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Tangential traction instability in fretting contact below fully developed friction load

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Summary. Fretting experiments were run below fully developed friction load levels, and the stability of friction was investigated. It was observed that stable friction behavior can be achieved if friction load per normal load is limited to maximum of about 0.5. Exceeding this value leads to increasing instability in friction until gross sliding is achieved. Minute surface sliding, in range of few micrometers, occurred even at these load levels, which may contribute to friction instabilities.

Key words: fretting, friction, stick

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Description

Fretting stands for the action of reciprocating surface sliding, where the sliding amplitudes are, typically, in the range of few to some tens of micrometres. Fretting can cause fretting wear and fretting fatigue. Fatigue damage in general can lead to catastrophic component failure, and in the case of fretting fatigue, it can initiate and propagate out of sight in the confinements of a contact, making it especially harmful. [1]

The coefficient of friction (COF) is typically close to unity in fretting [1]. In case of quenched and tempered steel (QT) single COF does not represent overall frictional behaviour very well due to so-called non-Coulomb friction phenomenon [2, 4]. Non-Coulomb friction can be observed from measured tangential displacement-tangential load plots, also known as fretting loops. During non-Coulomb friction, the tangential load increases gradually when tangential motion approaches its extreme value. Mulvihil et al studied non-Coulomb friction and suggested that it results from tangential fretting scar interactions [4]. This theory was validated by Hintikka et al [2]. Firstly, COF can be calculated from measured friction load amplitude and its ratio to normal load during fretting load cycle (COF_{max}). Secondly, COF can be calculated from frictional energy dissipation (area inside fretting a loop) and sliding amplitude (COF_{mean}). COF_{max}

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represents the maximum friction load and COF_{mean} the average friction load during a load cycle. Furthermore, both COFs may vary as a function of load cycles.

Previous fretting experiments, run in gross sliding conditions, have showed that in the case of QT-QT contact, the maximum of COF_{max} is about 1.4 and the expected value for steady state COF_{mean} is about 0.7, when normal pressure is 30 MPa [3]. It is known that both COFs first peak and then reduce and stabilize after about 10^5 load cycles [3], and initial high COF is related to presence of non-Coulomb friction [2]. In practise, engineer may need to utilize as much as of the available COF that is possible, while guaranteeing constant COF conditions. This study aims to investigate experimentally the stability of COF in the loading regime, where the ratio of friction load to normal load is in the range of 0.6 to 1.0, which is unknown at this stage. These load level are between stabilized COF_{mean} and max of COF_{max}.

Methods and experiments

Experiments were done using so called annular flat-on-flat fretting apparatus described fully in Refs [2, 3]. The contact is formed between two axisymmetric and identical specimens. Normal load (P), torque (T) and rotation (θ) were measured at 5kHz frequency. Experiments were run at 40 Hz loading frequency under closed loop control and the controlling parameter was the rotation amplitude (θ_a). Contact surface parallelism was adjusted using pressure sensitive film. Experiments were run in normal laboratory atmosphere.

The experiments in this study were run at loading levels below fully developed friction load. Under such loading conditions Eq.1 represents the ratio between tangential traction amplitude and normal traction ($p(r,\varphi)$), named here as torque ratio (TR). Under gross sliding conditions, TR corresponds to COF [3], where T_a is torque amplitude and r_i (7.5 mm) and r_o (12.5 mm) corresponds to specimen inner and outer radiuses, and φ is angle around contact surface (Fig. 1A).

$$TR = T_a / \left[\int_0^{2\pi} \int_{r_i}^{r_o} r \times p(r,\varphi) dr d\varphi \right] \quad (1)$$

Based on earlier results, it is known that COF_{max} has maximum value of about 1.4 [3]. Total rotation, including sliding and elastic deformation, is measured. The specimens' elastic deformation is known; therefore, sliding can be estimated from measured total rotation and torque [3]. Due to specimens' elastic deformation, under reciprocating torque load, the experiment can be run under displacement control even below gross sliding threshold.

This study's experiments were run at load levels where the friction-induced torque was below fully developed friction load (limited TR). The target levels for TR were 0.6, 0.8 and 1.0, while value of 1.4 corresponds to fully developed friction load [3]. The normal pressure was 30 MPa. In the beginning of each experiment there is 400 load cycles long start-up time, during which the rotation amplitude is ramped up linearly to its target value. Specimens had ground surfaces, with circumferential scratching, and surface roughness Sa in the range of 0.16 µm to 0.26 µm. Also, previously reported experiments with 30 MPa normal pressure and multiple sliding amplitudes are re-analysed and reproduced here for convenience when appropriate [2, 3]

Results and discussion

The development of TR during the experiments is illustrated in Fig. 1B. Initially, TR was close to its target value and it gradually reduced and stabilized to a lower value, hence it was instable. The upmost curve (5 µm-30 MPa) is an example from previous gross sliding experiments [3]. The maximum and stabilized values of TR (TRM and TRS) were extracted from the data by finding the maximum of TR, and by calculating the average of TR over $1.0 \cdot 10^6$ to $3.0 \cdot 10^6$ load cycles, respectively.

Fig 1C shows the expected max of COF_{max} and expected steady state values for COF_{max} and COF_{mean}, plotted as dashed grey lines (previous gross sliding results, circles with exes) [2, 3]. The solid black line corresponds to perfectly stable TR conditions where TRS is equal to TRM.

