PLASTIC MATERIALS FOR FRICTION AND WEAR APPLICATIONS


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Qualitative descriptions of many plastic materials include the language, "excellent wear performance", however this has limited utility when choosing among plastic formulations for a specific application.

Specifying polymers with suitable friction and wear characteristics is one of the most complex issues that plastic part designers contend with. Qualitative descriptions of many plastic materials include the language, "excellent wear performance", however this has limited utility when choosing among plastic formulations for a specific application. Polymer tribology (the science describing the friction and wear behavior of plastics) is a vast discipline and many books have been written about the subject. This paper is not intended to provide a comprehensive overview of this topic but rather to introduce some key concepts and provide machinery designers with a framework for selecting plastic materials for friction and wear applications.

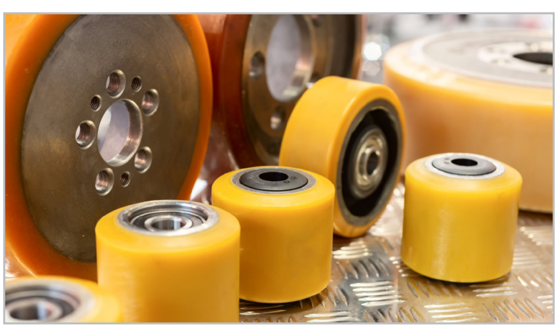
MECHANISMS OF POLYMER WEAR

There are a number of distinct mechanisms of polymer wear including (but not limited to) the following:

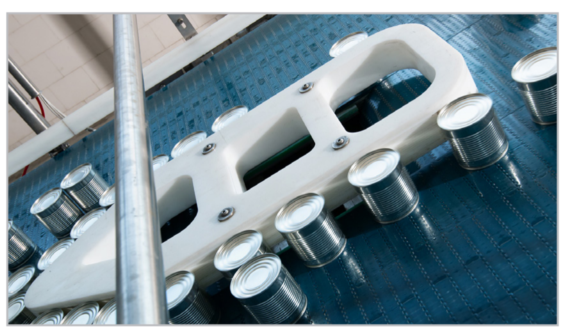
- **Sliding wear** – plastic part rubs against a relatively smooth mating surface (usually metal).
- **Abrasive wear** – plastic part rubs against a rough mating surface and/or abrasive particles that scratch the surface of the plastic.
- **Rolling contact fatigue** – plastic wheel or spherical bearing rolls against a mating surface.
- **Impact fatigue** – plastic part is repeatedly impacted during use.

Sliding wear

Abrasive wear



Rolling contact fatigue



Impact fatigue

As a general rule, semicrystalline thermoplastics such as UHMW-PE, nylon, acetal, semicrystalline PET, and PEEK have superior friction and wear characteristics when compared with amorphous thermoplastics including ABS, polycarbonate, and polyetherimide. Higher molecular weight grades of semicrystalline plastics tend to have superior friction and wear properties compared with lower molecular weight grades. Depending on the type of wear that a plastic part will be exposed to, different semicrystalline polymers with or without wear-enhancing additives may be suitable for an application.

SLIDING WEAR

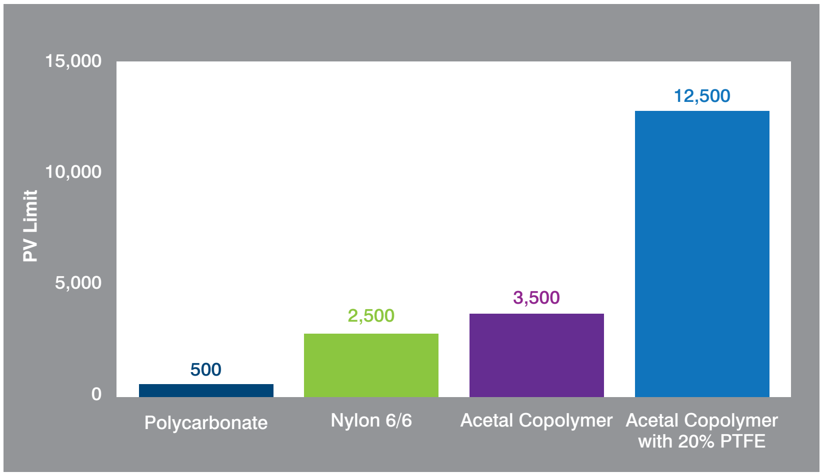
Sliding wear involves two parts in direct contact and in relative motion to each other. Wear is the result of micro-cutting, adhesion, and fatigue of the mating sliding surfaces (Galloway, 2008). For most sliding wear applications, low friction and long wear life are desirable. Additionally, it is important that the plastic material does not damage the mating surface since this can detract from the appearance and/or functionality of the mating part.

Sliding wear performance for a pair of materials is often quantified based on the following metrics.

- **Static coefficient of friction** – the force required to cause motion divided by the normal force on the contacting surfaces.
- **Dynamic (or kinetic) coefficient of friction** – the force required to maintain motion divided by the normal force on the contacting surfaces.
- **Wear rate** – the rate at which a material loses mass or volume during the wear process.
- **Limiting PV (pressure-velocity)** – the approximate combination of pressure and velocity that a plastic bearing material can withstand before failing due to frictional heat. The limiting PV ratings against steel for a number of plastic materials under specific test conditions are shown in Figure 1.

These green ultrahigh molecular weight polyethylene conveyor guides have low friction and long wear life against PET bottles. The soft surface of the polyethylene allows the machine to convey the bottles without scratching them.

