TECHNICAL WHITEPAPER

Friction and Wear of Polymers

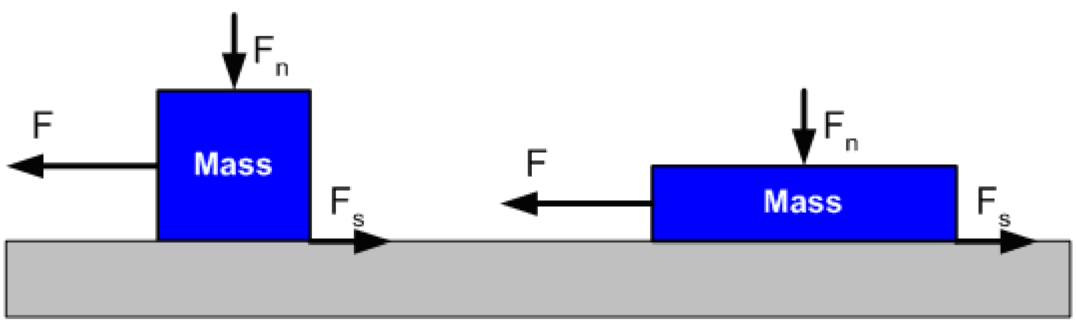
Introduction

This month's Newsletter is all about tribology. Some readers will immediately think of the classic Star Trek episode "The Trouble with Tribbles" but tribology is not about round fluffy animals that clog up Scotty's intakes. Tribology is the science and technology of interacting surfaces in relative motion; and therefore covers friction, wear and lubrication, a big topic and of great importance to us all.

Friction and wear are generally treated by engineers as being negative, and they generally seek to reduce them. However, without friction and wear, we would not be able to use pens or pencils (they write by wearing away the soft graphite), we would slide uncontrollably down the slightest incline, and our cars would not operate (the wheels would spin and we would always continue in a straight line if we ever got moving). Equally with very high levels of friction and wear we would also not be able to write and our cars would seize up at the first start (if we could make them in the first place). We depend on manageable values of friction and wear for almost everything we take for granted.

Friction – The Basics

One of the first people to investigate friction was Leonardo da Vinci, and he made one of the fundamental but least intuitive discoveries about friction. Imagine two blocks on a plate as shown below:



The blocks have equal mass and surface finish but one has twice the contact area of the other. If the blocks have a vertical force (Fn) applied and are made to slide by the application of a horizontal force (F) then a frictional force (Fs) will resist the sliding.

The surprising, and counter-intuitive, thing is that the frictional force (Fs) will be the same for both blocks even though the surface contact area is vastly different. The frictional force (Fs) is related only to the vertical applied force (Fn) and the relation is:

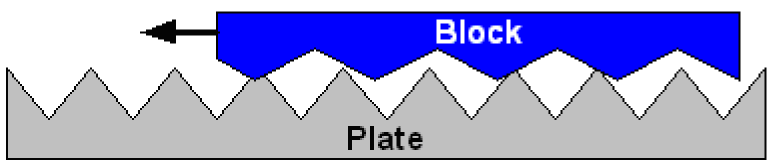
Fs = μ x Fn or μ = Fs / Fn

where μ (pronounced mu) is the 'coefficient of friction' for the material combination of block / plate and is approximately 0.5 for many materials combinations.

The frictional force resisting the movement does not depend on the apparent contact area - simply on the vertical force!

The reason for this apparently strange result is that the surfaces do not contact completely over the measured contact area. Even the smoothest surface is 'rough' at the very micro scale and at the junction between the two surfaces the materials only touch over small patches, called 'asperities'. The asperities support the load and deform (both elastically and plastically) to reach equilibrium. What we measure as the apparent contact area has little to do with the real contact area in tribological terms and the apparent contact area is generally much larger than the true contact area.

