Development of Surface Dynamic Mechanical Analysis Tests for TPU Materials

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The stick-slip behaviour of elastomers plays an extremely important role under service relevant loading conditions in many tribological applications. In a number of practical situations, the friction instability (stick-slip) causes negative influence on the sliding performance of various components (e.g. seals, wipers or dampers). To characterise the stick-slip behaviour of polymers a rotation based test set-up was used on an axial/torsional dynamic testing machine (BOSE 3200AT) with the ring-on disc specimen configuration. This paper describes under which conditions stick-slip occurred (for both monotonic and dynamic loading) and how to use these results to make a more efficient material selection. In that case the load, velocity and amplitude dependencies were summarized in form of diagrams as a "Running condition stick-slip map".

Keywords: *stick-slip, TPU, hysteresis.*

1. INTRODUCTION

The stick-slip phenomenon as described in literature plays an extraordinary important role for thermoplastic and elastomer materials in many tribological applications. Especially for seals, that phenomenon causes friction induced vibrations which become noticeable as acoustic waves or material damage [1].

The occurrence of the stick-slip is strongly influenced by material properties and ambient conditions [2]. Although there are many possibilities to measure stick-slip we used a novel axial/torsional testing unit [3]. Both monotonic and cyclic tests can be performed using this axial/torsional test set-up. For these experiments two (one filled and one unfilled) thermoplastic polyurethane (TPU) types were investigated to locate the stick-slip under monotonic and cyclic conditions.

2. EXPERIMENTAL

To adequately characterise the stick-slip phenomenon of elastomers (TPUs), first monotonic and cyclic torque-angular displacement curves were measured and the critical/instability points were defined in terms of max/min torque/stress and strain values. Furthermore, these data were plotted as the function of normal load sliding rate amplitude and frequency.

The applied test set-up is shown in Figure 1. The used test specimen and counterpart are visible in Figure 2. Due to the very small friction instability range of the materials, one rebound difficulty was the time consuming identification of the stick-slip region.

The shown test set-up (Fig. 1) displays where the test specimen and counterpart are implemented.

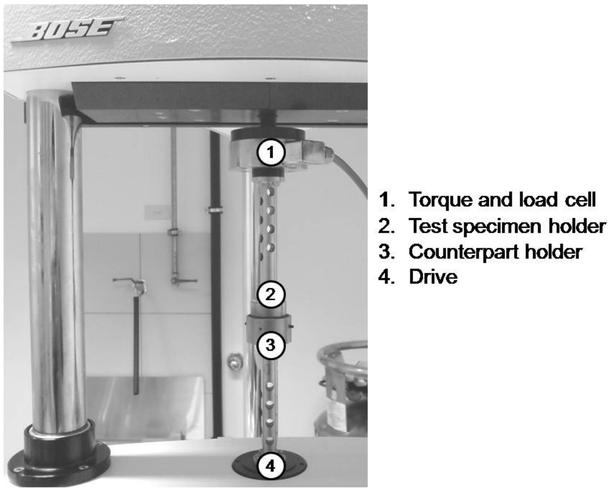

Figure 1. Axial/torsional test set-up

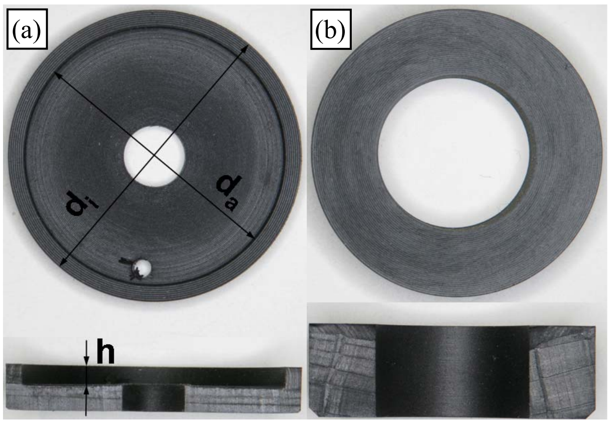

Figure 2. (a) test specimen and (b) counterpart

Important geometry information of the test specimen (Fig. 2a) is defined for later calculations in the following:

- h – height of the sliding surface;
- d_a – external diameter of the sliding surface;
- d_i – inner diameter of the sliding surface.

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2.1 Material

Both thermoplastic polyurethanes which are used for these tests have the same basic polymer and only the filler is the difference. TPU_{uf} stands for the unfilled grade and TPU_f for the filled grade.