Figure 1. Limiting PV of Various Thermoplastics at 100 fpm (Dry Wear Against 12 RMS SAE 1040 Steel)



Source: Adapted from Arkles, 1973

In order to compare the sliding wear performance of different plastics in a meaningful way, it is important that the test methods including the counterface material, surface finish, load, velocity, and part geometry be exactly the same for each material tested.

Although coefficients of friction, limiting PV, and wear rate are sometimes reported on plastic material properties sheets, this can be somewhat misleading. Tribological properties cannot be reported for a single material since they are "system properties" that involve two or more components in direct contact and in relative motion to each other. This becomes apparent when someone slides the tips of their fingers over concrete and then slides them over non-stick cookware. Their skin experiences different friction and wear when in contact with the two different surfaces.

Figures 2 and 3 illustrate the importance of considering the metal counterface when selecting plastics for tribological applications. In this example, both the coefficient of friction and the wear rate for UHMW-PE are dramatically different depending on if the polymer is sliding against stainless steel (SS), mild steel (MS), or aluminum (AL).

Figure 2.

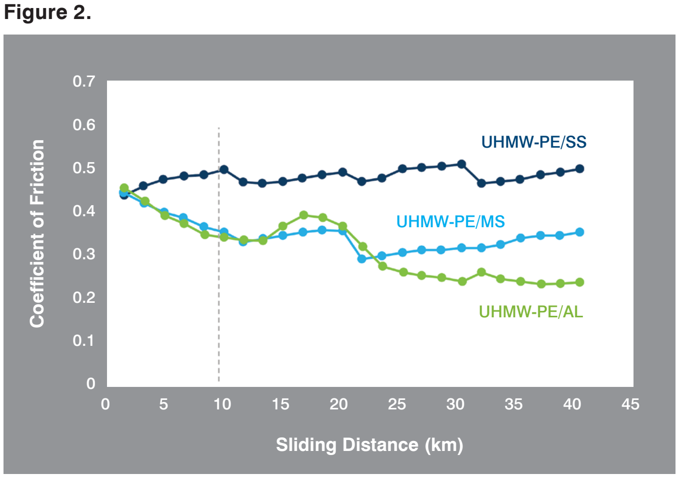
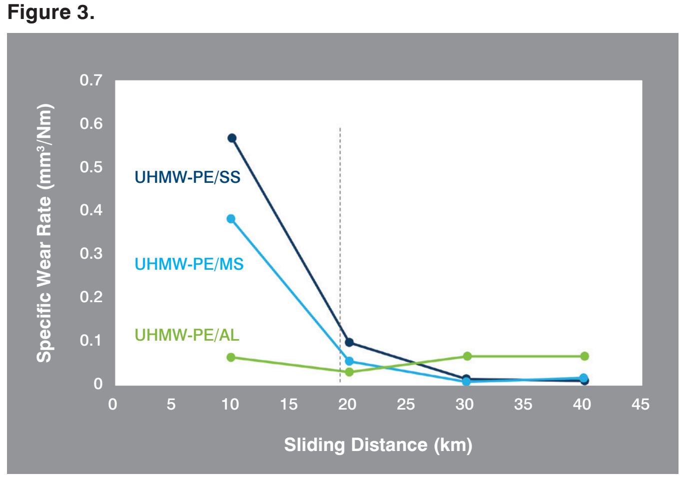


Figure 3.



Friction coefficients and wear rates for UHMW-PE sliding against stainless steel (SS), mild steel (MS), and aluminum (AL) in dry conditions. The vertical dashed line indicates the sliding distance where a steady state of wear is achieved.

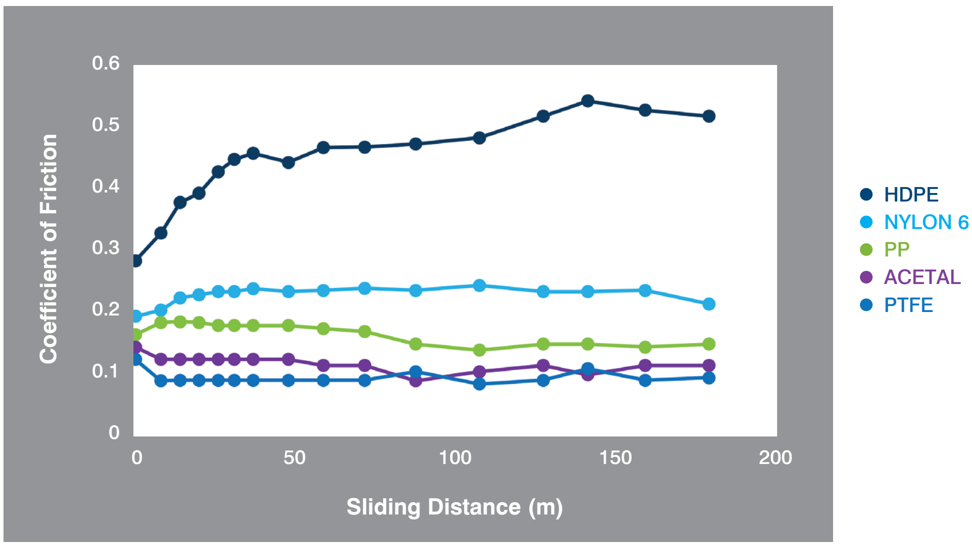
Source: Yousif, 2010

Plastics used for sliding wear applications are most often in rubbing contact with metal counterface materials. Generally speaking, plastics exhibit superior friction and wear performance sliding against hardened steels compared with sliding against softer metals such as soft stainless steels or soft grades of aluminum. Particle-filled PTFEs are one of the few categories of filled thermoplastics that exhibit good friction and wear performance in applications that involve rubbing contact with stainless steel (Michael, 1991).