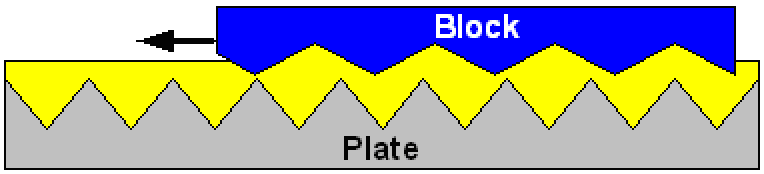
To visualize this, the contact between the block and the plate can be considered at the micro level to be as shown below. Both the block and the plate are 'rough' in tribological terms, and the peaks and valleys shown are the asperities that cover the surfaces. The vertical force will crush the asperities on both the block and plate (elastically and plastically) until the plate uniformly supports the load. If the apparent contact area increases for no increase in load, then the asperities simply do not deform as much before the force balances out. Asperities also hold the key to wear, but more of that later.



When movement occurs, the asperities rub against one another creating a natural resistance to movement as they slide over and deform one another. This resistance to the movement is the frictional force (Fs) as defined by the equations above.

What about Lubrication?

With two dry surfaces the deformation of the asperities controls the frictional force, but what happens when we introduce a third material (a lubricant) between the two contacting surfaces? The incompressible solid or liquid lubricant tends to fill the gaps between the asperities (as shown below) and acts as a fluid bearing surface to allow smoother movement of the two materials. This gives a much reduced frictional force (and hence a much reduced μ) than for unlubricated movement. Traditional fluid lubricants are oils from a wide range of sources, but it is also possible to use solid lubricants such as graphite, molybdenum disulphide (MoS_2), or PTFE as a stable dispersion in oil or water.



Lubrication with liquid lubricants is classified as partial when there is some contact between the block and the plate or as fully hydrodynamic when there is a total separation of the block and the plate by a layer of lubricant. Lubrication is effective even for materials with a very low coefficient of friction because the lubricant layer not only greatly reduces the coefficient of friction but also reduces the surface damage caused by the asperities rubbing together. For partial lubrication the coefficient of friction is generally between 0.01 and 0.1, and for fully hydrodynamic lubrication this is further reduced to between 0.001 and 0.01. While some materials such as PTFE have extremely low coefficients of friction (around 0.05 against dry steel) even these can be improved by the introduction of effective lubrication.

With many plastics it is possible to provide internal lubricants by incorporating solid lubricants into the basic polymer to give products such as Nylatron® lubricant filled cast nylon, Nyloil® oil filled cast nylons and a variety of other products such as those containing PTFE which create a low friction PTFE film between the plastic and the opposing surface.

Testing for Friction

There are actually two coefficients of friction that can be measured. The static coefficient of friction (μ_s) is found from the force that is just enough to start the block moving. Once the block is moving it is possible to measure the dynamic coefficient of friction (μ_d) from the force that is just enough to keep the block moving. For most combinations of materials μ_d is less than μ_s.

There are many methods for measuring the coefficient of friction:

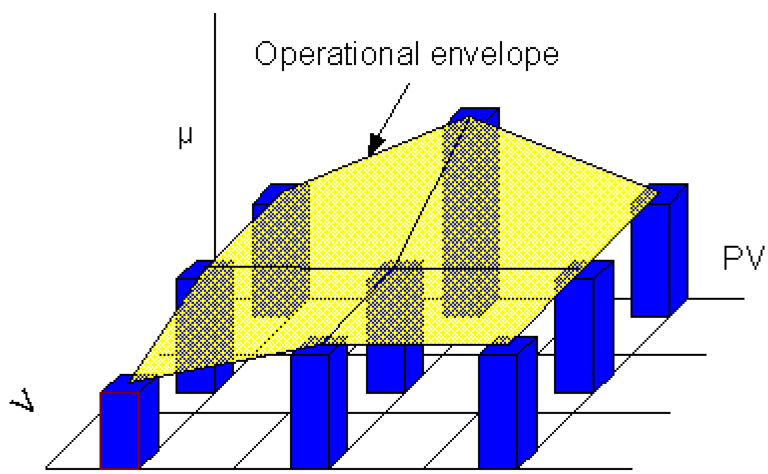
- Leonardo da Vinci attached a load to blocks with a string and pulley and measured the load at which the block began to move to measure μ_s.
- A spring balance can be attached to the block and the forces needed to start and continue movement can be measured to find μ_s and μ_d.
- The block can be mounted on an inclined plane that is tilted until the block starts to move. The angle of tilt can be used to resolve the forces to calculate both μ_s and μ_d.