The test specimens (Fig. 2a) and the counterparts (Fig. 2b) were produced with a turning centre under the same conditions at the company partner SFK ECONOMOS Austria GmbH. Table 1 shows the measured surface roughness [4] for both testing parts and materials after the production process.

Table 1. List of measured surface roughnesses according to DIN 4768

Roughness	Test specimen		Counterpart	
	TPU_{uf}	TPU_f	TPU_{uf}	TPU_f
R_q [μm]	2.71	2.54	0.71	0.70
R_a [μm]	3.89	3.31	0.90	0.89

Both data (R_q and R_a) show that the surface roughnesses are almost at the same level. The roughness of the test specimen from the unfilled TPU grade is slightly lifted. The reason for that is the unfilled grade's lower modulus and the tolerances of the manufacturing method.

2.2 Monotonic tests

The measurement technique allows us to record the specific stick-slip movement as demonstrated in Figure 3. To classify the intensity and the strength of the occurrence of stick-slip, it was necessary to use the most important points at that instability [5,6]. These are the point at the maximum stick and the point at the maximum slip, which are also outlined in the Figure 3. The characterisation of the stick-slip phenomenon is manageable with these two points.

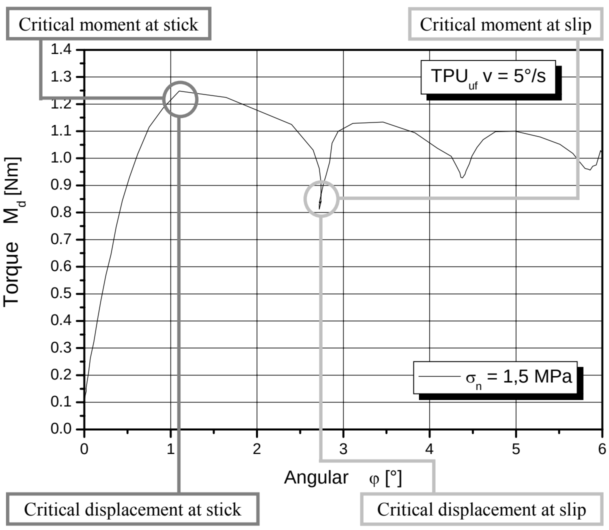

Figure 3. Definition of the important points (monotonic)

The knowledge of the different parameters φ (angular), F (load applied as normal stress σ_n) and v (velocity) gives a good basis to perform cyclic tests.

2.3 Cyclic tests

The used test settings for the monotonic tests have been transferred into cyclic test parameters and first stick-slip hystereses were measured. In Figure 4 hystereses are presented under different rotation amplitudes, from 0.5° up to 4°.

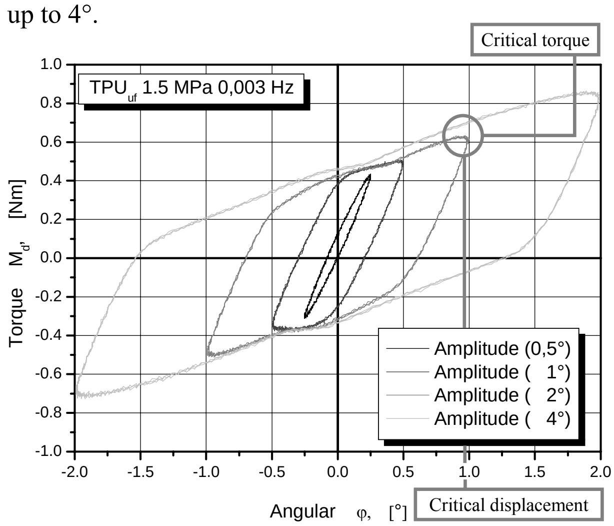

Figure 4. Definition of the important points (cyclic)

To verify the intensity and to compare the different hysteresis two techniques were used and combined.

The first technique is similar to the monotonic tests. We applied the maximum torque and rotation for every hysteresis to compare the different parameters.

The second technique uses the same approach as the quantification of the fretting damage where three different sliding conditions where defined [7,8].

For the measured hysteresis we described three different states for stick-slip which are leant on the different regions of the fretting damage:

- The partial slip region, where the hysteresis shape looks like the hysteresis with amplitude of 0.5° (see Figure 4). In this region the torque is directly proportional to the displacement and show linear elastic behaviour,
- The non linear region, where a transition from partial slip to gross slip happens, and
- The gross slip region (see Figure 4, 4°) where a continuous sliding over the whole contact zone takes place and this region is defined by a quadratic like hysteresis shape.

Based on these three regions defined and determined, RCSSM were created and are shown in Figures 7 and 8.