Plastic sliding against plastic in a wear application is often more problematic than plastic sliding against a metal counterface. The low thermal conductivity of plastics reduces the speed with which frictional heat is conducted away from the wear surfaces. Excessive heat can result in softening and premature failure of plastic components. When plastic on plastic wear is required for an application, it is generally advisable to use different plastics for the two mating parts. Most plastic materials have poor friction and wear characteristics when components made from the same plastic are slid against each other.

Figure 4 shows the high coefficient of friction of HDPE sliding against itself compared with the material sliding against PTFE, polypropylene, acetal, or nylon.

Figure 4. Friction coefficients for various polymers sliding against HDPE



Source: Yamada, 1997

Most unfilled plastic materials, with the exception of PTFE and certain grades of polyethylene, have relatively high coefficients of friction and high wear rates when sliding against dry steel (Thorp, 1986). Semicrystalline thermoplastics with PTFE added to their formulations such as PTFE-filled acetal and PTFE-filled PEEK often far outperform the unfilled base polymers in sliding wear applications. Figures 5 and 6 illustrate the dramatic effect that PTFE fillers can have on the sliding wear performance of plastic materials.

Figure 5. Wear Rate for Acetal and PEEK With and Without 15% PTFE in the Formulation

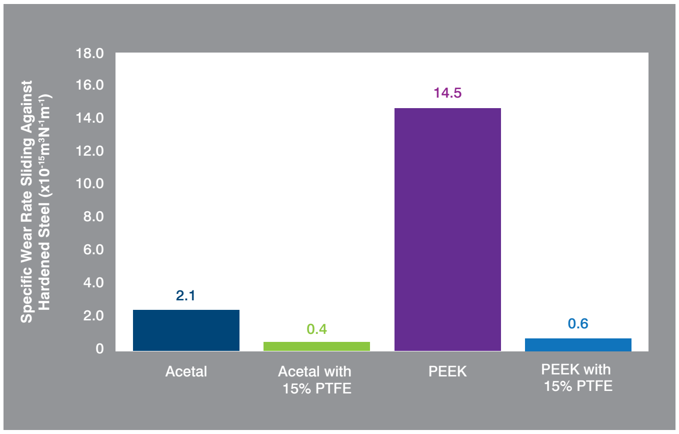
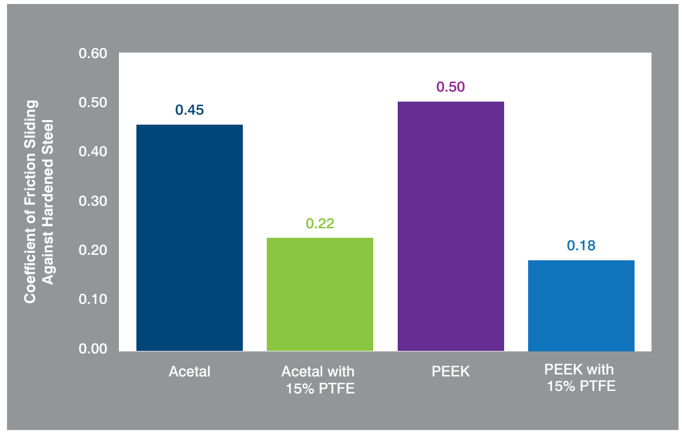
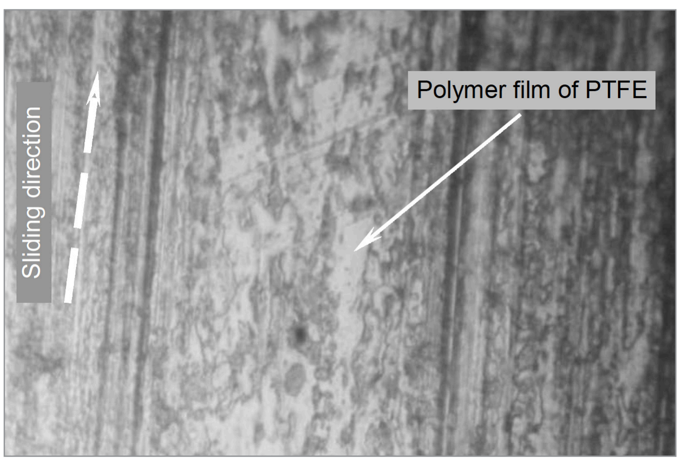


Figure 6. Coefficient of Friction for Acetal and PEEK With and Without 15% PTFE in the Formulation



Source: Adapted from Mens, 1991

In the case of acetal, the PTFE filler reduces the wear rate by 81% and reduces the friction coefficient by 52%. The PTFE filler has an even greater effect on the wear performance of PEEK, reducing the wear rate by 96% and the friction coefficient by 64%. The PTFE additive accomplishes this by depositing a wear film on the mating metal surface, filling in microscopic roughness in the metal and creating a smooth, low friction interface between the plastic and metal parts. This is analogous to the way that a wax crayon deposits a film of wax on rough sandpaper, filling in low areas and creating a smooth surface. PTFE wear additives may have limited benefit in applications where water is present since water tends to inhibit the formation of the PTFE transfer film on the surface of the metal (Mens, 1991, Wieleba, 2007).

