of the hub.

two mating parts, Fig 2. The internal surface of the hub was partly machined to limit the load required during the adjusting nut operation, and the rear surface of the hub was rigidly fixed to the external frame of the test rig. Due to its shape, the hub resembles a bridge-type pad with a fixed side, along with a round geometry which eliminates any misalignment and lateral edge contact as previously mentioned.



**Fig. 2.** Proposed fretting layout and tested diameter ratios and material combinations.

Two strain gages were used to control the testing loads. One strain gage was applied at the outer periphery of the hub component, along the hoop direction, and was used to calibrate the interference generated during the nut tightening. The

hoop stress  $\sigma_\theta$  can easily be related to the strain gage measure:

$$\sigma_\theta = E_h \varepsilon_\theta \quad (1)$$

where  $E_h$  is the Young's modulus of the hub and  $\varepsilon_\theta$  is the measured strain during the shrink-fit operation. The relation between the shrink-fit pressure and the strain gage measure can then be derived from Lamé's theory for thick cylinders:

$$p = \sigma_\theta \frac{D_E^2 - D_I^2}{2D_I^2} \quad (2)$$

To monitor the bending load during the test, **another** strain gage was applied on the shaft along the axial direction. This strain gage was placed at a certain distance with respect to the fretting point, to prevent any perturbation due to stress concentration. The bending stress can be derived from the strain gage at the measurement position:

$$\sigma_a = E_s \varepsilon_a \quad (3)$$

where  $E_s$  is the Young's modulus of the specimen. **In accordance with the beam theory, the bending load follows a linear distribution, thus the stress at the fretting section (calculated without taking into account any concentration) can easily be deduced from the measuring point where the strain gage is placed:**

$$\sigma = \sigma_a \frac{L_f}{L_a} \quad (4)$$

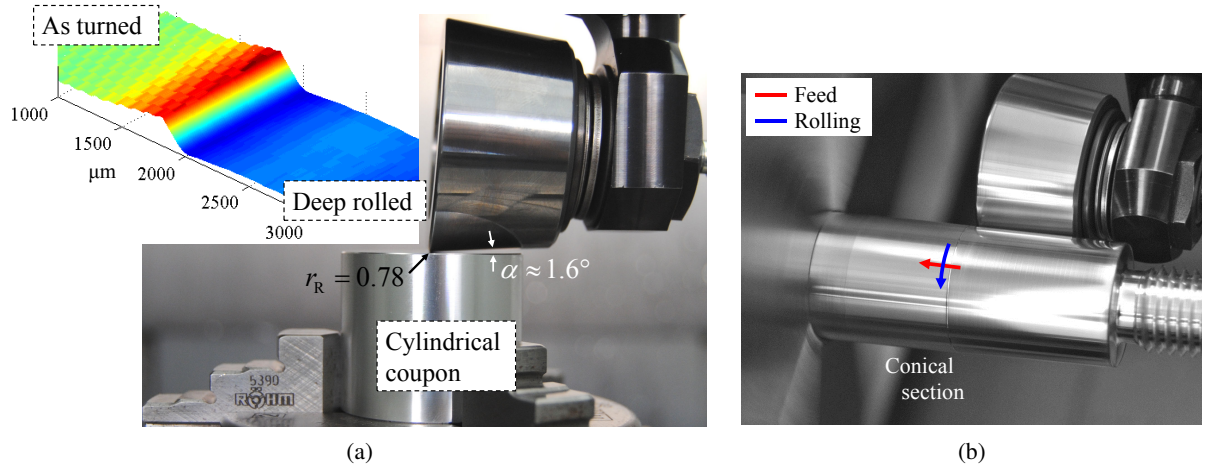
$L_f, L_a$  are the distances from the bending force to the fretting section and to the axial strain gage position respectively (Fig. 2).  $p, \sigma$  are the nominal stresses which define the applied load. Though not reported in this paper, the actual distribution of stresses at the fretting interface can be derived from analytical studies, such as Dini and Hills [21], and quantified with finite element analyses. The pressure  $p$  was kept (approximately) equal for all the specimens of each series while the bending amplitude  $\sigma_a$  varied from test to test in order to draw the  $S - N$  curves.

