Device for Measuring Sliding Friction on Highloft Nonwovens

ABSTRACT
When measuring the sliding friction on highly compliant materials such as fabric batting and foam rubber, a substantial portion of the apparent friction is due to the deformation of the substrate. A new friction instrument consisting of a sled within a sled has been developed that eliminates the contribution of this deformation and provides the true sliding friction, as well as the force required to deform the substrate. The friction coefficient as measured using a conventional steel sled sliding on high loft polyester batts increased as the number of polyester batts increased. Using the new, guarded friction sled, the friction coefficient was independent of the number of supporting batts, thus separating the deformation forces from the sliding forces.

INTRODUCTION
Friction is a critical property for many applications. In some applications, high friction is desired, while in others low friction is preferred. It is not surprising then that understanding and measuring friction have been investigated for more than 2500 years[1]. Amonton's law was originally published by Da Vinci and later rediscovered by Amonton[2]. Amonton's law states that the friction depends only on the force normal to the contact plane. From this, the friction coefficient can be defined as:

$$\mu = F / N \qquad (1)$$

where F is the force required to move an object on a horizontal surface and N is the load normal to the surface. The friction coefficient is independent of the apparent contact area, but depends upon the two surfaces that are in contact and upon the speed. For metals and ceramics, Amonton's law works well. However, for polymeric materials that have both plastic and elastic deformation in the contact zone, it has been found that the frictional force is better represented by a power-law behavior:

$$F = \mu N^{n} \qquad (2)$$

where N is the power-law exponent and has values between 2/3 and 1.[3-5] Many textiles have been found to behave according to equation (2), including woven fabrics, knits and nonwovens. However, there is no theoretical justification for this power-law dependence.

Ramkumar, Leaf, and Harlock[6] have used this approach to represent the friction of a large number of ribbed knit cotton substrates. In this case, the substrate consisted of the same material (cotton), but its method of construction (yarn size and knit structure) and hence ease of deformation was varied over a wide range. The authors attributed the frictional behavior of their knits to the shearing of the looped structures, with the largest loops having the highest friction. However, these knits also are those that are most easily deformed during shearing and no attempt was made to isolate these factors. Similar effects are expected to occur for high loft nonwovens and for fabric-foam laminates.

Friction has also been found to depend on sliding speed, temperature and relative humidity. Of these, the sliding speed has been the most studied. At low speeds, the measured friction is "boundary friction," while at high speeds the friction is "hydrodynamic friction."

In hydrodynamic friction, the surfaces are kept apart due to the shearing of a liquid layer. The frictional force is due to viscous losses in the thin fluid layer and the friction coefficient is directly proportional to the viscosity of the lubricating liquid. On the other hand, at low speeds (or high pressure), the fluid layer is forced out of the interfacial region and the solid surfaces come into direct contact. In this case, the boundary region where the solid materials come into contact is sheared. The ratio of the shear strength of the material and its yield pressure determines the friction coefficient. For many materials, these properties are speed dependent, and thus the friction coefficient varies with speed. For further details on friction, the reader is referred any of the excellent reviews [c.f. Slade[7], Hutchins[8] and others].

Since friction is such an important parameter, several devices have been built to measure friction. The most common way to measure the friction coefficient on a planar structure is to place a sled on the surface to be tested, adding weight to the sled if necessary, and pulling the sled at a fixed speed while measuring the force required to pull the sled. This method was documented by Da Vinci[9] and has been used ever since with little change. ASTM methods D-7, D-20, D-1894, D-2047, D-2394, D-3247, E-303, F-489, F-609 and F-695-81 for horizontal sleds and D-3248, D-6, D-13, and D-3334 for sleds on inclined planes are all variations of Da Vinci's sled method. However, when measuring the friction of high loft nonwoven fabric batts using these methods, large scale deformation of the fabric occurs and the apparent friction changes with the number of batts or the thickness of the batts, even though the material, the pressure and the normal load are unchanged. This implies that the measured friction includes components due to the deformation of the substrate as well as the sliding friction. The result is an incorrect value for the friction.

