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Micro-patterned Polypropylene Films: Reduced Sliding Friction

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Micro-patterned Polypropylene Films: Reduced Sliding Friction

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Introduction

Polymeric films are used in numerous applications where low sliding friction surfaces are required, e.g., high speed packaging equipment and low-friction tape wraps. Typical methods of reducing the apparent sliding friction of polymeric surfaces are: (a) the use of liquid lubricants such as silicone oil or erucamide, (b) powdered solid lubricants such micro-sized starch or talc, and (c) fluoropolymers additives[1, 2, 3]. Studies on modifying the coefficient of friction (COF) by adding different chemicals have been previously reported[1, 2]. Such chemical moieties are partially transferred from the film to other surfaces upon contact, and may contaminate those surfaces. Therefore, in this study, the sliding friction of micro-textured isotactic polypropylene films was assessed. We investigated two micro-patterned extrusion dies, one with a rectangular texture and the other with a trapezoidal one. A non-textured die was used as a control. The effect of the resulting film texture on the apparent film-on-film COF and film-on-metal COF is reported. The primary educational objective of this project was to establish a protocol for providing “cascaded research mentoring” to undergraduate and graduate students. The advising was to be provided through interactions with researchers from a graduated NSF Engineering Research Center working collaboratively with industrial researchers.

Experimental

Materials

The polymer used throughout this study was poly(propene), PP Dow INSPiRE™ 114, a film grade isotactic polypropylene (i-PP). It has a melting point of 164°C, density of 0.9 g/cm^3 and a melt flow index (MFI) of 0.5 g/10 min at 230°C.

Micro-textured Dies and Processing

Figure 1 schematically shows die patterns used to determine how the die shape influences the film texture.

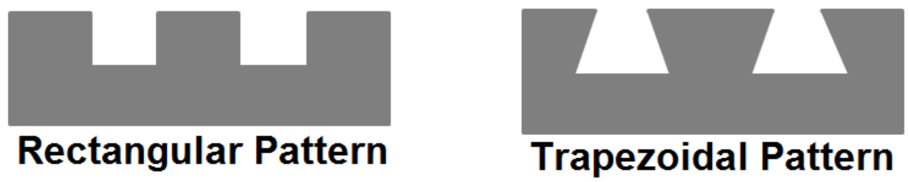

Figure 1. Schematic representation of die micro-geometries in the shapes of rectangular (left) and trapezoidal (right) features.

The micro-patterned dies were 25 mm wide and had a 10 mm deep land. The rectangular features had straight sides and a flat bottom. The trapezoidal features have a narrow top and a large base, providing a large cross-sectional area to overcome material draw down and shrinkage in order to create extrudate that results in more straight walled structures. The films were extruded at 220°C in a custom-built cast-film line consisting of a 25-mm single screw extruder to the micro-textured dies. The films were produced at a constant throughput of 0.8 cc/min by using a gear-pump and a take-up speed of 100 mm/min.

Microstructural Characterization

To obtain sharp cross-section samples, the films were mildly cooled in liquid N_2 and cut with special scissors (Kevlar® cutter grade). The resulting profile was analyzed by reflective optical microscopy (Olympus BX 60) and scanning electron microscopy (SEM, Hitachi S-4800 Field Emission Scanning Electron Microscope). For SEM, the films were platinum-coated prior to the profile inspection. For each cross-section of the film, about 3 spots were imaged by OM and SEM.

Coefficient of Friction Measurements

The kinetic coefficient of friction (COF) measurements were performed according to ASTM D-1894 (Method of Assembly C), “Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting” with the following exceptions: (a) Crosshead speed of 50 mm/min (due to limitations of the equipment), when ASTM requires 150±30 m/min. (b) Films width of 25 mm, when ASTM requires 127 mm wide films. (c) Consequently, a 19-mm wide (63.5 mm in length and 6.3 mm thick) stainless steel sled, polished to a standard roughness of 400 grit, was required for such a width of the films, instead of the 63.5-mm wide ASTM sled. In this manner, the bead-edges effects during the COF measurements were avoided. In addition to such sled, sleds: 63.5 mm (ASTM), 44.5 mm, 38 mm, 25 mm and 13 mm wide were also made for carrying out steel-on-steel control experiments. The metallic sleds were made of an austenitic

304 grade Stainless steel (SS). The COF measurements were performed using a replication of four (n = 4) for each film type and configuration.

