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Finite element simulation of the influence of fretting wear on fretting crack initiation in press-fitted shaft under rotating bending

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ABSTRACT

A Finite element based methodology for fretting wear and fretting fatigue prediction in press-fitted shaft is developed. This methodology integrates wear modelling with fretting fatigue analysis to quantitatively predict of the effects of stress redistribution and material removal induced by the fretting wear on fretting crack initiation properties. The fretting wear-induced evolutions of mean normal stress, a mean correction multiaxial damage parameter and accumulated fatigue damage are predicted by this methodology. The results show that the fretting crack initiation at the contact edge is significantly suppressed by the severe fretting wear, since the server stress concentration is relieved and the surface material with high accumulated fatigue damage is grinded off. While, the fretting crack initiation at the inner surface of the contact area is greatly promoted by the slight wear by introducing the large stress concentration near the edge of fretted wear scar.

1. Introduction

When the press-fitted assembly, for instance, the railway wheelsets [1–3] and gear hubs/shafts [4], is subjecting the rotating bending loads, micro-slip occurs near the contact edge and the fretting fatigue happens inevitably. Consequently, the durability of the assembly is reduced significantly [5].

The press-fitted part, such as the wheel seat, is the critical part of the railway axle, since the cracks are easily initiated because of the fretting fatigue [6]. Thus great emphasis has been placed on the fatigue cracks of railway axle around the world. In Japan [7], if there is a crack larger than 0.15 mm in depth, the railway axle will be scrapped. Therefore, expensive regular maintenance and inspection are indispensable to regard the fretting crack initiation. It has been reported that the crack initiation life is often short, which only reaches approximately 10–30% of the total fretting fatigue life for the press-fitted shaft [8,9]. Nevertheless, it is still necessary to investigate the fretting crack initiation properties in press-fitted shaft, thereby scientific guidance for the regular maintenance and inspection of the railway axles can be provided.

In order to study the fretting damage of press-fitted shaft, both Lee et al. [8] and Zhang et al. [9] have carried out the interrupted fretting fatigue tests, and the results show that the contact surface profile evolves with the fretting cycles gradually due to the fretting wear. Meanwhile, the experimental studies [1,5,8–11] conducted with the press-fitted shaft show that the fretting cracks are found at the inner surface of the contact area instead of the contact edge where there is a very high stress concentration. It can be seen that the fretting wear has a significantly effect on the fretting crack initiation properties. Therefore, Kubota et al. [10] pointed that to clarify the mechanism of the crack initiation in press-fitted axle, a comprehensive investigation related to the balance between the crack initiation and fretting wear and the stress condition surrounding the incipient cracks is necessary. However, the corresponding researches are very limit for the press-fitted shaft. Zeise et al. [12] has presented a finite element (FE) based methodology to predict the fretting wear in press-fitted shaft, and the evolutions of the contact surface profile and the contact parameters are obtained, however the influence of fretting wear on the fretting crack initiation properties is not clarified in detail. Lee et al. [13] also presented a numerical analysis of the fretting fatigue of press-fitted shaft considering the effect of fretting wear, however the investigation is mainly focused on the effect of contact pressure. In previous study presented by Zhang et al. [9], in order to discuss the formation mechanism of each fretting wear zone, a FE model with the fretted wear scar for interrupted specimens was developed, while the FE model did not contain wear model and the fretted wear scars were artificially added to the FE model based on the measured surface profiles. The effect of fretting wear on fretting fatigue of press-fitted shaft is discussed qualitatively and simply. Therefore, the influence of fretting wear on the fretting crack initiation properties in press-fitted shaft still far from thorough research.

Comparing with the press-fitted shaft, the fretting wear and fretting fatigue problems of other applications [14–20] have been well

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investigated. More recently McColl et al. [18] developed an incremental wear approach using Archard equation [21] for the simulation of fretting wear in cylinder on flat configuration. Follow this work, Madge et al. [14] combines the Archard-based wear model with the critical plane SWT [22] damage accumulation fatigue model to predict the effect of fretting wear on fretting fatigue. It turned out that the nonlinear relationship between fatigue life and the slip range obtained from the experiment [23] can be reasonably interpreted, when the impact of fretting wear is considered. Then the FE based methodology proposed by Madge is widely used for complex configurations, such as the spline couplings [15], thin steel wires [16] and modular hip implants [17]. It turned out that the predicted fretting fatigue life is more accuracy after considering the fretting wear effect.

In this paper, a FE based methodology similar with the one proposed by Madge [14] is developed for the press-fitted shaft. In this methodology, the wear model used for the fretting wear simulation is the energy-based wear approach proposed by Fouvry et al. [24]. This approach relates the wear volume to the accumulated dissipated energy which considers the impact of tangential force. It has been validated by the experiments [25,26] that this approach is superior to the Archard-based wear model; Since the SWT parameter might be non-conservative [27,28], for the cyclic loads that involve relatively large compressive mean stress, the SWT parameter is replaced by a mean correction model proposed by Ince et al. [28]. The fretting wear-induced evolutions of the parameters related to the fretting fatigue have been investigated. The influence mechanisms of fretting wear on the fretting crack initiation site and initiation life in press-fitted shaft have been discussed in detail, with the combination of the experimental results presented in previous work [9] and the simulation results.