2.4 Data reduction and calculations

The measured torque as shown in Figure 3 is converted to the torsion stress as shown in (1):

$$\tau_{\max} = \frac{M_d}{W_p} \tag{1}$$

$$W_P = \frac{\pi \cdot (d_a^4 - d_i^4)}{16 \cdot d_a} . \tag{2}$$

The rotation is converted to the torsion strain at the maximum radius (r_a) of the test specimen. We used r_a because at this radius exists the maximum strain (see (3)):

$$\gamma = \frac{\varphi \cdot r_a}{h}. \tag{3}$$

With (1) and (3) calculation it was possible to create stress strain curves to perform further investigations.

3. RESULTS AND DISCUSSION

3.1 Results of monotonic tests

As described in the experimental part, the maximum and the minimum amplitude (torque and rotation) of the stick-slip movement are the interesting parameters for our investigations, so we decided to set these two points in relation. The minimum (stress and rotation) was subtracted from the maximum (stress and rotation). The result for the unfilled material is shown in Figure 5.

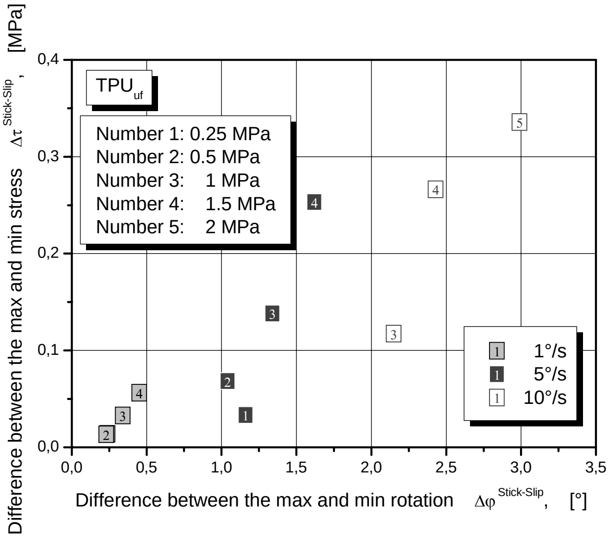

Figure 5. Diagram of the stick-slip deltas in connection to the load and velocity for TPU_{uf}

The intensity of the stick-slip is definitively dependent on the load and velocity. Figure 5 shows also a clear detachment of the load and velocity regions.

The same observations were made for the filled material and are displayed in Figure 6.

For TPU_f there is no clear dependence of the load and velocity evident. In comparison to the unfilled material (Fig. 5), especially in the area from 0° to 1° and 0 MPa to 0.1 MPa, no explicit distinction of the stick-slip intensity is possible.

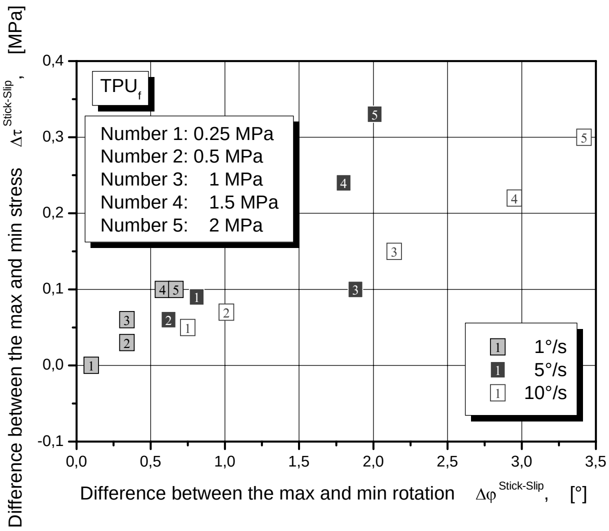

Figure 6. Diagram of the stick-slip deltas in connection to the load and velocity for TPU_f

The main reason that there is no visible separation of the load and velocity influences (in contrast to TPU_{uf}) is the existence of the filler. The filler reduces the stick-slip occurrence and intensity.

3.2 Results of cyclic tests

To combine all ambient conditions (load, frequency and amplitude) for a better material selection we created a "Running condition stick-slip map" which was proposed by [9] and generated based on our experimental data. The RCSSM displays different levels of stick-slip (Fig. 7).

For low amplitudes the friction behaviour is mostly located in the partial slip region and for high amplitudes in the so called gross slip region where normally steady slip takes place.

To show the regions also for the filled material in Figure 8 the RCSSM is displayed.