The COF supporting base was adapted to an ATS Universal 900 Tensile Tester to pull and record the applied force to move the sled over the film (Figure 2). The system using 10% of the load cell capacity (5 lb) have a force sensitivity 2.25 g. The system uses a Nylon® monofilament over a Teflon® pulley according to the ASTM D-1894 Method of Assembly C. A flat stainless steel sheet was used on top of the supporting base. All experiments were performed at approximately 25°C and relative humidity of about 50 %.

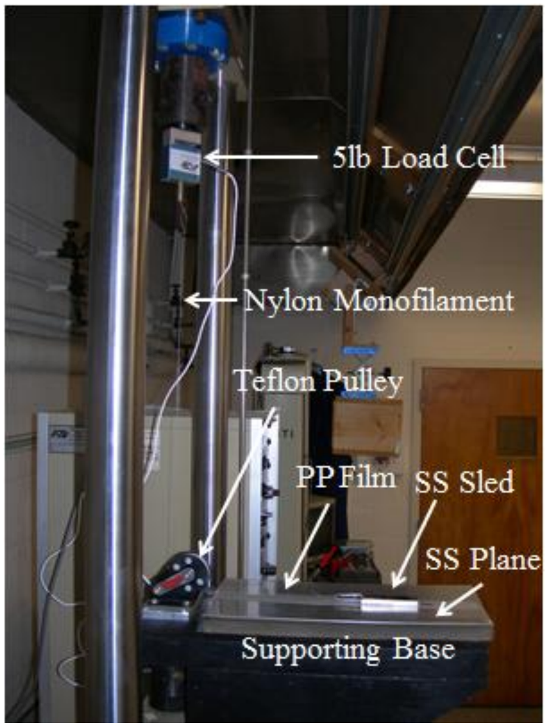

Figure 2. Customized experimental set up for measuring COF of films.

Due to the longitudinal texture of the films, two orientations of the films were studied: machine direction (MD) and transverse direction (TD). For film-on-film COF measurements a piece of film was stuck to the sled surface and slid on top of the other film. Three configurations were investigated: MD-on-MD, MD-on-TD and TD-on-TD. Performance of non-textured film on textured films was also analyzed for the MD and TD configurations of the textured films.

Results and Discussion

Microstructure

Figure 3 displays the cross-sectional and top views of the films obtained from the dies with rectangular (R) and trapezoidal (T) patterns. The rectangular-patterned die led to a hill-like texture on the film, whereas the trapezoidal die micro-pattern to a rectangular shape on the film. The difference in die shape and film texture is likely a consequence of the viscoelastic nature of polymeric fluids, and will be investigated further in future studies [9].

