RUNNING CONDITION FRETTING MAPS OF POLYMER MATERIALS

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Abstract

Due to the industrial demand, the determination of the wear behaviour of polymeric materials is an important research task. Rubbers and elastomers are used widely in contacts, where wear is the dominant failure mechanisms. Furthermore, only the material properties under large displacements were investigated in the majority of existing studies. Depending on the input physical parameters of the tribological systems small oscillations are also observed on the measured signals (due to stick-slip like effect) in the contact zone of the elastomers. To describe the failure behaviour under this special condition, a novel fretting fatigue test system was developed and built on a electro-dynamical shaker in this study. The contact area were defined with some additional test, like 2D full field strain analysis, compression and creep tests. Based on the methodology developed and applied for steels and polymer composites, Running Condition Fretting Maps for two elastomer grades (HNBR and TPU) were determined.

Key words: fretting map, fretting fatigue, wear, elastomers, system development.

1. Introduction and objective

Due to the industry demand, fretting damages of metallic materials have been widely investigated since 30 years [1,2]. Fretting wear and fretting fatigue are now determined as the material responses of materials under global overstraining or local overstressing of the surface [3]. In vibration contact, depending on the normal load or on the displacement amplitude, the contact condition can include either partial slip or gross slip. These two states do not produce the same local loading on the surface. Under partial slip conditions as it was described by Mindlin, in sphere/plane contact, in the middle dominates the sticking surrounded by circle oscillating domains [4]. When gross slip occurs, however, a full sliding phase can be observed after the initial partial slip evolution. The dominant sliding conditions are depending on the normal force (P), and the displacement (δ) and they are described in Sliding or Running Condition Fretting Map [5]. These two fretting conditions (partial slip and gross slip) result in three different fretting regimes. When the sliding condition does not change throughout the test duration, partial slip (PSR) or gross slip (GSR) regimes are considered. Mixed slide regime (MSR) is that area in the displacement-normal force diagram, where the sliding condition changes during the test time [6]. Determination of this transition criteria for steels was published by Fouvry et al. [7]. This fretting fatigue failure can rapidly occur in the contact area of the moving mechanical components under these special conditions.

In a surface contact with low relative displacement between two components and at high frequency the fretting wear mechanisms are also a potential failure behaviour for polymeric materials [8]. During the fretting wear the debris, as a third body in the interaction, can not be easily outcome from the sliding zone and play a basic role in the wear of materials [9, 10]. Polymeric materials are frequently used in engineering applications (e.g., gears, bushings, sealing), where wear and also fretting are the dominant failure mode. Hence, in addition to the characterization of the fretting wear and fretting fatigue behaviour of metallic materials and fiber reinforced polymer composites which has already been described by several authors [11, 12], the characterization of the fretting fatigue and wear of the elastomer and unreinforced polymers become an important research task.

The methodology for characterizing the fretting behaviour can be described in the following steps:

- Description of the sliding conditions according to Fouvry et al. [13].
- The special attributions of the contact zone and multiaxial stress state with the inherent viscoelastic behaviour of the specimens makes the analysis of the fretting process for polymers very complex. To get more details about the contact conditions, two dimensional full-field strain analysis, compression and creep tests were also performed.
- Determination of the fretting regimes of the materials and to correlate them with the sliding

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conditions is the third phase of the investigations.  
- If fretting fatigue failure is observed during the measurements, the definition of the crack initiation and propagation as the function of cycle number is the following challenging task.  
- Furthermore, finite element simulations using viscoelastic material data will also be performed in the future.  
- Finally, the fretting fatigue behavior of the materials will be compared with the bulk fatigue behaviour under various stress conditions.

The overall objective of our research work is to characterize the fretting fatigue behavior of polymeric materials and to determine the Running Condition Fretting Map (RCFM) and the Material Response Fretting Map (MRFM) according to the proposal of Fouvy et al. [13, 14]. However, in this paper, the development of a novel fretting machine and the determination of the Running Condition Fretting Maps for two rubbers, hydrogenized nitrile rubber (HNBBR) and for a thermoplastic polyurethane elastomer (TPU) is described and discussed.

2. Experimental
2.1 Materials
Two different materials were investigated in this project: thermoplastic polyurethane (TPU) and hydrogenized nitrile rubber (HNBBR). The materials were produced and provide for this study by the SKF Economos Austria GmbH (Judenburg, A) as plates shape with the dimension of 6x20x150mm. All experiments were conducted at room temperature without any lubricant.