2. Experimental details

An extended description of the experimental details and results used to study the fretting wear-induced surface damage in press-fitted shaft is reported in [9]. In this section, the specimens, materials, test rig and load conditions for the interrupted fretting fatigue tests are briefly outlined.

2.1. Specimens and materials

Fig. 1 shows the shape and dimension of the press-fitted specimen. The diametral interference 2δ is approximately 21 µm and the corresponding nominal contact pressure P is approximately 141 MPa. Alloy axle steel (35CrMo) and ER8 wheel steel are used for the shaft and hub, respectively. And the corresponding mechanical properties are shown in Table 1.

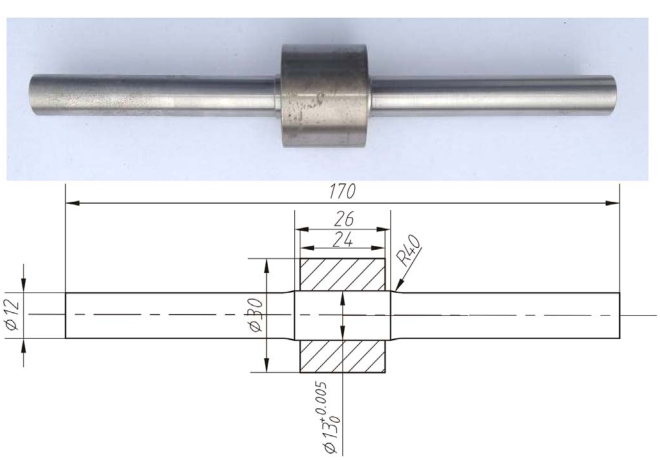

Fig. 1. Specimen shape and dimension (mm).

2.2. Fretting tests

The interrupted fretting fatigue tests were conducted on a rotating bending fatigue machine at four different predefined cycles of 10, 30 50%, and 70% of the total fatigue life. The rotary speed is approximately 3000 rpm. As it has been mentioned in previous study [9], the nominal bending stress on the press-fitted part is set to 220 MPa, and the corresponding total fatigue life N_f is approximately 1.31×10^6 cycles. After the tests, as it is shown in Fig. 2, all samples were sectioned by wire electrical discharge machine and then cleaned ultrasonically. The fretted surface and the fretting cracks near contact edge are observed by a scanning electron microscope (SEM). The contact surface of the shaft at 10% of the total fatigue life, observed by using SEM, showed no micro-cracks. Meanwhile, the shaft at 30% of the total fatigue life (N = 393000 cycles), as shown in Fig. 3, possesses micro-cracks of 30–50 µm in length located approximately 200 µm away from the contact edge. The surface profiles near contact edge are measured by a confocal laser scanning microscope (CLSM). The detail processes of surface profile measurement were presented in [9].

3. FE based methodology

3.1. FE model

The FE model used in this study is the same that has been validated in a previous work [29], for the simulation fretting wear in press-fitted shaft. The model consists of shaft and hub as shown in Fig. 4, due to the symmetry structure and loading, only half of the press-fitted specimen is created. The axial direction parallel to the X-axis, and the origin of X-axis locates at the contact edge. Three-dimensional eight-node linear elements (C3D8) are employed. Based on the optimization conducted in previous study [29], the highly refined meshes with the size of 15 µm are adequate to capture the complicated variation of stresses, relative slip and to give a well representation of the wear scar profile. A master-slave contact algorithm is employed, and according to the optimal result of the coefficient of friction (COF) in previous paper [9], a value of 0.6 was used in this study. The penalty approach is used in this paper, due to the fact that the Lagrange multiplier contact algorithm induces the convergence problem under cyclic rotating bending applied loads. To ensure that the penalty approach gives as good results as the Lagrange multiplier contact algorithm, the optimization of the maximum elastic slip tolerance has been conducted in previous paper [9] and according to the optimal result, the maximum elastic slip tolerance is set to 0.0001 in this study.

The elastic–plastic material behaviour is modelled using linear kinematic hardening condition with the material properties shown in Table 1

Fig. 4(a) shows the loads and constraints imposed on the FE model. The symmetric constraint along x-axis is applied to the centre of FE model and the end of the shaft (point A) is fixed in y and z directions. The concentrated forces varying with the computation time t, $F_y = F_0 cos(2\pi t)$ and $F_z = F_0 sin(2\pi t)$, are applied at point B along y-axis and z-axis respectively, and as a result, the constant bending load F_0 rotating around the axis of shaft with computation time t is applied to the shaft. Therefore, one fretting fatigue cycle can be simulated within one load step. More details about the loads and constraints are presented in previous work [29].

3.2. Wear modelling

The specific method used in this study for the wear simulation of press-fitted shaft, which was validated by the experimental results, is described in detail in the previous work reported by Zhang et al. [29].

The wear model used for fretting wear simulation is the energy wear approach proposed by Fouvry et al. [24]. This approach assumes that fretting wear can be evaluated by applying local energy wear approach