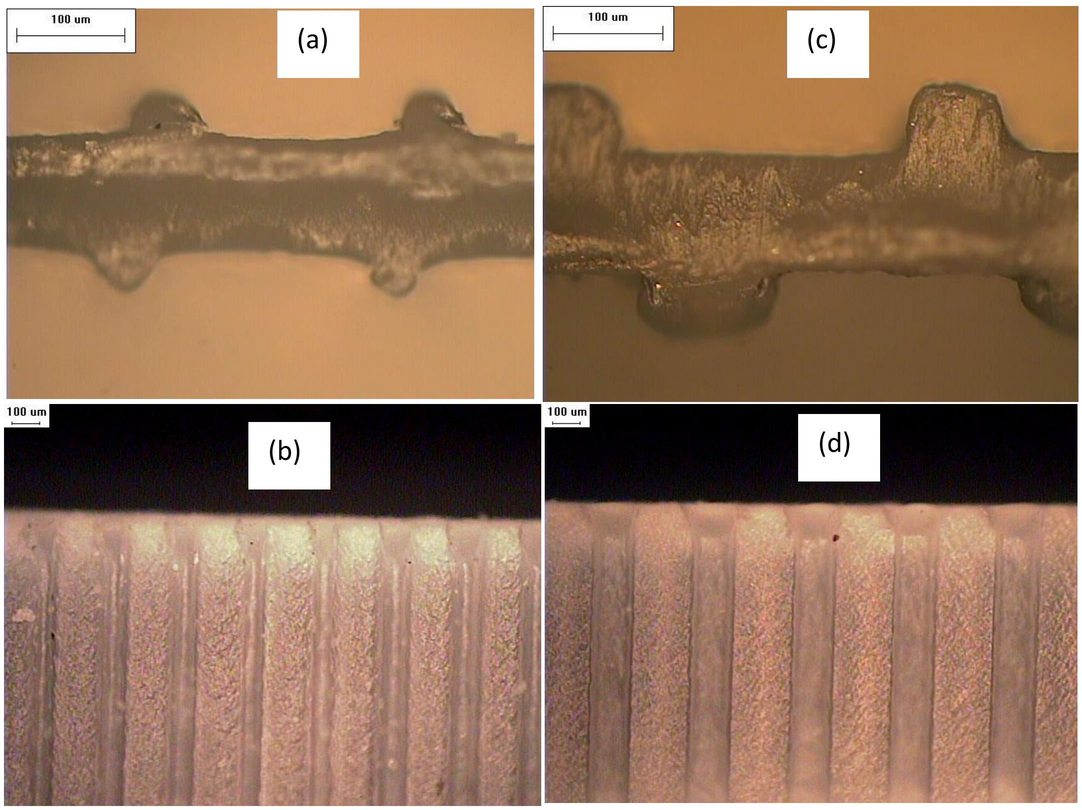

Figure 3. Optical micrographs of i-PP film produced from rectangular die pattern: (a) cross-section and (b) top view, and from the trapezoidal die pattern:(c) cross-section and (d) top view

Coefficient of Friction

A control experiment first was carried out to check the accuracy of the sled system. Stainless steel (SS) sled on stainless steel (SS) substrate was first tested for different sleds widths; Figure 4 displays the kinetic COF values. It is evident that the ASTM sled width (63.5 mm) displayed no significant differences in the COF values with respect to those measurements for other sled widths. The consistent values result from the fact that all sleds applied a constant surface contact pressure (i.e., sled weight per contact area) of about 500 Pa. Thus, experimentally, sleds widths smaller than that suggested by the ASTM standard are suitable if the same surface contact pressure is used.

Rusinek & Molenda[4] reported a kinetic COF for SS-on-SS ranging from 0.17 to 0.23 obtained by the shear test method, whereas Budzynski et al.[5], using a ball-on-disk tribo-tester, measured a friction coefficient in air between 0.2 and 0.6 for different Nitrogen-implanted Stainless steel AISI 316L grades with an average roughness of 0.08 µm. Similarly, Marchev et al.[6] found values for coefficient of friction for a 410 Stainless steel (a martensitic grade) between 0.2 and 0.5 at different temperatures using the pin-on-disc method. Wei et al. found COF values ranging from 0.4 to 0.5 and from 0.45 to 0.65 for stainless steel 304L and 304[7] respectively, and for a ferritic 430 stainless steel[8] grade from 0.4 to 0.65, all three grades with an average surface roughness of 0.5 µm. Thus, the experimental COF hereby measured (0.24±0.05) is consistent with the values found in literature studies.

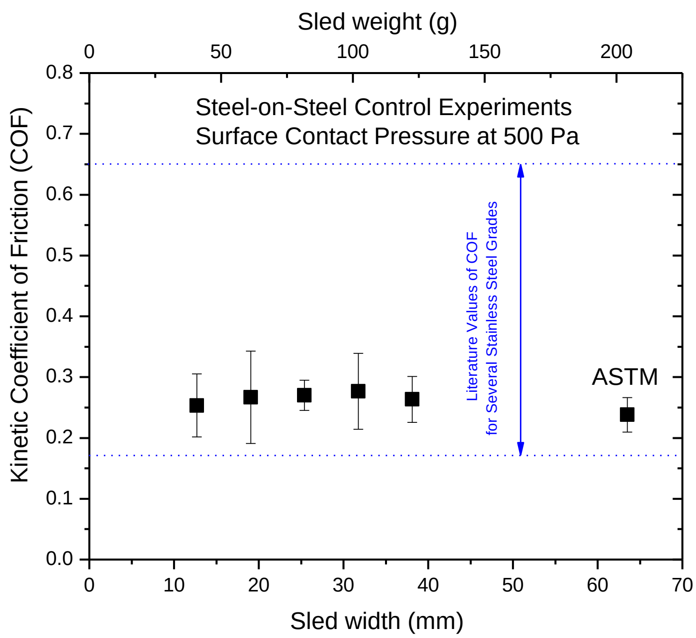

Figure 4. Kinetic COF for different sleds widths and weights (at 500 Pa of Surface Contact Pressure). Error bars represent 95% confidence intervals.

Figure 5 displays the COF for the metallic-sled on film experiments. For the film-on-metal tests, the kinetic COF of non-textured films was measured to be 0.340±0.024. Interestingly, Yamaguchi[10] reports a value of 0.3 for the kinetic COF of steel on polypropylene at a surface contact pressure of 0.83 kgf/cm^2 (~81000 Pa). The textured films in the MD displayed a COF of 0.225±0.024 and 0.220±0.010 for the hill and rectangular textures, respectively. Thus, a reduction in COF of about 35% was observed in this particular configuration as compared to that of the non-textured films. Likewise, in the transverse direction (TD), such films displayed COF values of 0.287±0.033 and 0.278±0.032 respectively. This is a reduction of about 17% relative to that of the non-textured film. This result confirms the hypothesis that less surface contact area should lead to lower frictional behavior.