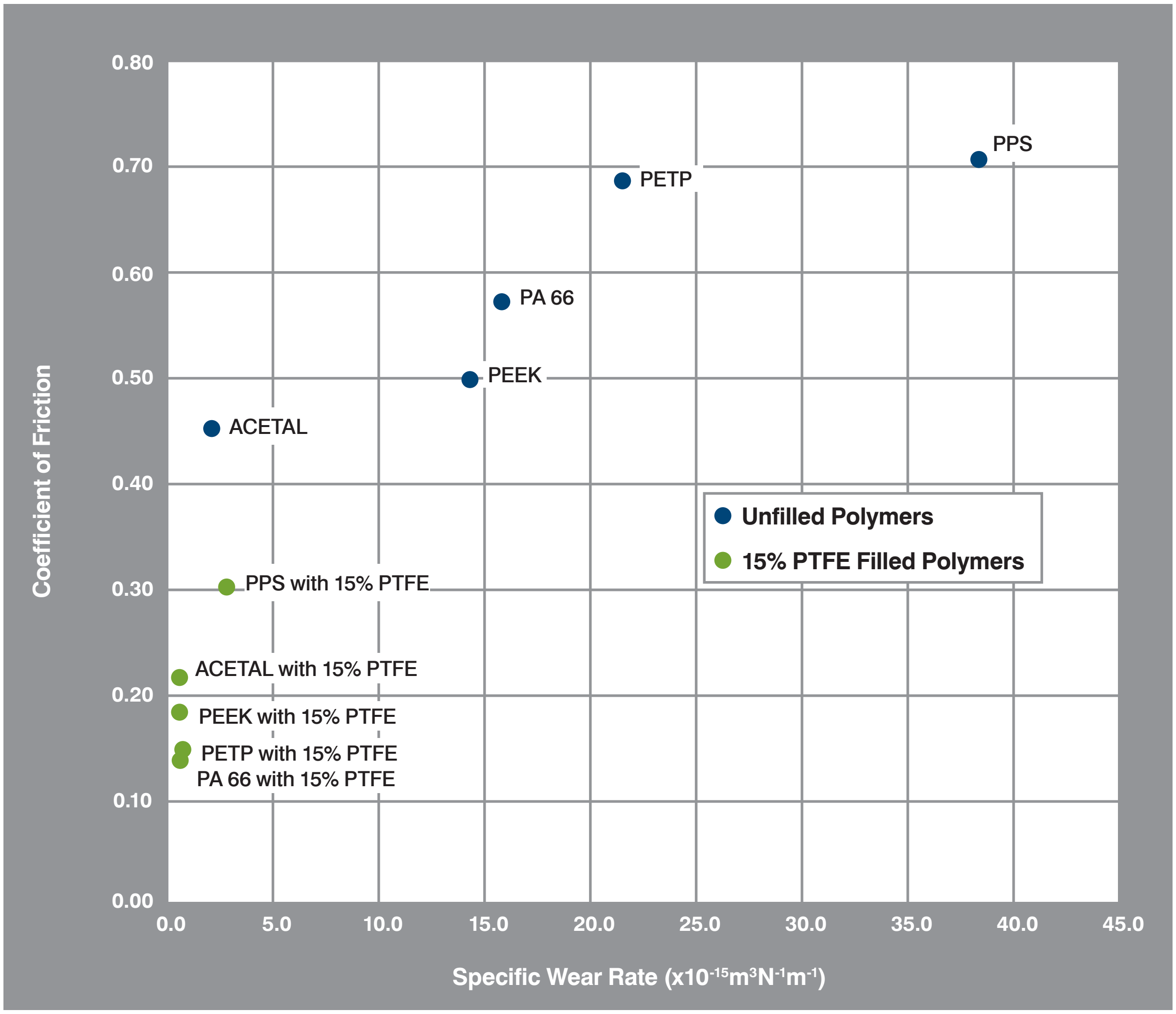


PTFE film is deposited on the surface of steel during sliding wear in much the same way that a wax crayon deposits a smooth film of wax on the surface of sandpaper. Source of the PTFE film photo: Wieleba, 2007.

It is important to note that although adding PTFE to the formulation of a thermoplastic reduces friction and increases wear life in many sliding wear applications, PTFE reduces the strength, modulus (stiffness), and creep resistance of most thermoplastic materials. PTFE fillers also tend to increase the coefficient of thermal expansion of plastics, making it more challenging to hold tight dimensional tolerances. Plastics with PTFE in their formulations are also generally more expensive than the unfilled base polymers.

Figure 7 shows the wear rates and coefficients of friction of a number of unfilled and PTFE-filled polymers sliding against hardened steel in dry conditions. The chart clearly illustrates the effectiveness of PTFE as a friction and wear additive to enhance sliding wear performance. It also illustrates the range of friction and wear characteristics for various unfilled and PTFE filled thermoplastics.

Figure 7. Coefficient of Friction and Specific Wear Rate for Various Unfilled and PTFE-Filled Thermoplastics Sliding Against Hardened Steel



Source: Adapted from Mens, 1991

Although PTFE is the most widely used additive to reduce friction and extend wear life, a number of other additives are also used to enhance the sliding wear properties of thermoplastics. It is important to note that additives can be combined to enhance multiple mechanical and tribological performance characteristics of a base polymer. Table 1 includes additives that are frequently added to plastics to improve their friction and wear performance.

