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Fretting wear-induced evolution of surface damage in press-fitted shaft

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ABSTRACT

The evolution of surface appearance and the initiation characteristics of fretting fatigue cracks in press-fitted specimens were studied by interrupted rotating–bending fatigue tests. The results show that the distance from each fretting damage zone boundary to the contact edge changes with the number of fatigue cycles, while the wear mechanism remains unchanged. The depth and width of the fretted wear scar near the contact edge increase gradually. Fretting fatigue cracks initiate from the contact area 50–200 μm from the contact edge and appear at approximately 30% of the total fretting fatigue life. Three-dimensional finite element models with the fretted wear scars for interrupted specimens were developed to investigate the effects of fretting wear on surface damage. The models show that the wear scar induced by fretting wear is a source for changes in each fretting damage zone boundary. The stress concentration near the contact edge is reduced and the locations of the maximum values of both the Smith–Watson–Topper (SWT) and Fatemi–Socie (FS) multiaxial fatigue parameters move inward towards the contact zone because of the fretting wear. This causes the crack initiation sites to shift from the contact edge to the inner area; the initiation life increases accordingly.

1. Introduction

For press- or shrink-fitted applications, such as railway wheels and axles [1–3], bearings, and shafts [4], micro-slip occurs near the contact edge under cyclic bending or torsional loads. Fretting damage is inevitable and eventually causes remarkable reductions in the durability of the component [5].

Fretting can introduce surface damage in the forms of changed surface appearance and micro-crack initiation [6,7]. Recently, many experimental investigations and numerical simulations have been performed with cylinder-to-flat [8,9] or ball-to-flat [10,11] fretting surface contact scenarios. It was gradually realized that a strong link existed between fretting wear and surface damage. For gross slip conditions, fretting wear induced broadening of the contact patches with associated drops in the peak contact pressure, suppressing the initiation of micro-cracks. For partial slip conditions, fretting wear only induced narrow wear regions around the contact patches and the development of significant contact pressure peaks at the stick–slip interface, followed by micro-crack initiation. In considering the effect of fretting wear, the non-linear relationship between the slip range and fretting fatigue life presented by Vingsbo and Soderberg [12] was interpreted reasonably by Madge [8]. The accuracy of life predictions using critical plane approaches, such as the Smith–Watson–Topper (SWT) [13], Fatemi–Socie (F-S) [14], and Dang Van [15] criteria, was greatly improved for fretting components with cylinder-to-flat configurations [8,16,17], wire couplings [18], and spline couplings [19–21].

Experimental and numerical studies on fretting damage in press-fitted shafts are clearly fewer than those on punch-to-flat configurations. In one experimental study, Song [22] indicated that the wear mechanism for a press-fitted shaft was a combination of abrasive wear, oxidative wear, and delamination. Lee [23] found that the crack initiation life of a press-fitted shaft occurred after only 10% of the total fretting fatigue life. Alfredsson [5] determined that the press-fitted interface reduced the rotating–bending fatigue limit by more than 60%. Characterizations of the fretting damage in press-fitted shafts below the fretting fatigue limit were also investigated by Kondo [24] and Lee [25]. However, experimental studies on the influence of fretting wear on the evolution of surface appearance and the characteristics of fretting fatigue crack initiation for press-fitted shafts are scarce. In simulations, because the effects of fretting wear were not considered, Lee [26] found that critical plane approaches (SWT and F-S criteria) could not accurately predict the fretting fatigue crack initiation sites for press-fitted shafts. Alfredsson [5] also suggested that the Ruiz criterion could neither predict the fretting fatigue trend in diameter grip nor the crack position for a shrink-fit pin. Meanwhile, a fretting wear simulation model for press-fitted assemblies was developed by Zeise [27]; the model showed that the distributions of contact pressure and frictional shear traction on the contact surface were significantly changed by change in the surface profile induced by fretting wear. Therefore, it is clear that fretting wear strongly affects the fretting fatigue crack

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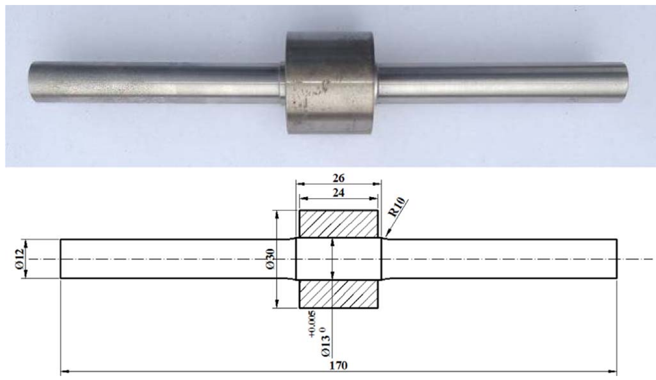

Fig. 1. Specimen shape and dimensions (mm).

initiation of press-fitted shafts; this influence should be studied.

In this study, interrupted rotating–bending fatigue tests were conducted with a press-fitted shaft, and the evolution of surface damage was observed and measured. Based on the surface profiles obtained from the experimental results, three-dimensional finite element (FE) models with fretted wear scars simulating the interrupted specimens were developed, and the effect of fretting wear on the evolution of surface appearance was discussed. In addition, the influence of fretting wear on the crack initiation characteristics of a press-fitted shaft was investigated by adopting critical plane approaches (SWT and F-S criteria).