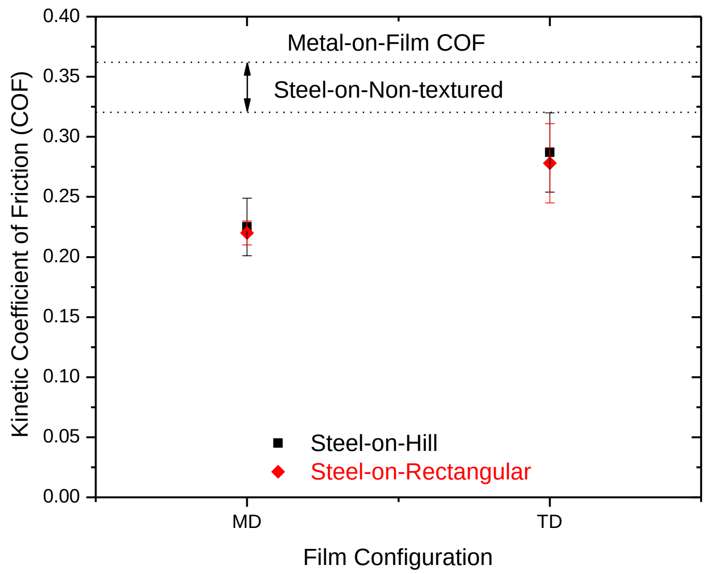

Figure 5. Kinetic COF for metal-on-film. Sled width was 19-mm and it weighs 60 g. Error bars represent 95% confidence intervals.

The film-on-film COF experimental data for the different film configurations are displayed in Figure 6. The non-textured films displayed a film-on-film COF of 0.193±0.016. The MD-MD configuration led to COF values of 0.161±0.013 and 0.139±0.013 for the films with hill and rectangular textures respectively. The values are about 17 and 28 % less than that of the non-textured films (0.193±0.016). The MD-TD configuration displayed COF values of 0.153±0.008 and 0.120±0.002 for the hill-like and rectangular textures, respectively. Thus, the films with rectangular texture in MD-TD configurations had the least friction of this set, at about 38% less than that of the non-textured films. This result might be brought about by the lower contact area provided by the combination of configuration and micro-pattern shape. Finally, the TD-TD configuration of the rectangular films had a similar COF to that of the non-textured, whereas the films with hill texture behaved highly frictional at a COF of 0.302±0.034 (i.e., 57% more than that of the non-textured films), which likely arises from the mechanical interlocking of the configuration. Interestingly, the films with rectangular micro-texture did not undergo the same level of mechanical interlocking, probably due to their flat micro-pattern.

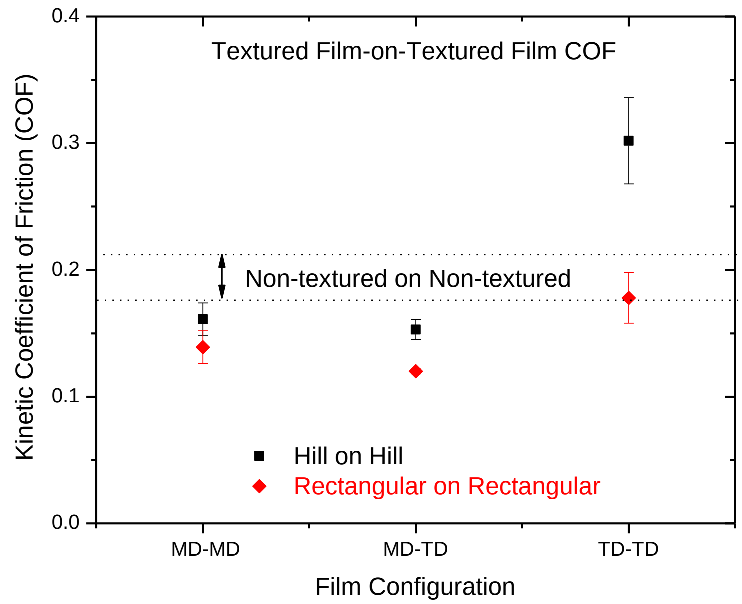

Figure 6. Kinetic COF for film-on-film. Sled width was 19-mm and it weighs 60 g. Error bars represent 95% confidence intervals.