To address the issue of sliding *and* deformation in the critical area of automobile tires, special test devices have been built, including highly instrumented automobiles with professional drivers. The sliding friction and tire deformation are separated by modeling.[10] In another example, when someone is sitting in an upholstered seat and tries to get up, they both slide across the seat and deform the cushions. Thus the energy required to get out of the seat includes both friction and cushion deformation. However, the engineering solution to manipulate the required energy for each component is different and it would be useful to clearly separate these factors so that the seat or tire could be designed rationally for each contribution to the energy.

This manuscript describes a new friction measuring instrument designed to directly separate the force required to deform the substrate from the force required to overcome friction. The concept that led to our design is the same as that used to eliminate the effects of stray electrical fields or edge effects in measuring high impedances in dielectric measurements or bulk conductivity in polymers. In these measurements, an additional electrode surrounds the test electrode, thus screening edge effects. This approach is mimicked in the new, guarded friction sled, where an outer sled deforms the substrate and acts as a conventional sled, while an inner sled – which is the guarded sled – measures only the sliding friction on the already deformed substrate.

DESCRIPTION OF FRICTOMETER

Figure 1 shows a picture of the guarded friction meter. It is made from a single piece of steel, measuring 12 cm x 15 cm x 2.5 cm. The outer, conventional sled, S, is pulled by a tension load transducer (Omegadyne LCFD-50, Sunbury, OH), F_c, via cord C. A semicircular section is cut out of the center of this sled to form the guarded sled, G, which is pulled by a compression load transducer (Omegadyne LC8100-250-25), F_g, via a screw that passes through F_g, through a washer, and through a slot, which allows G to move vertically relative to S. Appropriate spacing between S and G is maintained by an additional washer. Both S and G are made from the same material and are the same thickness so that the pressure is the same under both sleds. Additional weights can be added to alter the loads and the pressures. The shape of the inner sled can be chosen as appropriate for the desired test conditions. In our instrument, it is semicircular to avoid snagging on a fibrous substrate. The front edges of both sleds are rounded slightly to avoid digging into soft substrates. A motor (1 rpm, Merkle Korff Industries, Des Plaines, IL) attached to a 10:1 reduction gearbox (Gam Gear, Chicago, IL) pulls the compound sled via a cord at a rate of 5.30 mm/min. The load transducers are read using an A/D card (CIO-DAS801 from Omega Engineering, Inc., Stamford, CT) and the data are collected using LabView (National Instruments, Austin, TX).

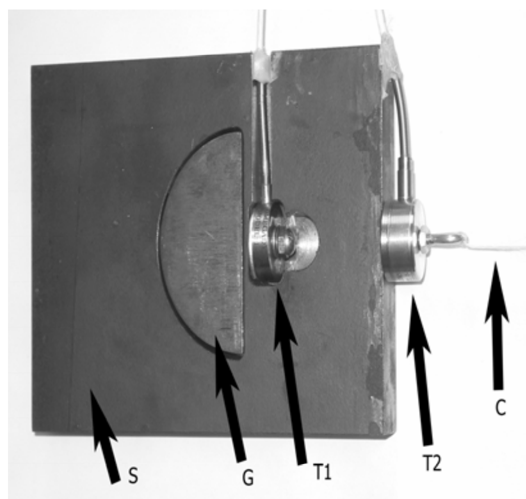

FIGURE 1. The compound sled that forms the guarded friction meter is shown. The conventional sled, S, is pulled by cord, C, and tension load transducer, T_2, which measures the force, F_c, required to pull the compound sled. S, in turn, pulls the guarded sled, G, via compression load transducer, T_1, which measures the force, F_g, required to pull only the guarded sled. The guarded sled floats freely within the conventional sled, restrained only by T_1.

TEST PROCEDURES

During a test, the sample is placed on an aluminum block and the back edge is clamped in place. The compound sled is placed on a flat surface and the unloaded readings, $R_{unloaded}$, for the transducers are read. Next, the load cells are calibrated by suspending the compound sled via the towing cord and reading the load cells again to obtain the loaded reading, R_{loaded}. The calibration factor is simply:

$$C = \frac{W_{sled}}{R_{loaded} - R_{unloaded}} \qquad (3)$$

where W_{sled} is the weight of the sled. Finally, the sled is placed on the sample, the cord is wrapped around the motor drive shaft and the motor is started. The transducers are read while pulling the sled, R_{pull}, and the force, F, required to pull the sled is

$$F = C\left(R_{pull} - R_{unloaded}\right) \qquad (4)$$

The friction coefficient is determined using equation (1) where N = W. All measurements and calculations are performed within LabView and the friction coefficients are recorded.