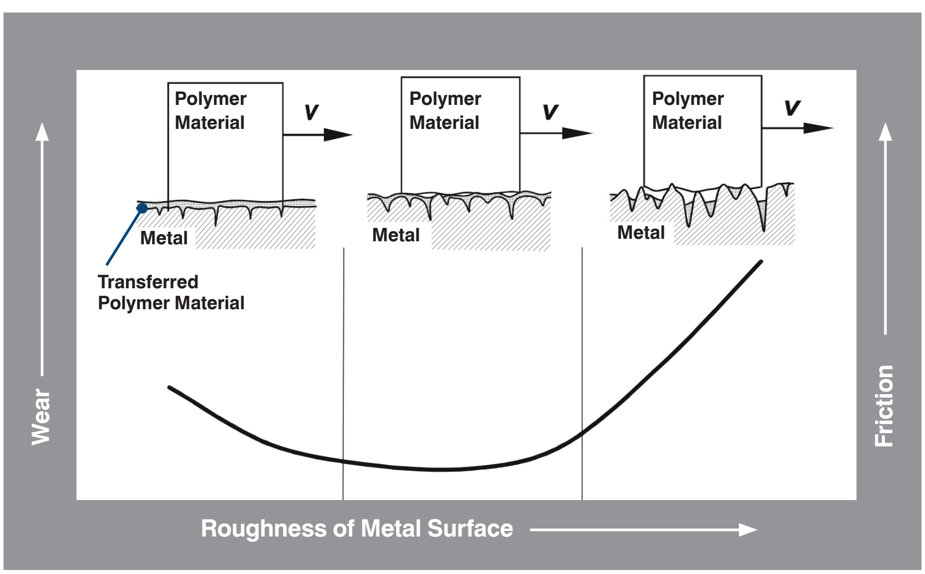
Table 1. Additives Frequently Added to Plastics to Improve Friction and Wear Performance

Carbon fiber	Lowers friction and increases strength, modulus, and thermal conductivity. Also improves creep resistance. Is less abrasive on mating metal parts compared with glass fibers.
Carbon powder	Lowers friction and increases thermal conductivity. Also improves creep resistance.
Glass	Increases strength, modulus, thermal conductivity, and creep resistance.
Graphite	Increases thermal conductivity. Also reduces friction as the graphite molecules slide past each other. Graphite is less effective as a friction and wear additive in dry or vacuum conditions.
Molybdenum disulphide (MoS_2)	Reduces friction due to the easy cleavage of the crystal structure (Winer, 1967). MoS_2 tends to adhere to mating metal surfaces, which makes the surface of the metal smoother. Unlike graphite, MoS_2 is an effective friction and wear additive in dry and vacuum conditions. MoS_2 is often added to nylon to make the material harder and increase its wear life.
Polyethylene	Used as a solid lubricant in plastic formulations. Deposits a wear film on mating metal surfaces to reduce friction and increase wear life.
Silicones and other oils	Liquid lubricants can be applied externally to machine components or they can be compounded into polymer formulations allowing them to gradually migrate to the surface of the plastic. Liquid lubricants separate the two sliding surfaces and help to conduct heat and wear debris away from the system. Liquid lubricants can reduce friction and extend the wear life of certain plastic materials. It is important that liquid lubricants be compatible with the polymer that they are being used with. For example, certain oils can plasticize nylon, softening the material and reducing its wear performance in some applications.

Source: McKeen, 2010

The surface finish of the mating metal component plays a role in the friction and wear performance of a polymer material. If the surface of the metal is excessively smooth, this can inhibit the formation of the polymer wear film and detract from wear performance (Rhee, 1978, Bely, 1982). If the surface finish of the metal is too rough, it can mechanically gouge the surface of the polymer, reducing part life. Figure 8 illustrates how a moderately smooth surface can optimize wear in semicrystalline thermoplastics.

Figure 8. Coefficient of Friction and Wear Rate of a Polymer as a Function of the Surface Roughness of the Metal Counterface



Source: Adapted from Wieleba, 2007 and Bely, 1982

ABRASIVE WEAR

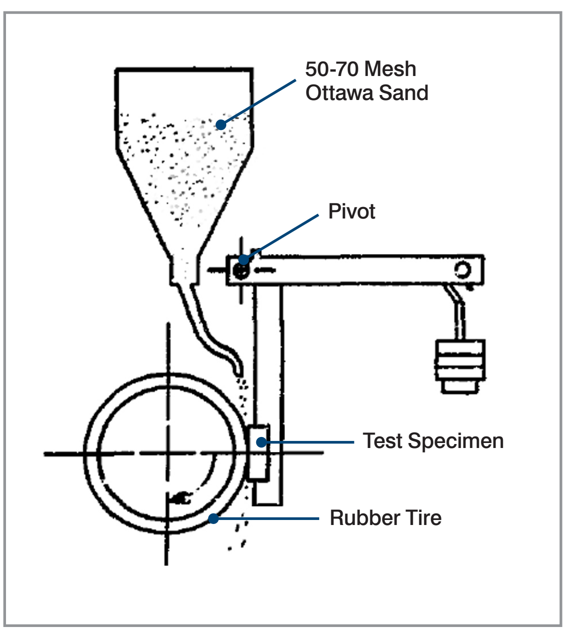
Abrasive wear involves plastic parts in direct contact with and in relative motion to either a rough metal surface with hard asperities (microscopic sharp points sticking up from the surface) or abrasive particles such as sand, sawdust, salt, or wear debris (Malucelli, 2012). When abrasive particles are suspended in a gas or a liquid slurry moving over a plastic surface, the process is referred to as erosive wear. The scratching and gouging action of abrasive particles can result in rapid wear of plastic parts.