The COF values for a combination of non-textured film on textured films are presented in Figure 7. This combination had the greatest impact in friction reduction as compared to the non-textured films (0.193±0.016). In the MD configurations, both micro-textures showed a similar COF at about 0.116±0.003, which is 40% less friction when compared to the non-textured films. On the other hand, the TD configuration led to COF of 0.149±0.015 and 0.139±0.011, respectively, for the films with the hill and rectangular micro-textures. This is about 25% reduction in friction when compared to non-textured on non-textured experiments.

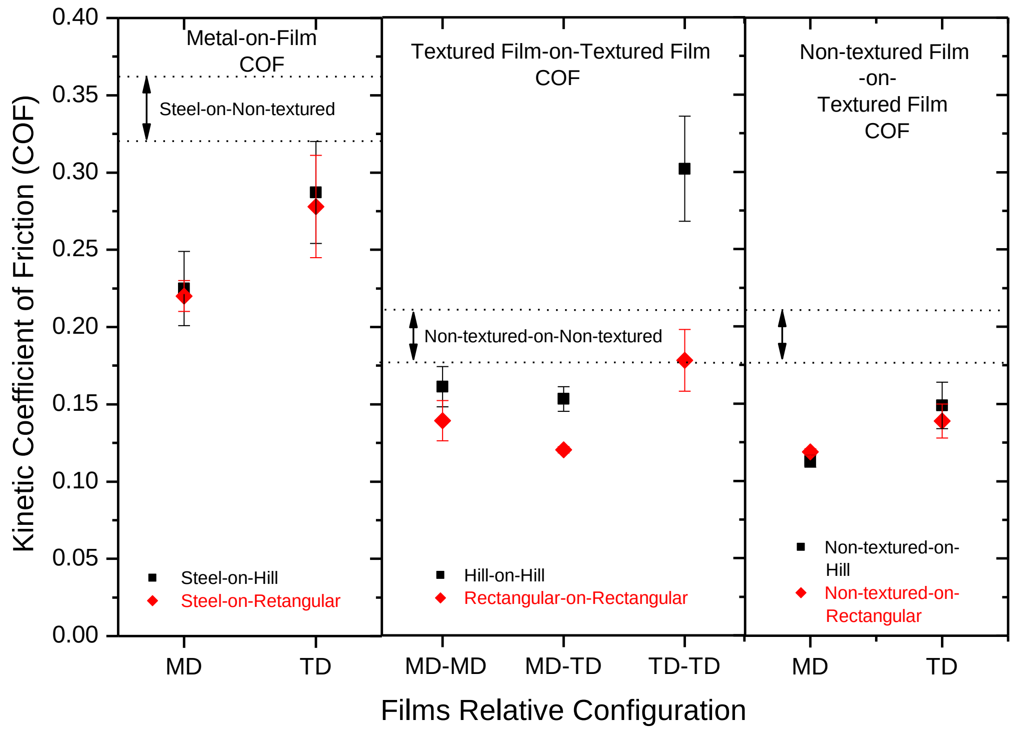

Figure 7. Kinetic COF for non-textured film on textured film as compared with the metal-on-film and textured film-on-textured film COF. Data for the metal-on-film and textured film-on-textured films are also shown for visual comparison. Sled width was 19-mm and it weighs 60 g. Error bars represent 95% confidence intervals.

Cascaded Mentoring

The educational goal of this project helped to provide research training to two students: one undergraduate and one graduate (PhD) Chemical Engineering student. The undergraduate student conducted several friction tests and was trained in the use of advanced research instrumentation. The graduate student helped established the research instrumentation and statistical tools for analysis of results.

Conclusions

From experiments conducted with metal sled on films, the micro-textured films displayed a reduction in COF of about 35% as compared to that of the non-textured films. This reduction is a direct consequence of the reduction of surface contact area. On the other hand, film-on-film experiments proved that micro-patterned films can also reduce or increase friction depending on the configuration of the films and their texture. Therefore, reductions of about 38% in COF were found for the films with rectangular micro-textured in the MD-TD configuration, as well as increments as high as 57% were observed for the TD-TD configuration for the films with hill-shape micro-texture. Such effects are dependent on lower contact surface area of the films or mechanical interlocking. A greater reduction in film-on-film experiments was observed when a combination of non-textured films on textured films was used, with reductions of up to 40%. These results indicate that micro-textured polypropylene films might be effectively used in applications where low-sliding and clean surfaces are required.

Finally, as an educational outcome, this project established a protocol for providing “cascaded research mentoring” to undergraduate and graduate students through interactions with researchers from CAEFF researchers (a graduated NSF Engineering Research Center) working collaboratively with industrial researchers from Hoowaki LLC, a small-business involved in innovative research.

Acknowledgments

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