TEST MATERIALS

Several test materials were chosen such that they would not readily deform under the conditions of the test. These included a transparency film (3M type CG3300), a solid aluminum plate that acted as the sample support, a 200 g/m^2 poly(ethylene terephthalate) double knit jersey fabric (TestFabrics, Weston, PA, style # 720), and a 102 g/m^2 plain, bleached cotton woven printcloth with 72 ends/inch x 72 picks/inch (TestFabrics style # 400), as well as miscellaneous materials found in the author's office. With the exception of the aluminum plate, the samples were placed on the aluminum plate and their back edge clamped to the aluminum plate so that the sample could deform, but not slide. The compound sled was placed on the sample. The motor was started and the sled was pulled across the top surface of the sample. *(Figure 2)* The friction coefficient was graphed as the sled began to move. After reaching a plateau in the friction coefficient, 10-20 readings of the friction coefficient were recorded over the next 2-3 minutes. The average value of these measurements for each sample is shown in *Figure 3* for both the guarded sled and the conventional sled.

TEST PROCEDURE FOR DEFORMABLE SUBSTRATES

<u>Multiple Highloft Pet Batts</u>

Poly(ethylene terephthalate), PET, batts, approximately 1.5 cm thick and having a basis weight of 124 g/m^2 were obtained from a local fabric store. Upon application of 4.14 kPa (0.6 psi) pressure, they compressed about 50% to 7.4± 0.9 mm. Two different types of tests were performed. In the first series, a single batt was placed on an aluminum plate, clamped in place, and the friction measured. Then, a second batt was placed on the aluminum plate and the first batt placed on top of the second batt. Both batts were clamped along the back edge and the friction re-measured. This was repeated for a third and a fourth batt, keeping the first batt on top and in contact with the sled. The data is shown in *Figure 4*. In the second type of test, a polyester knit fabric was placed on the aluminum plate, or on one to four batts, as described above. All of the material was clamped along the back edge and the frictional force measured. The data are shown in *Figure 5*.

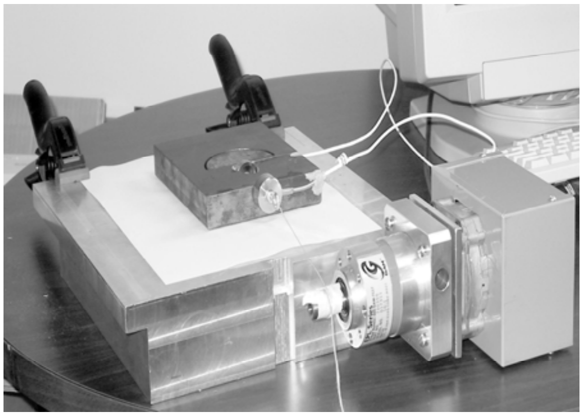

FIGURE 2. Fabric under test (white object) is placed on aluminum support block and its back edge clamped to the aluminum plate. The guarded friction device is placed on the test specimen, the towing cord is attached to the motor drive and the drive started.

RESULTS AND DISCUSSION

Figure 3 shows the friction coefficient for various substrates as measured by both the outer sled and the guarded sled. The friction coefficients vary with the substrate, from μ ~ 0.18 for a

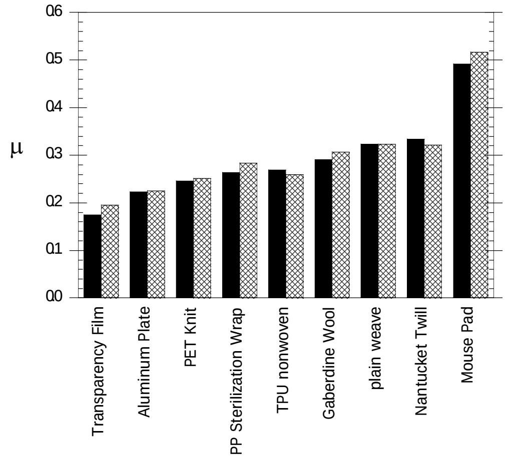

FIGURE 3. Friction coefficient measured by the guarded, G, sled (solid) and the conventional sled, S, (crosshatched) for several non-deformable substrates.

smooth polyester transparency film to 0.50 for a rubber mouse pad. Note that both sleds provide nearly identical friction coefficients for any one material. The difference between the friction coefficients determined by the two sleds for a single substrate is not considered significant. The substrates were chosen so that they would not deform significantly during this test. Thus both sleds measure the same friction coefficient when the sample does not deform readily under the test.

