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Friction, wear and transfer of pure and internally lubricated cast polyamides at various testing scales

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Abstract

Friction and wear of different cast polyamide composites (including two pure polyamides with sodium or magnesium catalysers, oil filled and solid lubricant filled polyamides) is evaluated on a small-scale and a large-scale tribotester to determine transitions in tribological behaviour and application limits. Small-scale tests are done at 50–200 N and 0.3 m/s on a cylinder-on-plate configuration (contact area <10 mm^2) and compared to sliding tests at 10–40 MPa and 0.005 m/s on a flat-on-flat configuration (contact area 22,500 mm^2) for investigating the efficiency of internal lubricants and reproducibility at different testing scales. Frictional heating and transfer are important and interfere with the sliding or lubricant mechanisms. The bulk and flash temperatures during sliding are calculated and the softening and/or melting mechanisms for the different polymers are closely related to differences in transfer, either on small-scale or large-scale tests. For pure polyamides, the magnesium catalysed polyamide (PA-Mg) has different softening behaviour compared to sodium catalysed polyamide (PA-Na) as revealed from thermal analysis and Raman spectroscopy. Therefore, sliding instabilities attributed to stick-slip for PA-Na do not occur for PA-Mg at low loads. Oil lubricated composites are not able to remove the sliding instabilities as oil supply to the sliding interface is controlled by migration effects that are restricted by deformation or softening of the polyamide matrix. A relatively thick and brittle transfer film develops when the polyamide bulk melts. Solid lubricants are able to stabilise friction and lower wear own to the formation of a thin and coherent transfer film. However, increasing the amount of lubricants induces lower mechanical properties and higher deformation. The friction coefficients for pure polyamides can be extrapolated as a function of a scaling factor. The wear behaviour of tests samples with small and large contact areas is significantly different for solid lubricated composites, with lower specific wear for large-scale samples. Transitions in lubrication mechanism due to softening and melting do not allow for extrapolation and justifies the use of large-scale tests. Only pure polyamides have identical specific wear rates on small-scale and large-scale under mild conditions.

Keywords: Polyamide; Large-scale; Small-scale; Softening; Melting; Lubricant

1. Introduction

Numerous works are published on the behaviour of polyamides under dry friction conditions, being an attractive industrial polymer for engineering applications since the 60s [1,2]. More recently, Gao et al. [3] tested pure polyamides sliding against austenitic steels with friction coefficients around 0.7, which is outside the range of meaningful technical applications requiring low friction. Different extruded polyamide (PA) composites with either polytetrafluoroethylene (PTFE) [4] or polyethylene (UHMWPE) [5–7] were developed. Palabiyik and Bahadur [8] used different blends of polyamide 6 (PA 6) and high density polyethylene (HDPE) resulting in a friction drop from 0.81 to 0.17 for a 40% HDPE blend. Tiny UHMWPE particles disperse evenly in the matrix and serve as a filler-reinforced composite. A strong bond between UHMWPE and PA results in a uniform and thin transfer film that acts as a lubricant for low friction and wear. Rajesh and Bijwe [9] studied extruded polyamides PA11 filled with different metallic-powders and glass fibers, showing that friction is reduced and wear resistance increases by addition of copper and bronzes. Bahadur et al. [10] also studied copper compounds. Wang et al. [11]

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investigated the effect of fillers and carbon short fibers in nylon 1010.

Polyamides can be favourably used in high-loaded sliding applications, characterised by large sliding areas, high loads and low sliding velocities. When loaded above the polymer's yield strength, extremely low coefficients of friction under steady state are obtained. Preliminary tests under high loads, low sliding velocities were done by Van de Velde and De Baets [12] on cast PA 6, concluding that a carbon steel/polyamide couple always produces high stick-slip with vibrations and reduced life-time. As the sliding distance for a polymer bearing element is often limited and many start/stop events occur, the running-in characteristics of different materials should be investigated and the in situ behaviour should be reliably estimated. For high precision instruments as, e.g. telescopes, high positioning accuracy is needed. Another problem is the generation of frictional heat that should be controlled by minimising the coefficient of friction. The build-up of electrical charge is generally solved by incorporation of graphite or carbon black, since it forms microdomains with a partially agglomerated structure that contributes to lower resistivity [13]. Kang and Chung [14] reported that also lubricant-impregnated cast nylons provide low friction in combination with AISI 52100 steel. A range of cast polyamides with proprietary solid wax additives or oil-impregnated nylons was developed to improve sliding resistance and minimise coefficients of friction. They are industrially available and produced by monomer casting, favourable for complex shapes with large cross-sections and free of voids, in contrast to extrusion. Cast polymers are already applied in off-shore design, but the selection of an appropriate polyamide grade is often difficult because the sliding mechanisms on large-scale tests conditions are unknown. The catalyst type influences the mechanical stiffness, but the influence on sliding stability need further investigations. Composites with solid or oil lubricant are selected to study lubrication mechanisms and efficiency at high loads and temperatures.