The influence of the filler is obvious. The material with no filler has higher tendency to stick-slip as the

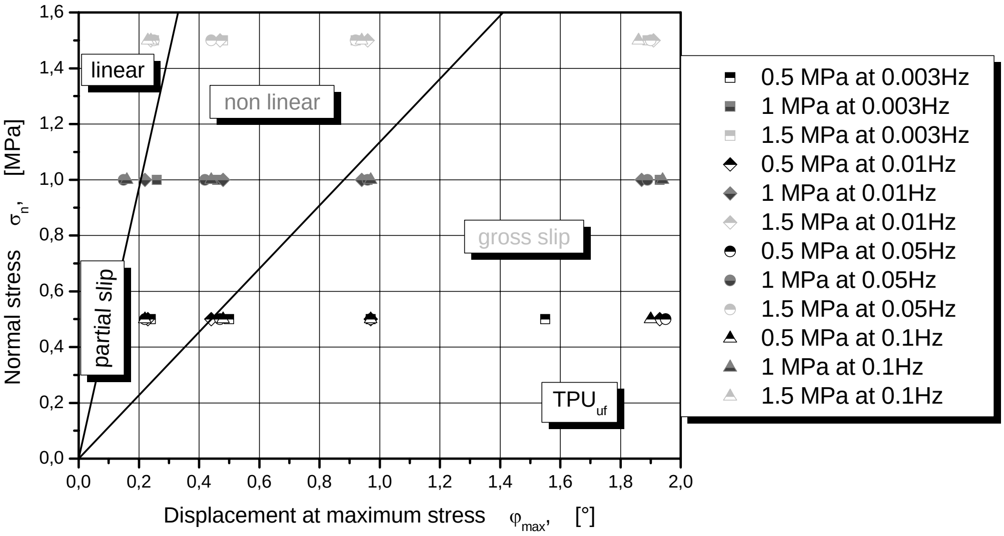

Figure 7. Running condition stick-slip map for TPU_{uf}

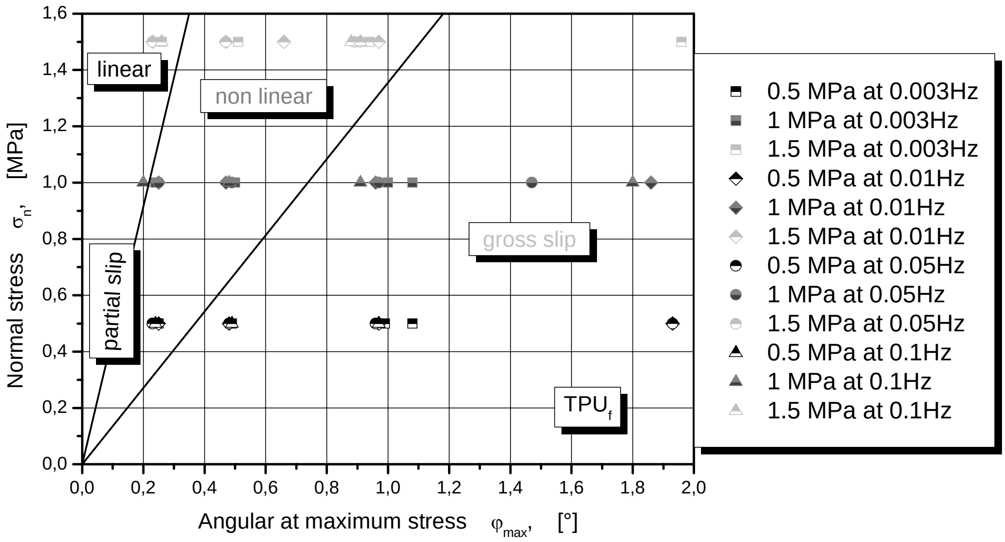

Figure 8. Running condition stick-slip map for TPU$_f$

filled one. Especially the ranges of the partial slip and non linear region show differences. For TPU$_{uf}$ the linear ranges from 0° up to 0.33° and from 0° up to 0.35° for TPU$_f$. A clear difference between the materials appears at the end of the non linear range. The non linear range goes up to 1.41° for TPU$_{uf}$ and up to 1.18° for TPU$_f$. This shows that the filled material has a less pronounced tendency for the stick-slip movement. In case of stick-slip the intensity at filled material is lower than the unfilled material.

Due to the fact that we performed these cyclic experiments the first time we also looked exactly at all hysteresis shapes. We found out that there is a big difference between the materials at higher rotation angels. In Figure 9 the difference between the filled and unfilled grade is demonstrated.