Figure 4 shows the measured friction coefficient for one to four batts of PET where the sled always slides on the same batt. Since the normal load is constant, the test speed is constant, the laboratory temperature and humidity are constant, and the two surfaces sliding against each other are identical, one should expect the friction coefficient to be identical. Indeed, the friction coefficient measured using the guarded sled is constant, regardless of the number of batts. However, the friction coefficients measured using the conventional sled increase with an increasing number of batts. Careful observation of the test shows that, as more batts are added, the sled nestled deeper and deeper into the batts. When the sled was pulled across the batts, it deformed the batts and the force required to compress the batts added to the frictional force due to sliding of the sled across the surface. On the other hand, the guarded sled slid only on the already deformed batt. Thus, the outer, conventional sled deformed the substrate during sliding, and measured the combined forces of sliding across and deforming the sample, while the inner, guarded sled only slid on the already deformed sample.

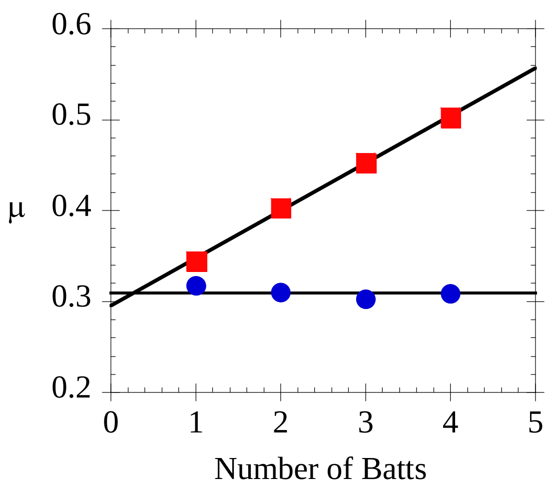

FIGURE 4. Friction coefficients of 1-4 polyester batts. The same batt is always in contact with the sled. Circles are friction coefficients obtained from the guarded sled while the squares are from the conventional sled. The horizontal line represents the average friction coefficient determined using the guarded sled. The other line is a linear regression fit to straight line through the friction coefficient data obtained by the conventional sled.

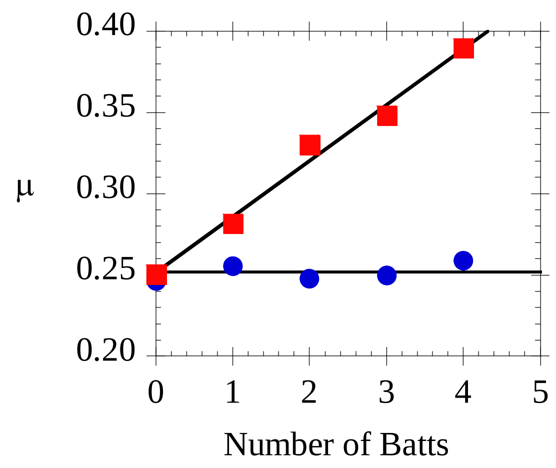

FIGURE 5. The friction coefficient for the polyester knit fabric resting on 0-4 polyester batts. Symbols and lines are the same as in *Figure 4.*

The true sliding friction was also obtained by extrapolating the friction coefficient to zero batts; i.e. a thin, incompressible PET layer which was identical to the batts in all other ways. If the conventional sled data were extrapolated to 0 batts, the resulting friction coefficient was 0.3. On the other hand, the guarded sled gave a value of 0.31, regardless of the number of batts. Thus no extrapolation was needed when the friction coefficient was measured using the guarded sled. This is especially important for materials where extrapolation to zero thickness is impractical. For example, in a fabric-foam laminate, changing the thickness of the foam may not be practical, while stacking multiple layers of the laminate may not faithfully represent the mechanic deformation behavior of the laminate.