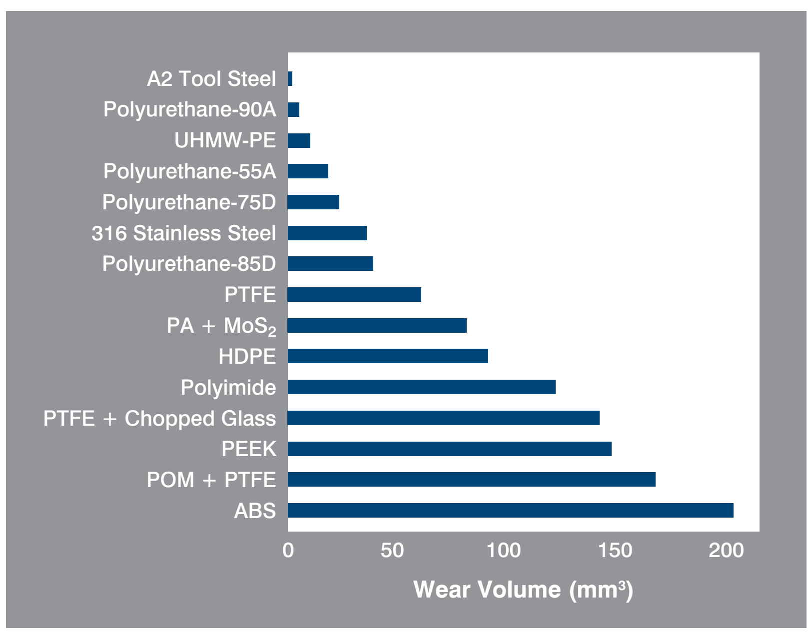
The plastic flights on this wood pellet conveyor need to have good abrasion resistance for long service life in extremely abrasive conditions.

The plastic roller covers in this stone chip conveyor need to have outstanding abrasive wear characteristics due to gritty contamination from the stone.

Figure 9 shows the abrasive wear resistance of various plastic materials in contact with silica sand and a rotating rubber wheel. Certain plastics including UHMW-PE (ultra-high molecular weight polyethylene) and hard grades of polyurethane tend to perform well in abrasive wear applications. Other plastic materials including HDPE (high density polyethylene) and PEEK have only moderate abrasive wear resistance.

Figure 9. Schematic of a Dry Sand-Rubber Wheel Abrasion Resistance Testing Machine and the Abrasive Wear Test Results for Various Plastic Materials





Source: Adapted from Budinski, 1997

ROLLING CONTACT FATIGUE

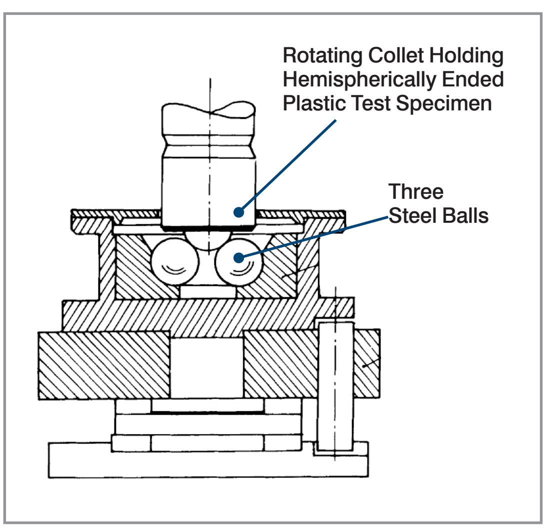
Rolling contact fatigue involves a round plastic part rolling against a mating surface. Due to the cyclic nature of rolling contact, any particular area of the part repeatedly experiences compressive loads followed by removal of those loads as that area of the part rotates past the point of contact with the mating surface. Applications that involve rolling contact include wheels and cylindrical or spherical rollers.

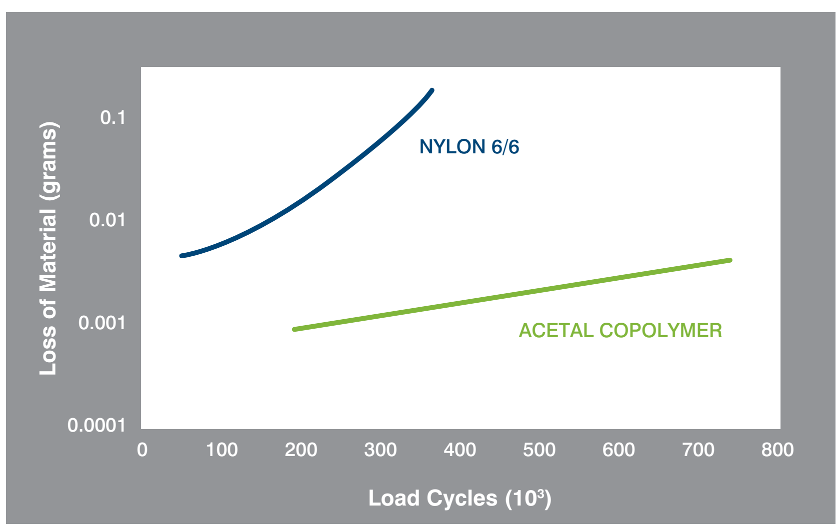
These plastic skateboard wheels need to have outstanding rolling contact fatigue resistance.

The ability of a polymer to perform in a rolling contact application depends on a number of factors including the applied load and the speed of the moving parts. Excessive loads may result in creep strain (permanent deformation over an extended period of time). Excessive speeds may result in the polymer melting from frictional heat. In some cases where high speed is required, lubricants can be used to remove heat from the system and increase the maximum speed for plastic parts in rolling contact (Stolarski, 1993).

The wear rate from rolling contact for different plastics (when operated below their maximum load and speed) varies among materials. Figure 10 shows a schematic of a rolling contact wear testing machine and the wear rate for nylon 6/6 and acetal copolymer tested in the machine for 700 cycles. In this test, acetal copolymer exhibited a much lower wear rate than nylon. Interestingly, using these same test conditions, unfilled PEEK exhibited essentially no measurable wear, illustrating the outstanding rolling contact fatigue resistance of this polymer.