2.2 Test system development
A novel testing machine was built an electrodynamical shaker (Brüel & Kjær, 4814 and 4805, Nærum, DK) using the experiences of previous studies [11, 13, 15, 16]. The disadvantage of this set-up is the difficult control of the amplitude and the stroke in the mid position. The test system works in displacement control mode, where the power amplifier (B&K type 2707) together with a signal generator controls this set-up. The specimen positioned in the mid-part is pressed from both sides by steel balls (R = 2.7 µm, E = 193 GPa, µ = 0.25) with the diameter of 10 mm (produced by Kugel Pompel Regina Geider GmbH, Wien, A).

The required horizontal force is realized by the two steel springs (produced by Febrotech GmbH, Halver, G) with the following properties: d = 1.4 mm, D = 10.67 mm, L = 44.45 mm, c = 2.57 N/mm. They pull the two sides together moving on THK SF10 (H6) and THK LMH-10UU linear bushing-shaft pairs (THK Austria, Pasching, A) reducing the friction to minimum. There are two options to clamp the specimens as depicted in Fig.1. Similar to the test configuration described in [17] the upper part is fixed and the specimen is exposed to bulk tensile cyclic loading (see setup 1) or the upper and the bottom holder can move simultaneously (see setup 2).

The displacement is measured by an inductive sensor (HBM W1EL, Darmstadt, D) and the force in setup 2 by an HBM U9B/2kN load transducer. With these configurations we are able to generate different stress states and fretting conditions on the specimen surface. To measure the normal and tangential load in the contact area a biaxial force sensor (Kaliber 9961, Budapest, H) is used. All data are acquired with a Spider 8 DAQ system (HBM) and the CatMan® (HBM) software (Fig. 2).

2.3 Measured values, test parameters
The displacement is variable over the range of ± 2 mm, the maximal frequency is 30 Hz, and the maximal normal load is 250 N. The sliding conditions were determined under different normal loads varied from 5 up to 50 N for both materials and at a frequency of 10Hz in the first part of the experiments. In the second part the tangential loading amplitude was varied from 0.025 to 1 mm. The parameter limits in terms of normal load and tangential displacement of the sliding conditions for the HNBBR and the TPU materials were determined at these loading conditions.

All measurements were performed in the configuration of the setup 1, and to avoid additional deformations outside the process region, the elastomer specimens were reinforced on both sides. Moreover, to reduce the size of measured region, the aluminium plates have a hole with the diameter of 13 mm.

3. Description of the contact zone
Preliminary measurements were performed on an Universal-Mikrottribometer (UMT-2, CETR, USA) for modelling the contact zones and strain distributions in the materials. Two cylinders local strain in the direction of the pressure applied (εx) is in the contact area and decreasing to the middle of the specimen (see Fig. 3b). It is expected that by the determination of the εx strain components under the contact region, due to the biaxility of the test conditions with ball contact the εx and the εy can also be calculated for incompressible materials (λx=λy=λz=1).

Fig 4 shows the strain distributions of the HNBBR sample in similar manner at the same load. Because of the higher elasticity of the material, here the two contact regions contiguous to each other, producing a nearly constant εy local strain distributions along the material.
These strain distributions in the contacting materials represent the behaviour under one direction loading. Due to the friction between the cylinder and the rubber plate, shear stresses can already be developed in uniaxial loading condition. The development of the shear strains can be deduced by changing of the horizontal strain component, $\varepsilon_x$, across the specimen in the images shown above.

Applying oscillation in tangential direction, this shear stress grows near to surface and may generate a crack formation. Determination of the strain distribution under both loading (tangential oscillation and normal compression together) applying this optical measurement technique is the forthcoming task. After the evaluation of these images, we can describe the relationship between the compression movement and the $\varepsilon_y$ local strain distribution between the contact area.