To confirm that the guarded sled measures the true sliding friction, the friction of the sled on a PET knit fabric was tested resting on the aluminum plate or on 1-4 of the batts used above, *(Figure 5)*. In this case, the sled slid on the same surface of the PET knit regardless of the number of batts interspersed between the fabric and the aluminum plate. Again, the guarded sled provided the sliding friction coefficient of the sled on the knit fabric, while the conventional sled included a contribution from the compression and deformation of the underlying polyester batts. When no batts were present, both sleds measured the same friction coefficient. In other words, while sliding across the surface of a deformable substrate, the conventional sled deformed the substrate and slid across it upon application of a force sufficient to deform the substrate *and* to overcome the frictional forces of the sled sliding on the surface. On the other hand, the guarded sled slid across a surface that had already been deformed by the outer, conventional sled, and thus required only enough force to overcome the frictional force for sliding on the surface.; i.e., the guarded sled measured the true sliding friction on both rigid and deformable substrates while the conventional sled measured the true friction only on rigid substrates. This distinction is particularly important for high loft nonwovens, seat cushions and other easily deformed materials.

Although the guarded friction sled described above can measure the sliding friction separately from substrate deformation, it also has several limitations. The current sled is heavy (>7kg) due to the limitations imposed by the transducers used and the material of construction (steel). For many textile applications, a much lighter sled would be beneficial. This could be achieved by using aluminum, poly(methyl methacrylate) or other lightweight material for the sled. More sensitive and smaller transducers would be needed in this case. In addition, the instrument is capable of only one speed. This could readily be improved by using a constant rate of extension machine to pull the sled or by adding a gear system to its motor drive. Finally, if the user wanted to measure the friction between two fabrics, there is currently no easy way to attach a fabric to the sled. Thus, the instrument described in this manuscript is only the first step in improving the measurement of friction of highly deformable substrates.

CONCLUSIONS

A new, guarded friction sled has been developed for measuring friction of highly compliant materials. On materials that do not readily deform during the measurement, the conventional sled and the guarded sled provide the same friction coefficient within a few percent. The measured friction coefficients obtained by both sleds vary with the materials being tested. However, on a highly compliant material, such as a polyester batt, the sliding friction between the sled and the substrate measured can be vastly different for the conventional sled and the new guarded sled. Friction measurements made using the guarded sled are independent of the substrate deformation, while the surrounding conventional sled measures an apparent friction coefficient that contains contributions due to both sliding friction and substrate deformation. This difference is especially important in compound fabrics such as fabric-and-foam laminates, or when using high loft nonwovens, even when they are used as a backing material.

REFERENCES

[1] Dowson, D.; *History of Tribology*; Longman Group Inc.: New York, 1979.

[2] Bowden, F. P.; Tabor, D.; *The Friction and Lubrication of Solids*; Oxford University Press: London, 1950.

[3] Bowden, F. P.; Young, J. E.; *Friction* 1951, *208*, 444-455.

[4] Lincoln, B.; Frictional and elastic properties of high polymeric materials; *British Journal of Applied Physics* 1952, *3*, 260-263.

[5] Howell, H. G.; Mazur, J.; Amonton's Law and Fibre Friction; J*ournal of the Textile Institute* 1953, *44*, T59-T69.

[6] Ramkumar, S. S.; Leaf, B. A. V.; Harlock, S. C.; A Study of the Frictional Properties of 1x1 Rib-knitted Cotton Fabrics; J*ournal of the Textile Institute* 2000, *91*, 374-382.

[7] Slade, P. E.; Tension, Friction, and Lubrication, in *Handbook of Fiber Finish Technology*,Marcel Dekker, Inc.: New York, 1998.

[8] Hutchins, I. M.; Friction; in *Tribology Friction and Wear of Engineering Materials*; CRC Press: Boca Raton, FL, 1992.

[9] Budinski, K. G.; Laboratory Testing Methods for Solid Friction; In *Friction, Lubrication and Wear Technology*; Blau, J. P., Ed.; ASM International, 1992; Vol. 18, pp 45-58.

[10] Canudas-De-Wit, C.; Tsiotras, P.; Velents, E.; Basset, M.; Gissinger, G.; Dynamic Friction Models for Road/Tire Longitudinal Interaction; *Vehicle Systems Dynamics* 2003, *39*, 189-226.