Laboratory testing for friction and wear is often carried out using a motorized tribometer and there are various standardized and non-standardized test methods available. One of the most common is ASTM D3702 for "Wear Rate and Coefficient of Friction in Self-Lubricated Rubbing Contact using a Thrust Washer Machine." This test uses a sample held against a rotating plate at a constant contact pressure (P) and at a constant sliding speed (V) to measure both the dynamic coefficient of friction and the wear properties of the sample.

Similar tests are available to assess continuous sliding (pin-on-disc test to ASTM G99) and reciprocating sliding (pin-on-plate test to ASTM G133). Measurement using a tribometer should always take place after a ‘running-in’ period as the dynamic coefficient of friction changes significantly during the initial stages of testing and only becomes relatively stable after running in.

For plastic film and sheeting the most common test is ASTM D1894 for "Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting," that is capable of measuring both the static and dynamic coefficients of friction.

As with any test, it is unwise to try to completely characterize a material by a single value and this is very true with frictional measurement where the tests are only valid for the specific conditions of test. The most effective way to assess the relative performance of a plastic material is to measure the coefficient of friction at various combinations of pressure and speed. These values can then be used to generate a PV surface showing the operational envelope of the material as shown below.

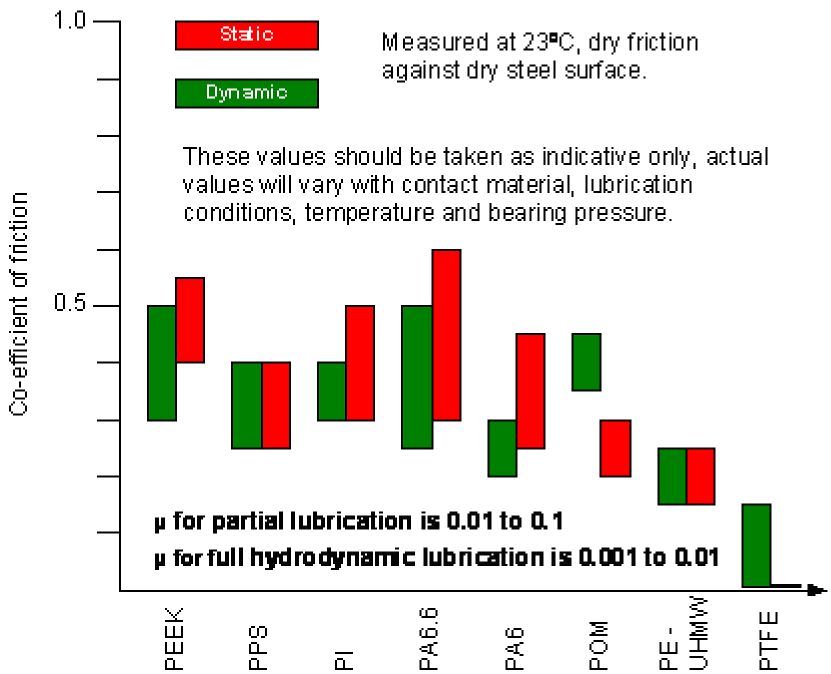


Friction in Plastics

Friction in actual applications is very difficult to predict because of:

- The wide range of surface combinations;
- The wide range of lubrication possibilities;
- The non-linear relationship between the contact pressure (P), the sliding speed (V) and the coefficient of friction (µd);
- The effect of any temperature rise due to frictional heating on the coefficient of friction (µd).

For plastics this can be even more complicated because plastics do not always follow the classical laws of friction that apply because of the large plastic deformations that occur at the tips of the asperities. Plastics do not react in this way, and the larger range of elastic deformation means that the coefficient of friction is generally lower than for other materials under the same conditions. It is therefore only possible to give indicative values for the coefficient of friction for plastics unless the specific application conditions have been tested. The chart below shows some typical values for a variety of plastics against dry steel.