Three kinds of specimens were prepared for this testing activity, as reported in Fig. 1. Aluminium alloy 7075-T6 in contact with steel was initially tested with a large  $D_E/D_I$  diameter ratio. A similar aluminium alloy (7xxx) was again tested in contact with steel but with a smaller  $D_E/D_I$ . The hardness of the steel hubs was notably higher than the aluminium shafts, since the internal hub surface was carburized and quenched. Finally, a small diameter ratio was also proposed for the third kind of test with steel specimen, quenched and tempered, while the external hub was manufactured in a high strength nickel-copper (non-ferrous) alloy whose Young's modulus was smaller than that of the steel. A comparative analysis was carried out by performing test series with untreated and deep rolled specimens in order to have direct evidence of the induced effect on the fretting fatigue strength.

### 3. Deep rolling of the specimens

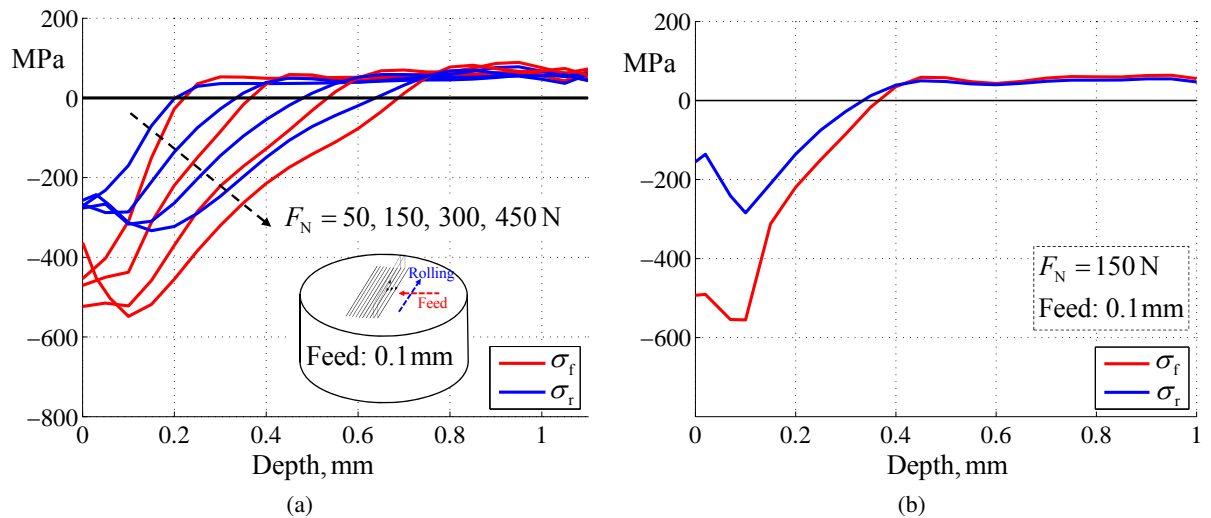
Fatigue strength is usually improved by any mechanical treatment that induces surface hardening and residual stresses. Shot peening is the most widely investigated treatment of this kind, for example Benedetti et al. [32] showed the enhancement produced by shot peening on aluminium alloy 7075-T651 notched specimens. Deep rolling introduces a compressive layer on the surface, even deeper **than** shot peening, and a common example in the literature is low plasticity burnishing with the ball type indenter [33]. The improvement effect on specifically fretting fatigue was reported by Majzoobi et al. [34, 35] regarding both shot peening and deep rolling on aluminium alloy 7075-T6, with dedicated equipment for the rolling of the flat specimens.