2. Experiments

2.1. Specimens and materials

The dimensions of the press-fitted specimen are presented in Fig. 1. For the press-fitted part with a length of 24 mm, the average roughness of the interference surfaces was approximately 0.4 µm, the diameter of the shaft was machined to 13 mm, and a hub with the outer diameter of 30 mm was assembled. The grip diameter 2Δ was set as approximately 21 µm; the nominal contact pressure calculated by Lame's solution (1) was approximately 141 MPa. The required temperature difference for assembly, as obtained from Eq. (2), was approximately 140 °C. The shaft and hub were manufactured from alloy axle steel (35CrMo) and ER8 wheel steel, which are used for the axles and wheels of railway vehicles, respectively. The mechanical properties of these materials are given in Table 1.

$$P_{ps} = \frac{E\Delta}{2a}\left[1 - \left(\frac{a}{b}\right)^2\right] \tag{1}$$

where a is the contact radius; b is the outer radius of hub; E is Young's modulus; $\Delta = a_{Shaft} - a_{Hub}$ is the grip radius.

$$\Delta T = \frac{2\Delta}{2a\alpha} \tag{2}$$

where $\alpha = 1.2 \times 10^{-5}$ °C^{-1} is the coefficient of thermal expansion.

Table 1
Mechanical properties of materials.

	Young's modulus (GPa)	Yield strength (MPa)	Plastic modulus (GPa)	Poisson's ratio
Shaft (alloy axle steel)	212	705	4.5	0.28
Hub (ER8 steel)	212	600	8	0.28

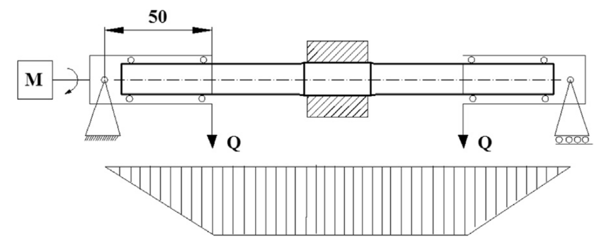

Fig. 2. The diagram of the sample load on the fatigue-testing machine and the corresponding bending moment distribution (mm).

2.2. Experimental procedures

A rotating–bending fatigue testing machine was used for the interrupted fretting fatigue tests at four different predefined cycles of 10, 30 50, and 70% of the total fatigue life. A diagram of sample loading and the corresponding bending moment distribution are presented in Fig. 2. According to the pre-testing results, the nominal bending stress on the press-fitted part of 220 MPa (the corresponding value of force being Q = 950 N) yielded a total fatigue life N_f of approximately 1.31 $\times$ 10^6 cycles, which was suitable for the interrupted fretting fatigue tests. Two new specimens were tested for each predefined cycle. After the test of one predefined cycle, the specimen was sectioned by a wire electrical discharge machine, following the process shown in Fig. 3, and then cleaned by ultrasonic cleaner. Then, two new specimens were tested for another predefined cycle. A camera, scanning electron microscope (SEM, JSM–6610LV), and confocal laser scanning microscope (CLSM, Olympus OLS4100) were employed to investigate the fretted contact surfaces. The surface profile near the contact edge and the fretting cracks on the cross-section of the shaft were measured by CLSM.

2.3. Experimental results

2.3.1. Observation of fretted contact surface appearance of shaft

A macroscopic view of the fretted contact surface appearance at 100% of the total fatigue life is shown in Fig. 4(a). Two annular fretting damage strips of approximately 3 mm in width were located at the two contact edges. The shaft, shown in Fig. 4, is fractured from the right fretting damage strip. Fig. 4(b) displays an optical microscopy image of the fretting damage strip indicated by the rectangle in Fig. 4(a). As is shown, three characteristic fretting zones (zone I, zone II, and zone III) are identified. Waviness of the surface is apparent from the machining of the bore; this is a typical problem in small-scale tests. According to the surface appearance shown in Fig. 4(b), the depth of each zone is generally uniform for a given hoop position around the contact region, indicating that the effect of waviness on the surface appearance is weak. Compared to zone II and zone III, zone I located the nearest to the contact edge is narrow and clean, with little wear debris present. Severe abrasive wear is found in zone I, as shown in Fig. 5(a). Deeper into the contact region, zone II is covered by black and red oxidized debris. As shown in Fig. 5(a), some flake-like detachment of debris layer and slight cracks are present in zone II; Song [22] confirmed that this is characteristic of delamination. It is thus clear that the main wear mechanisms for zone II are delamination and oxidative wear. Zone III is the widest, with very slight fretting damage. A few rust-red oxides are scattered on the contact surface, as shown in Fig. 4(b). Slight delamination can be observed in Fig. 5(b).

The fretted surface appearances of the shaft at 10, 30, 50, and 70% of the total fatigue life were observed by SEM, which showed that the wear mechanisms in each damage zone were the same, while the depth of each damage zone was changed with increasing fatigue cycles. The evolution of the contact surface appearance of the shaft, as observed by CLSM, is shown in Fig. 6. With increasing fatigue cycles, the depths of zones I and III (D_{I} and D_{III}) increased gradually, while the depth of zone