Moreover, to connect this effect into the ball contact configuration of our fretting testing machine, further measurements were performed. To determine the contact area, and also to describe the effect of the normal force used and the measurement time, monotonic compression and creep tests were performed on both materials using the tribometer system. The setup corresponds to the exist fretting fatigue test system, the steel balls had the same

Fig. 2. Testing modes and configuration: setup 1 (a) and setup 2 (b)

Fig. 3. Strain distribution of the TPU specimen: $\varepsilon_x$ (a) and $\varepsilon_y$ (b)

Fig. 4. Strain distribution of the HNBR specimen: $\varepsilon_x$ (a) and $\varepsilon_y$ (b) in setup 2 (b)

Fig. 5. Creep and compression tests of the HNBR and TPU materials
diameter and material properties are same as in the fretting measurements. Hysteretic force-displacement curves of the monotonic compression tests by steel balls are shown in Fig. 5a. The creep measurement with 50N normal load and with 1h hour testing time is seen in Fig. 5b. As expected, both elastomer types revealed time dependent deformation behaviour and HNBR shown significantly higher local indentation displacement values than TPU. From the 2D dimensional images, the compression and creep results, we are able to determine the strain distribution between the contact zones in any moment.

4. Determination of the running condition fretting map

To define the sliding condition for both materials, the tangential load was measured in the function of the normal load and the displacement amplitude, and the hysteretic curves of the materials were drawn. In the course of the hysteretic cyclic analysis, we have to attend to some special conditions of this test method. Depending on the position and the movements, the measured load consist not only the friction load. During the fretting measurement of steel materials, the unwanted strain of the test fixture (compliance of the test system) plays an important role. However, for elastomers another problem exists: in contempt of the used cyclic reinforcement, under and over of the contact area are always a strained and a compressed zone, which produce a measurable hysteresis curves with the smallest displacements also. Determination of an exact value of the friction forces are not simple with this parameters, the ball is pushed deeply into the surface, which has a rising effect on the measured values parallel with the change of the velocity. Because of these two influences, after the curves reach the sticking force of that displacement range, no peak value (sticking) or constant load (sliding) was observed.

To determine the Running Condition Fretting Map, the normal load and the displacement amplitude was changed as the parameters of the testing system. Based on the measured values, three region were defined:
• Gross slip (sliding) is that region, where the tangential forces have a well defined maximum and minimum.
• Assuming linear elastic material behaviour, where the tangential forces are directly proportional to the displacements, the partial slip was determined according to the linear elastic behaviour.

• Due to the high coefficient of friction of the elastomers and due to the deep dents between these two fields Partial slip in the non-linear range was observed.

Fig 6 presents a sample of the hysteresis curves of the HNBR specimens with constant normal load (Fig. 6a) and with constant displacement amplitude (Figure 6b). Some indications of the gross slip like behavior are observed on both diagram. Using 20 N normal loads a material specific sliding was determined at about 0.5 mm amplitude. The same effect is visible under at 0.5 mm amplitude when the value of the normal load was changed from 50 N to 20 N (see Fig 6b). The same diagrams are shown in Fig. 7 for the TPU material. Comparing these curves with Fig. 6, the reduction of the mixed region for the TPU materials was observed.

To describe the RCFM of both materials, four different normal loads were selected and the displacement amplitudes were changed. The amplitude limits of all wear region were determined for all normal load settings, and the points detected were fitted by a linear regression. The results of the HNBR and TPU materials are shown in Fig. 8. Due to lower coefficient of friction of the TPU materials, the Gross slip area is significantly larger than in the case of HNBR. The effect of the larger elastic modulus for

![Fig. 6. Contact behaviour of HNBR material under constant normal load of 20 N (a) and amplitude of 0.5 mm (b)](image)

![Fig. 7. Contact behaviour of the TPU material under constant normal load of 20 N(a) and amplitude of 0.5 mm (b)](image)

![Fig. 8. Running Condition Fretting Map of HNBR and TPU](image)
TPU is visible in the size of the non-linear partial slip region, that is, this region is significantly smaller for TPU than for HNBR.

5. Resume and future work

To characterize the material response under fretting contact, a novel test system was developed based on a magnet shaker. Although, the accurate setting of this setup is extremely difficult, the setup worked successfully during these first measurements. To predict the areas of the different presumable fretting behaviours in the displacement – normal load diagrams, HNBR and TPU grade elastomers were investigated, and the Running Condition Fretting Maps were determined for both materials in this study. Furthermore, to get more details about the strain distributions in the materials and to describe their creep and compression properties, some additional measurements were performed on a tribometer. Moreover, the description of the Material Response Fretting Map under different loading condition is a challenging task. Figure 9 shows two examples of wear behaviour of the HNBR materials observed in other experiments. While a typical wear was observed in Fig. 9a a combination of wear and fretting fatigue is obtained in Fig. 9b, respectively. The mechanism of the crack formation with fretting system for elastomers is still under investigation.

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