Tests showed that exceeding TRM = 0.5 value led to conditions where TRS was less than TRM (instable), and that increasing TRM led to increasing instability until gross

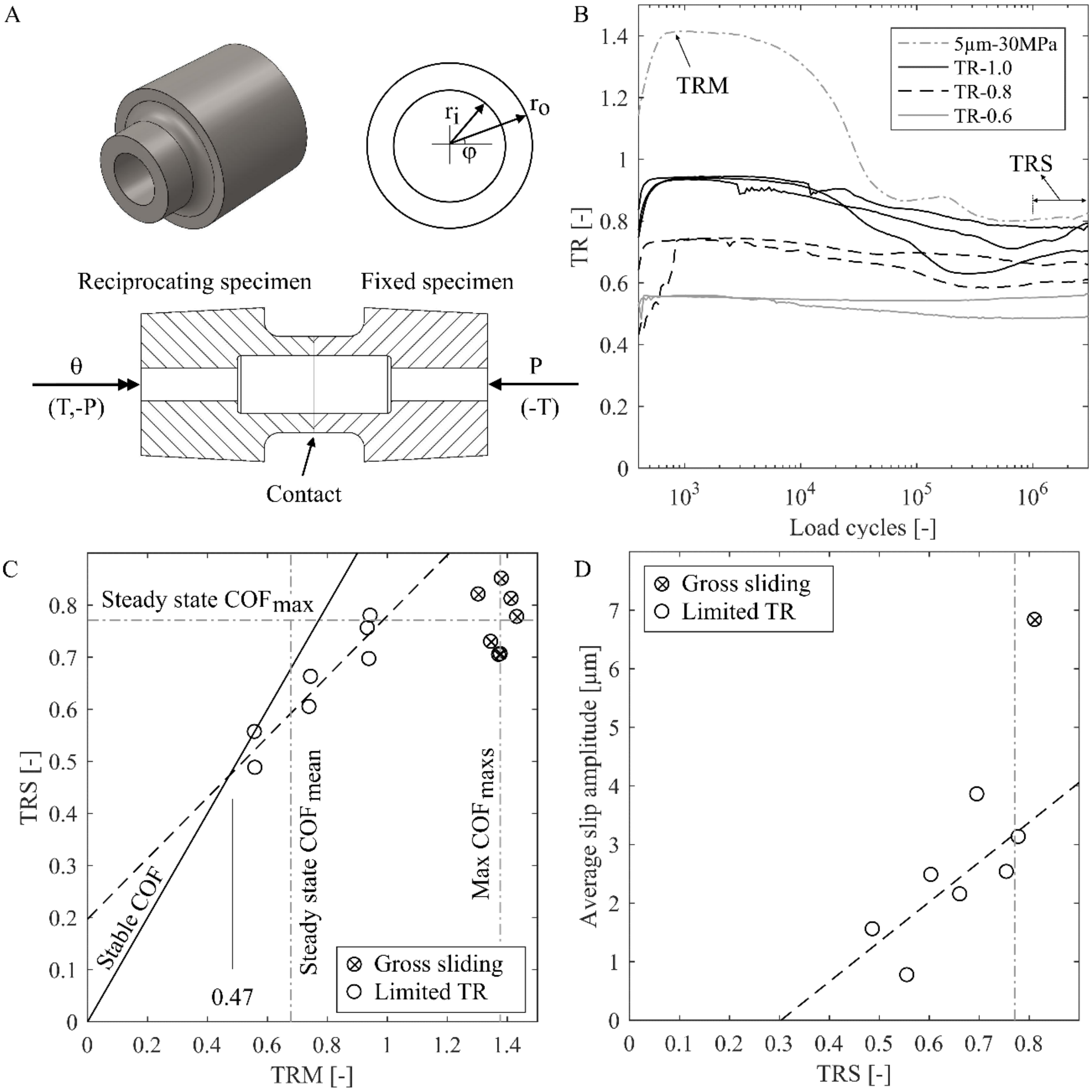

Figure 1. A) Contact and specimens B) Development of TR during experiments, C) TRM and TRS and D) average slip amplitude as a function of TRS

sliding occurred. Dashed black line is best linear fit to data, showing that the amount of TRS increases approximately linearly as a function of TRM (TRS=0.58·TRM+0.2). The maximum of TRS was about 0.8 corresponding to the steady state COF_{max}. In practice, stable running conditions can be guaranteed only when TR is less than about 0.5. Considering FE-simulations this value could be used as the maximum COF, if stable friction conditions are desired.

Fig. 1D shows measured average sliding amplitudes, extracted from fretting loops when torque is equal to zero. Full stick condition was not achieved at used load levels. These values represents the maximum slip that can exist; however, some points in the contact may remain stuck if partial slip (see Ref. [1]) occurs at the level of individual asperity tip contacts. Regardless, the measured sliding amplitude increased gradually as a function of TRS until gross sliding conditions prevailed (TRS~0.8). Obviously, in gross sliding regime, the amount of sliding was independent of TRS.

The presence of slip may play a role on the instability of COF. For example, COF may be effected by surface modifications brought about by fretting wear, such as in non-Coulomb friction, and by entrapped third body. Such phenomena may increase the compliance of the interface, effectively reducing frictional torque and ease the accommodation of fretting motion. It is also possible that interface yielding and deformation occurs at scale of individual asperity tip contacts, which is not strictly speaking sliding.

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