Figure 10. Schematic of Rolling Contact Fatigue Testing Machine and Material Loss from Rolling Contact 400 RPM, 10N Load, Dry Conditions





Source: Adapted from Stolarski, 1993

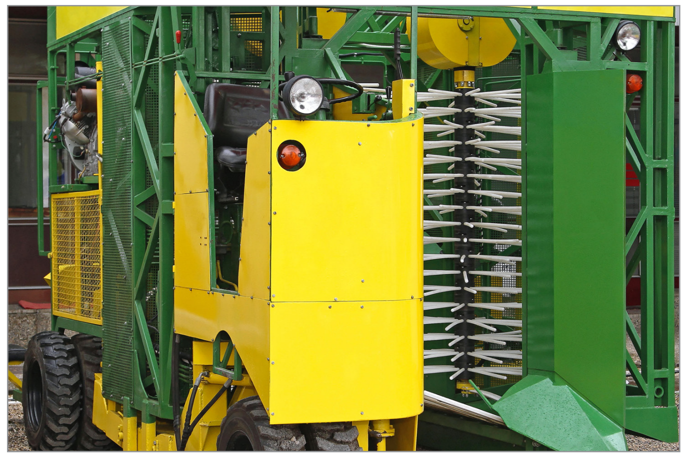
IMPACT FATIGUE

Single event measures of toughness such as notched Izod or Charpy impact tests may not be sufficient predictors of part performance for some applications. Impact fatigue occurs in applications where a plastic part is repeatedly subjected to mechanical loads at moderately high strain rates. The nature of impact fatigue is that the impact energy delivered to the specimen is not severe enough to destroy the part during a single event. Instead, impact fatigue involves multiple impacts that eventually damage a part to the point of failure (Adams, 1983).

One example of an application where impact fatigue resistance is essential is the plastic dispensing door at the bottom of a beverage vending machine that is repeatedly struck by cans during operation.

Another example of an application where impact fatigue resistance is important is the berry harvesting machine shown in the photograph below. The white plastic berry picker bars repeatedly strike branches to dislodge fruit during harvesting. Repeated impacts initiate microcracks that then coalesce into larger cracks that propagate through the material until eventually the part fails.

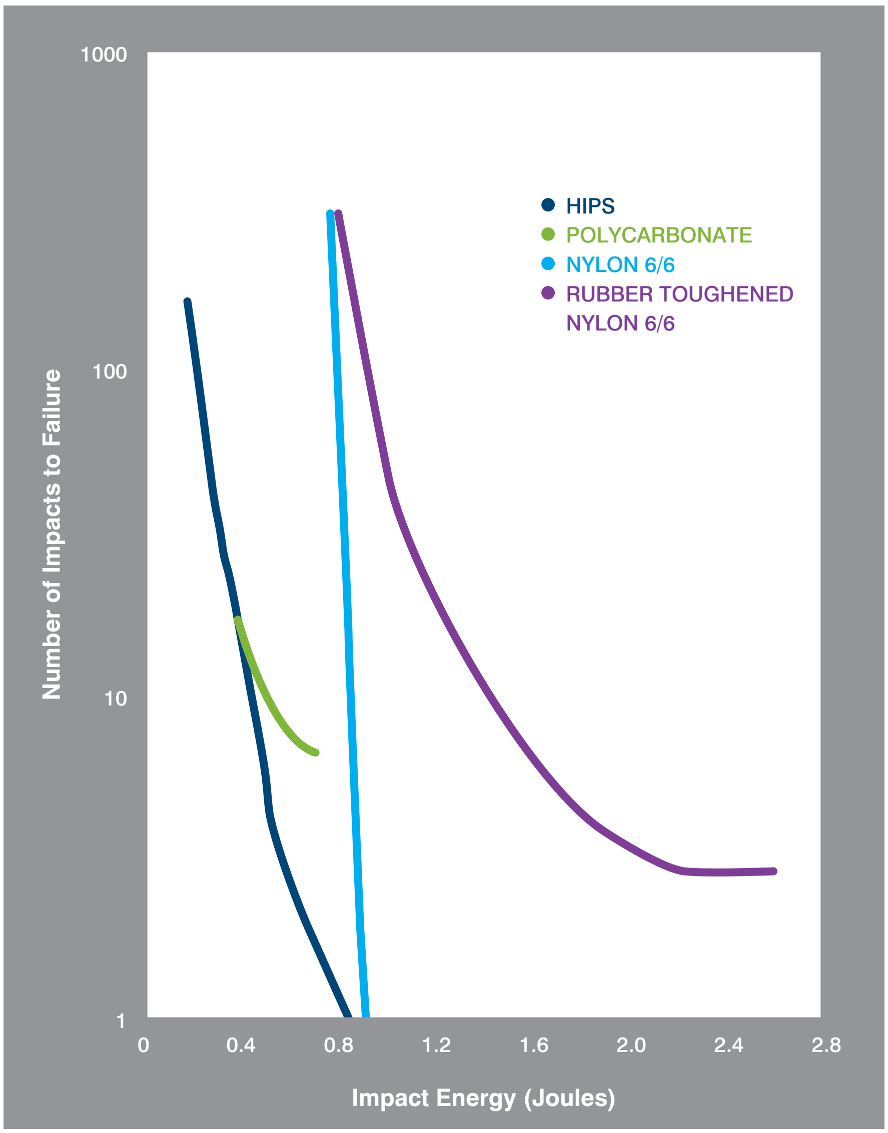
The transparent plastic access door at the bottom of this beverage dispensing machine is subjected to repeated impacts from falling cans of soda.