Beghini et al. [36] recently investigated a conical indenter, with rounded edge contact, which can be used both on milling and



**Fig. 3.** (a) Deep rolling applied to material coupons, milling machine. (b) Deep rolling applied to fretting specimens, turning machine.

turning machines, Fig. 3, and the parametric dependences of the residual stress distributions were experimentally obtained. The compressive depth was found to be primarily related to the rolling force, Fig. 4 (a), while the rolling feed mainly had effect on the surface residual stresses and the induced work hardening. An optimal trade-off between compressive depth, high compressive stress at the surface, and non-excessive plastic deformation on 7075-T6 was obtained with the parameter combination: rolling force 150 N and rolling feed 0.1 mm. Figure 4 (b) reports the residual stress distribution induced on the fretting specimens with these parameters. The maximum compressive residual stress was found to be almost as high as the material yield strength (approximately 540 MPa), thus producing the highest possible closure effect on the fretting fatigue cracks. The compressive depth obtained was a few tenths of a millimetre, thus thicker than a common shot peening, and larger than the process zone which is comparable to the material critical length [32]. Deep rolling also generated a surface finish enhancement, as mentioned above, which can further contribute to improving the fretting contact by evening out the pressure distribution on the real surfaces.



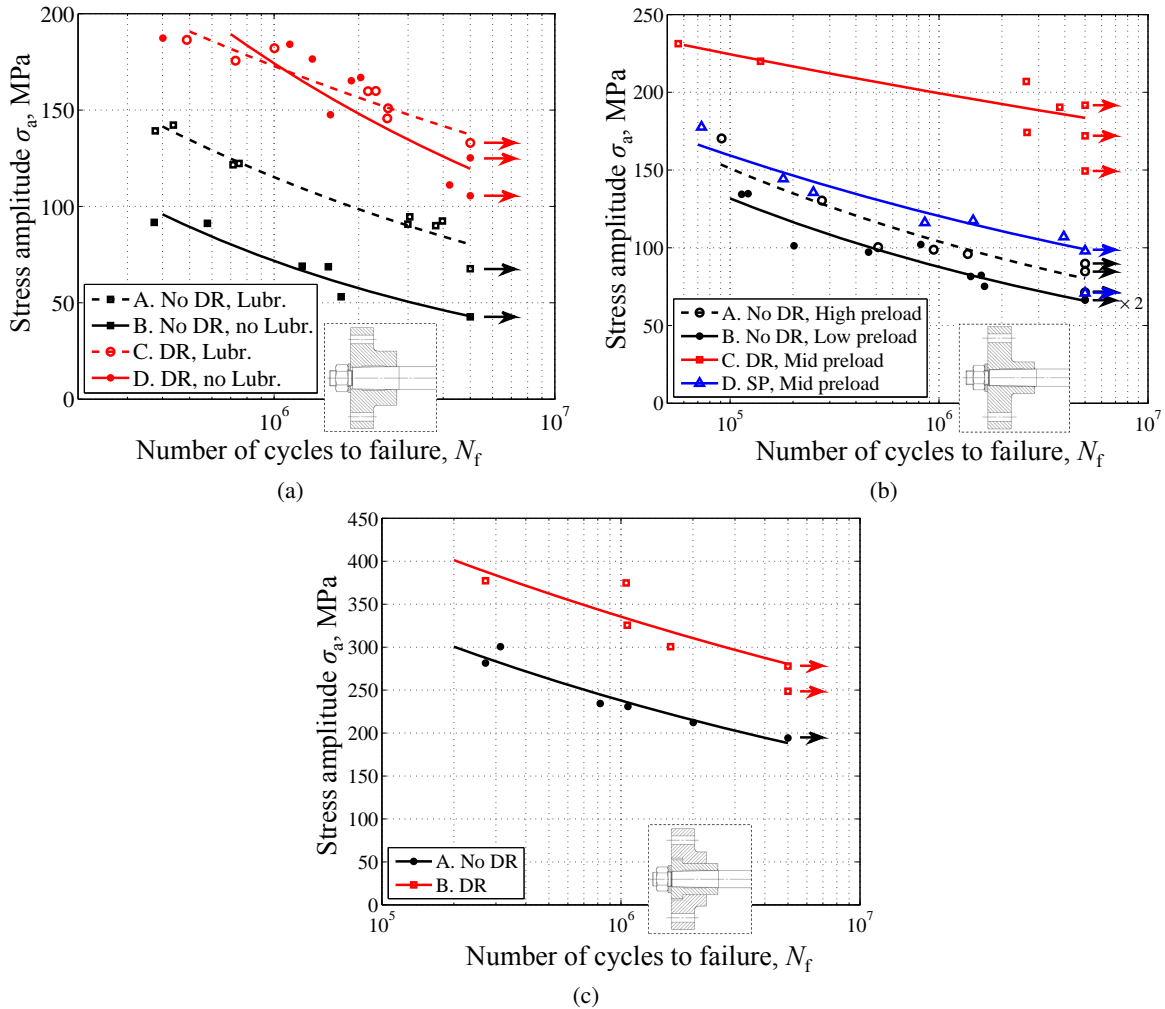
**Fig. 4.** (a) Residual stresses induced by deep rolling with different normal forces. (b) Residual stress induced on the fretting specimens with the selected combination of deep rolling parameters.