Present research focuses on a comparative study of different cast polyamides that are slid on a small-scale and large-scale tribotester under a broad range of contact pressures, sliding velocities and contact geometries. Possibilities for extrapolation are evaluated and would help the design engineer to estimate a correct value of friction depending on the effective contact situation. The steady-state sliding is influenced by transfer film formation and frictional heating. In this respect, it is important to consider the differences in degradation by softening and/or melting and how they influence the sliding stability and polymer structure.

2. Experiments

2.1. Test materials

Wear materials include pure polyamides PA 6 with sodium (PA-Na) or magnesium (PA-Mg) catalyst, a synthetic oil filled polyamide with homogeneous oil dispersion (PAo1) and a solid lubricant filled polyamide (PAs1). PAo1 contains 4–6 wt.% synthetic oil and PAs1 contains 8 wt.% wax ($MoS_2 + PTFE$). A polyamide with synthetic oil lubricant into separate holes on the surface (PAo2) is large-scale tested. Low pressure monomer casting is used with polymerisation of molten lactam monomers in the heated mould under atmospheric pressure. The polymerising reaction during casting, such as initiation and propagation mechanisms, is known with addition of, e.g. sodium as an activator, diisocyanates as a chain initiator and Na or Mg as a catalyst from liquid steams [15,16]. Polymerising in the mould produces a material with higher molecular weight and crystallinity, favourable for better dimensional stability, higher compressive and tensile strengths and higher modulus than achieved by extrusion or moulding. The mechanical parameters are given in Table 1. The melting point of cast nylons is somewhat lower than for extruded nylons, while cast nylons have better strength and stiffness. The effect of oil and wax contents on the homogeneity, strength and impact was studied by Kang and Chung [17], showing that the dispersity of oils becomes inhomogeneous in nylon above 8 wt.%.

Table 1
Mechanical properties of different polyamide grades (23 °C/60% RH)

	Test material	d (g/cm^3)	E (MPa)	σy (MPa)	ε (%)
Pa-Na	Pure nylon Na catalysed	1.150	1700	55	>50
PA-Mg	Pure nylon Mg catalysed	1.150	1500	75	>50
PAo1	Homogeneous oil dispersion	1.135	1450	45	>50
PAo2	Lubricating oil in holes	1.135	1600	45	>22
PAs1	Proprietary solid lubricated	1.110	1330	40	>25

Steel St 37-2 N (EN 1.0116) counterfaces with roughness $R_a = 1.6\ \mu m$ are used for small-scale and large-scale tests. The roughness grooves are perpendicular to the sliding direction. It has chemical composition as follows (in wt.%): $C < 0.17$, $Si = 0.02–0.30$, $Mn = 0.20–0.50$, $P < 0.04$, $S < 0.04$ and mechanical properties $R_e = 235\ N/mm^2$ yield strength, $R_m = 410\ N/mm^2$ tensile strength and Brinell hardness HB = 140.

2.2. Material characterisation

The polymer structures are characterised by Raman spectroscopy of unworn surfaces. Measurements are done on a Brucker FT spectrometer Equinox 55S (Bruker Optik, Ettlingen, Germany), equipped with a Raman module FRA 106 fitted to a nitrogen cooled (77 K) germanium high sensitivity detector D418-T. The applied laser wavelength during the experiments was the 1.064 μm line from a Diode Laser Pumped Nd:YAG laser. All spectra are recorded at a resolution of 3 cm^{-1} using a non-focused laser beam with a power of 70 mW between wavenumbers 0 and 3500 cm^{-1}. Each spectrum is collected as an average of 250 scans.

The polymer thermal stability is characterised by simultaneous thermogravimetric (TGA) and differential thermal analysis (DTA). Measurements are done on a Stanton Redcroft 1500 Thermobalance in air for a single heating cycle between 23 and 300 °C at constant heating rate of 10 °C/min. The initial polymer sample weight is about 17 mg. For TGA, the mass loss of the