Friction and the Fluorocarbons

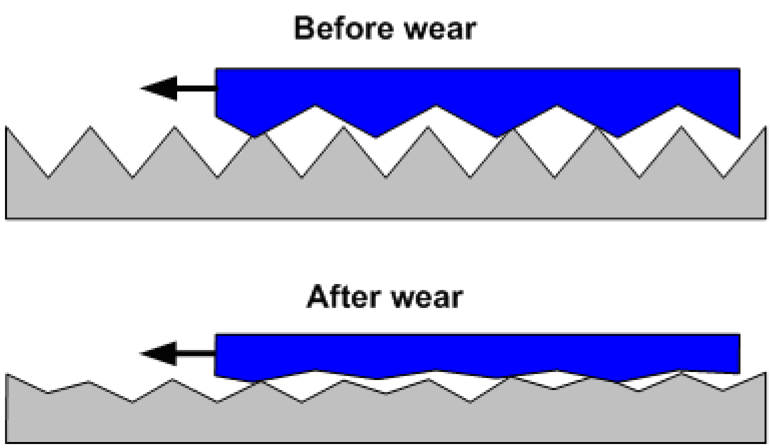
Most polymers have coefficients of friction in the range 0.2 to 0.6 but the fluorocarbons generally have lower coefficients of friction than this range. PTFE has the lowest recorded m value for any material with a dynamic coefficient of friction of between 0.05 and 0.15 and a static coefficient of friction of approximately 0.05. The other fluorocarbons i.e. FEP , PFA, ETFE and ECTFE all have extremely low coefficients of friction in the region of 0.14 to 0.25.

Wear – The Basics

Wear is "The removal of material from or the impairment of a solid surface resulting from friction or impact." When surfaces slide over one another, they not only experience friction, they also wear and material is lost from both surfaces, even when one is much harder than the other. This is true even with very hard materials such as diamond; diamond will scratch all other materials but still loses some material as it wears the other material (otherwise we couldn't polish diamonds as polishing is simply controlled wear to produce an apparently smooth and flat surface).

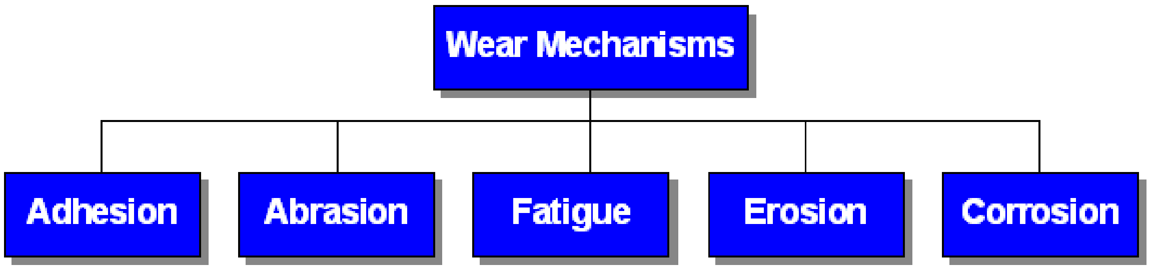
Wear is the direct result of the same processes that causes friction – the movement of the asperities on the surfaces over one another.

If the frictional block and plate model is considered, then it is easy to see that the constant movement of the asperities over one another, with the repeated elastic and plastic deformation, will lead to material removal and a grinding down of the asperities. The model shown is deliberately simple and would eventually lead to two smooth surfaces, in reality the removed material is trapped between the block and the plate and creates new grooves (and therefore new asperities) as the surfaces rub together.



Wear Mechanisms

While wear may appear to be simple there are a number of different mechanisms that can cause wear and a detailed description of these is beyond the scope of this paper. A broad classification of the main wear mechanisms is shown below and each of these mechanisms results in material removal and wear of different types.



Wear rate

The wear-rate, W, is defined as:

W = Volume of material removed / Distance slid (in m2).