**Table 1.** Shrink-fit average pressure values  $p$ , MPa, for all the tested series.

7075-T6				7xxx				QT Steel	
A	B	C	D	A	B	C	D	A	B
70.3	60.6	59.2	62.5	124.3	62.5	85.9	85.4	88.7	88.9

#### 4. Fretting fatigue tests

Several series of tests were performed on the three proposed configurations to compare the effect of various factors and specifically the introduction of the deep rolling treatment. The values of nominal pressure are reported in Table 1 for each tested series and the fretting fatigue results are reported in Fig. 5 as  $S - N$  curves. **The maximum number of cycles for unbroken specimens (runouts) was limited to  $5 \times 10^6$  due to the large number of tests and because the aim of the analysis was mainly comparative.**

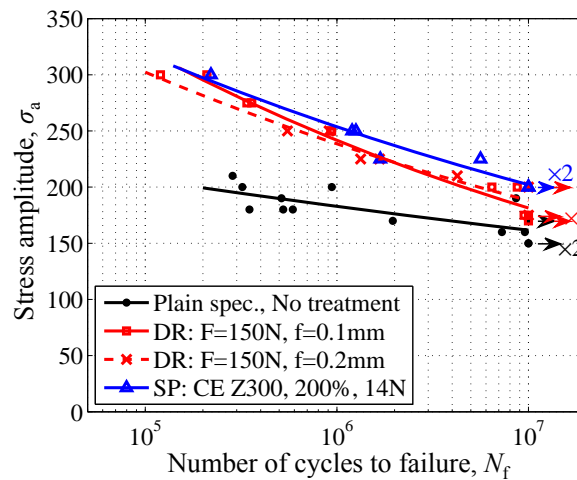


**Fig. 5.** Fretting fatigue tests: (a) aluminium alloy 7075-T6, large diameter ratio, (b) aluminium alloy 7xxx, small diameter ratio, (c) QT steel with a lower stiffness hub.

The first material investigated was aluminium alloy 7075-T6 in contact with steel, with a large diameter ratio, combining lubrication and deep rolling (DR), Fig. 5 (a). Lubrication was applied on the surfaces before shrink-fitting the connection. The reduced coefficient of friction led to a less detrimental shear traction at the contact interface, which in turn produced an increase in fretting strength. The effect of lubrication was less pronounced for deep rolled specimens, since the durability of the lubricant at the contact interface may have been limited due to the higher cycling load. As a consequence, the results