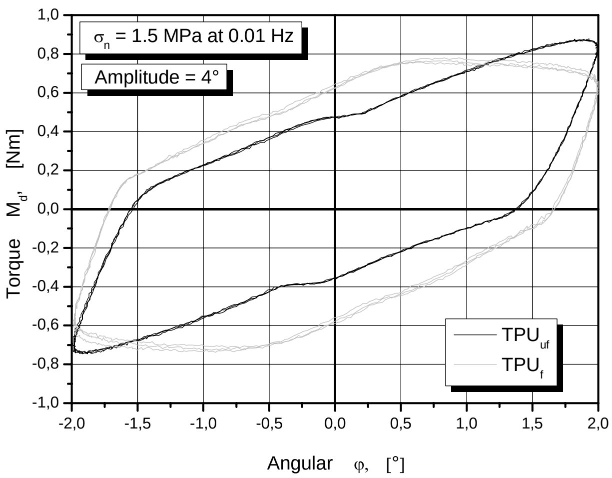

Figure 9. Difference between TPU$_f$ and TPU$_{uf}$ for high amplitudes

So we decided to look also at this phenomenon because it affects the region of the gross slip. We found out that there must be two possibilities for the gross slip region.

There is a stable and an instable condition for the gross slip and this state is highly influenced by the filler.

We looked at the critical displacements when the instability began and plotted that for both materials and for all amplitudes to characterise the occurrence of the gross slip instability (see Figure 10).

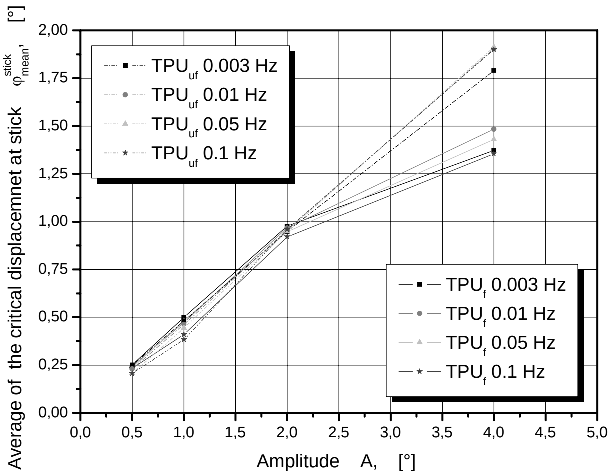

Figure 10. Mean value of the critical displacement at stick for different amplitudes for both materials

The unfilled grade shows a clear linear progress for low and for high amplitudes. In contrast the filled grade starts also linear, but from 2° amplitude the curves begin to buckle.

This appearance covers with the hysteresis shapes for the filled material. This also shows that the filler is responsible for this instability.

4. CONCLUSION AND OUTLOOK

Stable and reliable torque-angle curves were measured in both monotonic and cyclic experiments. The critical values for stick-slip transition conditions were determined in terms of shear stress and strain values.

The determination of running condition stick-slip maps (RCSSM) can support both material selection and development for a specific application.

To support further FEM simulations in previous experiments load and frequency dependent surface related bulk viscoelastic parameters were determined (DMA, creep). Measurements based on hysteretic stress-strain curves are ongoing. To establish a proper surface/bulk property relationship, these surface related parameters will be compared to the bulk viscoelastic parameters.

ACKNOWLEDGMENT

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РАЗВОЈ ПОСТУПКА ЗА МЕХАНИЧКО ИСПИТИВАЊЕ ДИНАМИКЕ ПОВРШИНСКИХ ПРОЦЕСА КОД ТЕРМОПЛАСТИЧНИХ ПОЛИУРЕТАНА

Андреас Хаусбергер, Иштван Годор, Томас Шварц, Золтан Мајор

Појава стик-слип (*stick-slip*) ефекта код елестомера, при одговарајућим радним условима, је јако битна код многих триболошких примена ових материјала. У пракси неравномерност процеса трења (стик-слип ефекат) има негативан утицај на карактеристике клизања различитих компонената (нпр. заптивки, брисача, пригушивача и амортизера). За одређивање карактеристика полимера у условима клизања са присутним стик-слип ефектом коришћена је посебна апаратура на принципу ротације типа „прстен на диску“, која је инсталирана на уређају са динамичким аксијалним и моментним оптерећењем (*BOSE 3200AT*). Овај рад описује под којим условима настаје стик-слип ефекат (при статичком и при динамичком оптерећењу) и како се добијени резултати могу искористити за квалитетнији избор материјала. У ту сврху су параметри оптерећења, брзине и амплитуде кретања дати дијаграмски и обједињени у мапу „стик-слип ефекат и услови кретања“.