It is also possible to define a wear rate (k) that will estimate the amount of wear for a given pair of materials at a given bearing pressure. This can be defined for a given contact pressure (P) and nominal contact area (A) as:

k = W / P x A

If k is high at a given contact pressure then there will be rapid wear between the two materials.

Testing for Wear

Wear testing can be carried out using the same motorized tribometer test as for friction (ASTM D3702) to produce wear rate values for a specified materials combination. As with friction testing, a single wear rate value will not adequately characterize the wear performance of a material and a range of tests should be carried out at various combinations of pressure and speed.

These values can then be used to generate a PV surface showing the operational envelope of the material similar to that generated for the coefficient of friction. If the ASTM test is used the wear rate is given in in/hr, i.e. the amount the sample height decreases in a given time.

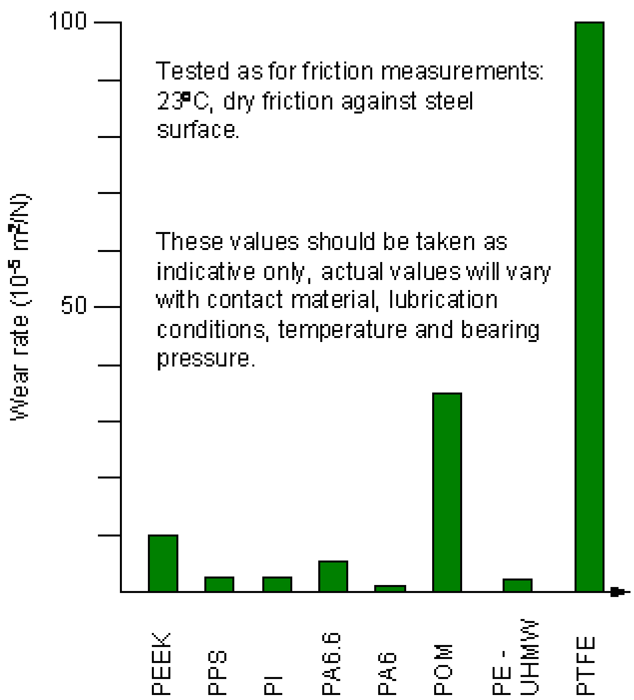
This is sometimes used as to produce a wear factor for plastics (K) expressed in the form:

Wear Factor K = Wear Rate/PV

This wear factor can be used for comparison but should not be used to predict actual service results. The Taber abrasion test (ASTM D4060) is an alternative method of testing for wear and abrasion resistance of coatings but reproducibility of the test is poor.

Wear in Plastics

As with friction, wear in real materials is very difficult to predict because of the wide range of variables and it is therefore again only possible to give indicative values for the wear of a given plastic unless the specific application conditions have been tested. The chart below shows some typical values for a variety of plastics against dry steel.



Wear and the Fluorocarbons

Most polymers have wear rates in the range 2 to 10 x 10-5 m2/N but the fluorocarbons generally have higher wear rates, a reflection of their generally lower hardness than comparative plastics.

Despite this the fluorocarbons have a unique range of properties, such as their extremely low coefficient of friction, that make them essential as additives for other plastics and for use as seals, gaskets and fittings in unloaded applications over a wide range of temperatures in aggressive environments.

Summary

Friction and wear are complex subjects where the results depend highly on the loading application and conditions. Despite this, plastics have unique properties that allow them to be used in applications involving friction and wear.

The fluorocarbon plastics, with their extremely low coefficients of friction have a unique place in the production of parts with low frictional effects, either as additives or as discrete parts.

How Zeus Can Help

With a technical inside and outside sales force backed up with engineering and polymer experts, Zeus is prepared to assist in material selection and can provide product samples for evaluation. A dedicated R&D department staffed with PHD Polymer chemists and backed with the support of a world-class analytical lab allows Zeus an unparalleled position in polymer development and customization.

Since 1966 Zeus has been built upon the core technology of precision extrusion of high temperature plastics. Today, with a broad portfolio of engineered resins and secondary operations, Zeus can provide turnkey solutions for development and high-volume supply requirements.

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