of the two deep rolled series, with and without lubrication, were quite similar. Some of the deep rolled specimens failed at the edge of the rolling treatment, instead of at the fretting interface, thus proving that the sensitivity to fretting had been overcome by the deep rolling treatment. The next tests were on a similar aluminium alloy, with a smaller diameter ratio, Fig. 5 (b). Four series were tested, just dry contact. No treatment was applied to the specimens of the first two series, thus only the shrink-fit preloads were compared. Although the high preload pressure was twice the low preload (Table 1), a similar  $S-N$  curve was obtained. More precisely, the fatigue strength of the lower preload series was slightly smaller. In theory this is questionable since the cyclic shear traction is less for a loose shrink-fit, however the slip amplitude displacement is larger, providing more microwear and thus a predominant detrimental effect. This is in agreement with the microslip dependence reported in the reference work by Vingsbo and Soderberg [37]. **Another possible effect is that a more compressive stress state, due to the higher shrink-fitting, can prevent fatigue cracks or delay them since they are oriented toward the pad and quite shallow, as shown and discussed below.** An intermediate preload was then applied to the further tests with mechanical treatments. Deep rolling with normal force 150 N and feed 0.1 mm (same parameters as in the previous 7075-T6 series) again considerably increased the strength. Shot peening (SP) was also tested on this specific geometry. **Plain specimens with an hourglass shape were preliminarily fatigue tested to compare the effect of deep rolling with two values of feed, 0.1 mm and 0.2 mm, and shot peening with ceramic shot Z300, coverage 200% and Almen intensity 14N, Fig. 6. The fatigue strength enhancement was quite similar for both deep rolling and shot peening, while the comparative beneficial effect induced by deep rolling on fretting was notable, Fig. 5 (b).** Shot peening with the aforementioned process parameters produced an increment in the range 30% – 35% on fretting fatigue, which is still significant and may be decisive in fretting applications for which deep rolling cannot be applied. By comparing the series of the two aluminium alloys (dry contact), it is also evident that the smaller diameter ratio produced higher fatigue curves both for deep rolled and untreated specimens. This provides experimental evidence for further investigation, and may possibly be due to the smaller stiffness of the hub, which in turn involves less cyclic shear load at the fretting interface.



**Fig. 6.** Plain specimen fatigue tests (no fretting) on aluminium alloy 7xxx comparing shot peening and deep rolling.

Finally, the third fretting fatigue material investigated was a quenched and tempered (QT) steel with a hardness of approximately 270 HV. The hub was manufactured in a nickel-copper alloy with Young's modulus 150 GPa, hence the hub material stiffness was lower than the shaft Young's modulus. However, the hub hardness was still larger and was in the range of 320 – 350 HV. The deep rolling treatment was applied with the same feed 0.1 mm while the rolling force was scaled proportionally to the material hardness. After taking into account several uncertainty effects, the rolling force applied to the steel specimens was set at 290 N. Deep rolling was compared to the untreated case just with the same shrink-fit preload and no lubrication. The enhancement effect is again evident, as shown in Fig. 5 (c), though less pronounced compared to the aluminium alloys, since the quenched and tempered steels already have quite a high base material fatigue strength.



## 5. SEM analyses

Sectioning and SEM investigations were performed on fretting test runouts. Figure 7 illustrates the crack formation for deep rolled 7075-T6, C series, while Figs. 8 (a) and (b) show the other aluminium alloy, A and C series, respectively (untreated and deep rolled). There is a dense distribution of cracks, clearly visible at higher magnifications, and multiple cracking was more pronounced for deep rolled specimens with a larger cyclic load. These cracks also are at quite a shallow angle with respect to the (horizontal) contact surface. Obviously, after the nucleation stage, only a single leading crack continues and follows a path almost perpendicular to the specimen axis (mode I propagation), however, this only happened after the crack was quite large.

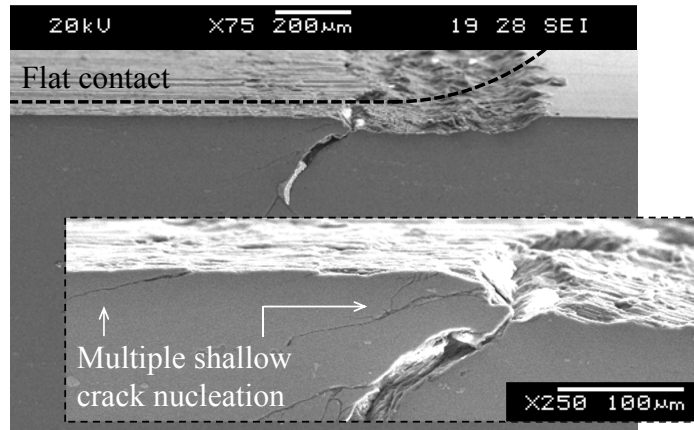


Fig. 7. SEM investigation of a 7075-T6 deep rolled specimen.