White plastic berry picker bars on a harvesting machine experience repeated impacts as the machine harvests fruit.

Impact fatigue curves provide useful data for selecting plastic materials for devices that must withstand repeated impact during use. Figure 11 compares the impact fatigue resistance of HIPS (high impact polystyrene), polycarbonate, nylon 6/6, and nylon 6/6 with a rubber toughening additive in its formulation. The graph clearly shows the outstanding impact fatigue resistance of rubber toughened nylon 6/6. This material was able to withstand more impacts at higher impact energies than the other plastics tested. Interestingly, although polycarbonate and HIPS are widely recognized as having outstanding impact resistance using single event tests, they exhibit only modest impact fatigue resistance.

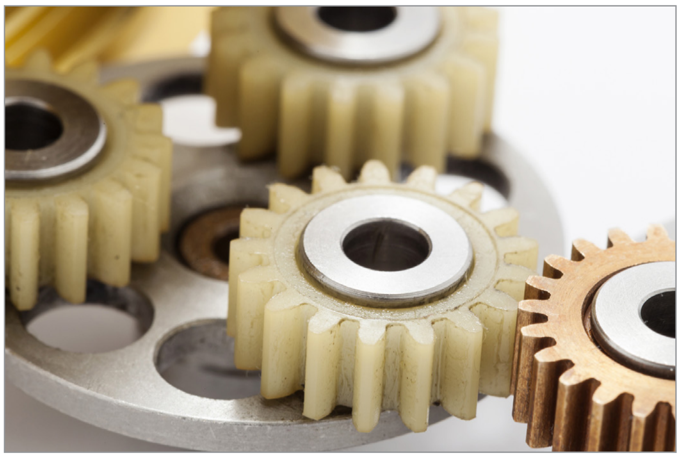
Figure 11. Impact Fatigue Resistance



Source: Adapted from Adams, 1983

APPLICATIONS WITH MULTIPLE MECHANISMS OF WEAR

For many applications, multiple types of wear may be occurring simultaneously. For example, the teeth of the plastic gears in the picture below experience both sliding wear and rolling contact fatigue. Potential mechanisms of failure could include the teeth wearing down from sliding wear, softening from frictional heat and deforming, or cracking at the base due to fatigue (Feulner, 2008, Kelley, 1995). Additionally, if the gears were subjected to heavy loads, they could fail due to creep strain (deformation of the gear teeth after being placed under load over a long period of time).



Plastic gears experience multiple mechanisms of wear including sliding wear and rolling contact fatigue.

Interestingly, investigating the mechanism of failure may suggest ways to improve the design. In the case of failure from sliding wear or excessive frictional heat, adding a solid lubricant such as PTFE to the formulation might help to increase part life. In the case of fatigue cracking, moving to a higher molecular weight grade of the polymer with better fatigue resistance could be a potential solution. In the case of creep strain, changing to a glass-filled or carbon fiber filled grade with superior creep resistance might extend the service life of the gear.

PLASTIC MATERIAL SELECTION FOR FRICTION AND WEAR APPLICATIONS

The following material selection process can be used to identify plastic materials as candidates for use in a friction and wear applications.

1. Determine the mechanism (or mechanisms) of wear that will be operating on the system (sliding wear, abrasive wear, rolling contact fatigue, and/or impact fatigue).

2. Consider the chemistry of the mating surface (soft metal, hard metal, or plastic).

3. Quantify the relevant tribological variables (load, velocity, surface finish, the presence or absence of abrasive debris, and the presence or absence of lubricants).

4. Consider environmental factors (operating temperature range, humidity, the presence or absence of water or other chemicals, vacuum conditions, exposure to UV or other radiation).

5. Identify base polymers that are capable of operating under the mechanical loads and the environmental conditions associated with the application. For example, a limited number of polymers, including PEEK, PAI, and polyimide, can function in friction and wear applications for extended periods of time at temperatures above 300 degrees F.

6. Consider which of the candidate base polymers has the required friction and wear characteristics. For example, UHMW-PE has excellent resistance to abrasive wear from gritty particulates and PEEK has outstanding rolling contact fatigue characteristics.

7. Determine which (if any) additives to the polymer formulation would enhance friction and wear performance in the application. For example, the addition of rubber particles to the formulation may enhance impact fatigue resistance.

8. Conduct empirical testing to determine which plastic material formulation is most suitable for the application. If testing can't be performed on the actual machinery where the plastic part will be used, it is important to simulate the application conditions as closely as possible.

CONCLUSION

This paper described several mechanisms of polymer wear, discussed additives to improve friction and wear performance, and outlined a process for selecting plastics for friction and wear applications. The intention of the author was not to oversimplify an extremely complex topic, but instead to offer practical information to help engineers as they select plastic materials for friction and wear applications. The reader is invited to review the papers listed in the references section for more detailed information on specific aspects of polymer tribology.

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TECHNICAL EXPERTISE

Curbell white papers are intended to provide engineers and designers with basic information about the engineering polymers available as sheet, rod, tube, and film stock from Curbell Plastics. We invite you to contact Curbell via e-mail at **technicalsupport@curbellplastics.com** to discuss applications in detail.

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Dr. Keith Hechtel is Senior Director of Business Development for Curbell Plastics. Much of his work involves helping companies to identify plastic materials that can be used to replace metal components in order to achieve quality improvements and cost savings. Dr. Hechtel has over 30 years of plastics industry experience and he is a recognized speaker on plastic materials and plastic part design.

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