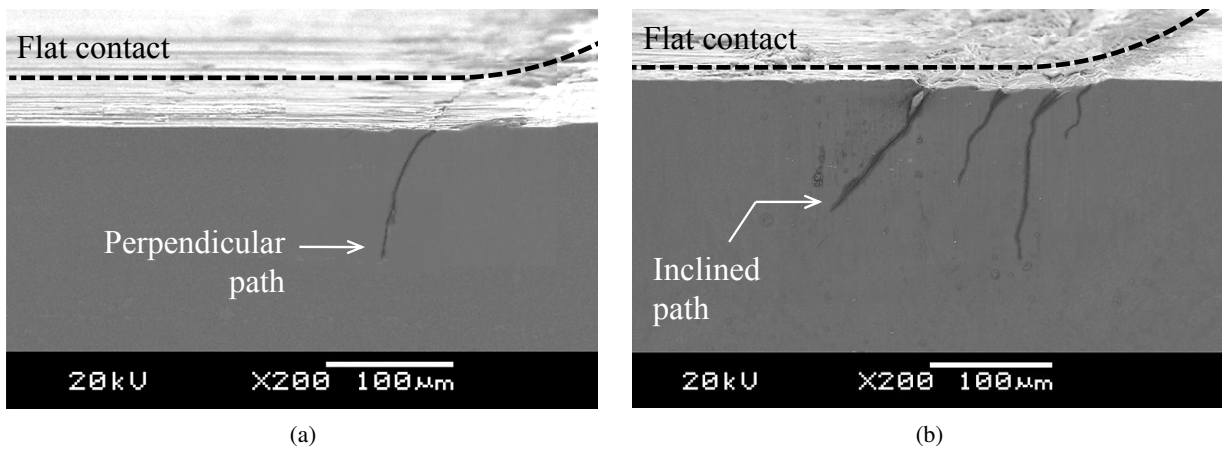


Fig. 8. SEM investigations of 7xxx aluminium alloy: (a) untreated and (b) deep rolled specimens.

The shallow nucleation is not unusual under fretting loading, as highlighted in the literature: Nishioka and Hirakawa [38], Croccolo et al. [39], which both show bending based fretting tests, and Lamacq and Dubourg [40] and Muñoz et al. [41]. The general understanding is that a crack nucleates along a shallow path, which is consistent with the direction of the maximum shear stress amplitude (type I crack), and then the crack kinks into the direction where the tangential stress is at a maximum in the mixed mode stress field. Alternatively, the crack path can just be mode I, even at its very early nucleation stage, when the normal stress is prevailing (type II crack), as reported by Giner et al. [26] and Mutoh and Xu [42]. Type II cracks were never observed for the larger diameter ratio tests, even without deep rolling. A possible explanation is that the large hub stiffness induced a pressure fluctuation, which in turn reduced the tensile stress concentration at the fretting

edge during the positive bending stress half cycle. Type II cracks were very seldom detected for the small diameter ratio, only without deep rolling, while type I cracks were predominant, as shown in Fig. 8 (a) featuring the inclined nucleation (Stage I) and then the deviated path (Stage II). Deep rolling not only prevented type II cracks but also constrained the path to keep an inclined orientation even when the crack was relatively large, Fig. 8 (b), thus confirming the inhibited role of tensile stresses.

## 6. Conclusions

The paper has proposed an experimental testing configuration that resembles the bridge type test with a fixed side. The round shape of the specimen eliminates any lateral edge contact and tilting, and facilitates deep rolling. Various material and size combinations were tested in order to compare the results. The clearest findings are:

- Deep rolling improved the fretting fatigue strength for any diameter ratio and material combination.
- Lubrication was only effective on untreated specimens for which the load level was smaller.
- Shot peening was tested for the lower diameter ratio only and also produced a satisfactory increment of the fretting strength.
- A higher strength was obtained with the lower diameter ratio both for the untreated and deep rolled series.
- SEM investigations clearly proved a shallow crack nucleation, especially for deep rolled specimens, implying that the shear stress was predominant over the tensile stress.

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