

Friction Behavior of Press-Fit Applications: Test Apparatus and Methodology

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Abstract— The industry has been expanding the surface material combinations used in press-fit connection systems. This paper describes the development of an instrument to measure friction coefficients at force levels typical of press fit pin applications. Our testing provides accurate and repeatable measurement of lateral force on sliding samples. Representative press fit pin blanks are dead weight loaded against a representative half plated through hole (half PTH) that is moved with reciprocating simple harmonic motion. The reciprocating motion is produced using a micrometer adjustable eccentric cam driven by a DC motor. Lateral force is measured with a 222 N (50 lb) load cell and saved using a computer data acquisition program. Data analysis is possible using commercially available computer spread sheet or analysis programs.

Combinations of maximum velocity and distance ranging between 0.02 – 20.8 mm/s and 0.125 – 12.7 mm, respectively are possible. The instrument is capable of loading forces of 4 – 93 N. A broad overview of typical results illustrates the application of the instrument.

Keywords—compliant pin; friction; test method; plated through hole

I. INTRODUCTION

The origin of compliant pins was in the late 1960's and early 1970's. They were introduced to be a reliability improvement over soldered through holes. There were various patented designs from a variety of suppliers including:

- ACTION PIN[®]™ Contacts
- Eye-of-the-Needle
- Winchester C[™] Contacts
- Etc.

The early applications were in the telecommunications industry where back plane wire wrap was common. This mechanically intensive procedure was the greatest hurdle for a pin design to be accepted. It was determined that if the pin provided about 45 N (10 lb) of retention force, the contact interface would not be disturbed during the wire wrap process. Subsequent industry standards for compliant pin retention forces were based on back plane wire wrap. Even if a pin was not intended for wire wrap; it was still required to provide the

same amount of retention force. The European standard was set at 40 N and the US standard was 34 N (7.5 lb) minimum.

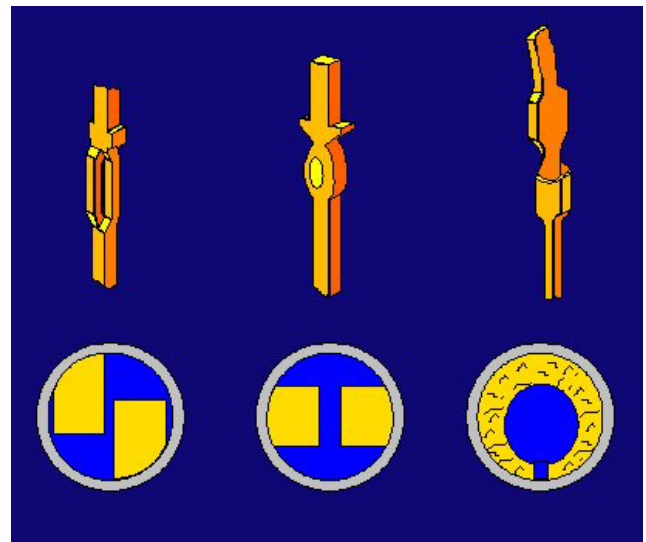


Figure 1. Press Fit Pin Design Schematic

Over the years, due to increasing density, the plated through hole (PTH) diameter and the stock thickness of the contacts reduced. At these smaller sizes, the higher retention forces were not practical. The international specifications began to reflect this. The IEC (352-5 First edition 1995-01) standards specified a 20 N retention force for applications without back plane wire wrap and the EIA specified 13 N (3 lb). Both standards maintained the higher values for back plane wire wrap applications. The communications industry was able to operate under these requirements. Over time, the computer industry could not. With continued advances in printed circuit board (PCB) density, the computer industry was required to accept compliant pins with even lower forces. In fact, pins have been successfully used with retention forces as low as 7 N (1.5 lb).

Today, the drive to higher densities continues as well as the gradual reduction of the required retention force. Even the communications industry has adopted lower values. To reflect this, the IEC (60352-5 Second Edition 2001-03) standard does

not specify the required retention forces. Instead, it lets the connector vendor define it.

This gradual trend toward reducing the retention force requirements has been with the primary use of only one interface, SnPb. Naturally, as the industry became confident in the reliability of a pin with a 40 N retention force on a SnPb interface, it became acceptable to try a one with a lower value. Over the decades, this occurred incrementally. Today, pins are designed with retention force values of 10 - 20 N. Ultimately, the minimum retention force requirement must be based on what is required for a stable electrical interface and the mechanical environment. If the mechanical environment requirements are minimal, further reductions in retention force may be possible. They could be in the range used for conventional SnPb finished separable interfaces (3 N).

Today, recent trends requiring Pb-free interfaces present a new challenge. A variety of alternative finishes have been proposed which will impact compliant pin design requirements. From a design perspective the retention force is based on the amount of normal force between the pin and PTH and the frictional behavior. The normal force (F_N) is determined by the geometry and materials of the pin and PTH, which are evaluated using many analysis methods. The frictional behavior is usually represented by the coefficient of friction (μ). To help define retention forces as part of the design process, the frictional behavior needs to be quantified.

This paper proposes a test methodology for determining the μ for alternative interfaces between the compliant pin and PTH. The requirements include:

- Independent control of F_N applied to the interface
- Ability to generate high normal force levels for applicability to traditionally stiffer parts
- Ability to measure the sliding frictional force ($F_{friction}$).
- Evaluation of actual PTH interfaces

In addition to providing the test methodology, a variety of finishes were evaluated and a broad overview illustrates typical experimental results.

II. EQUIPMENT AND PROCEDURES

The flat blanked design geometry of the eye-of-the-needle (EON) press fit pin is advantageous for clamping. The EON pin design used was modified by removing the eyehole in the center. The concern was that pin deflection would allow contact between the clamp and printed circuit board, which could influence the measurement. Removing the eyehole eliminated any possible deflection of the pin during measurements at high loads. The drawing shown in Fig. 2 depicts this arrangement.

The clamped EON pin blank and half PTH are mounted in the friction apparatus. Then the EON pin blank is dead weight loaded against the half PTH which is moved with reciprocating simple harmonic motion. A clamped EON pin blank and sample half PTH are shown in Fig. 3.

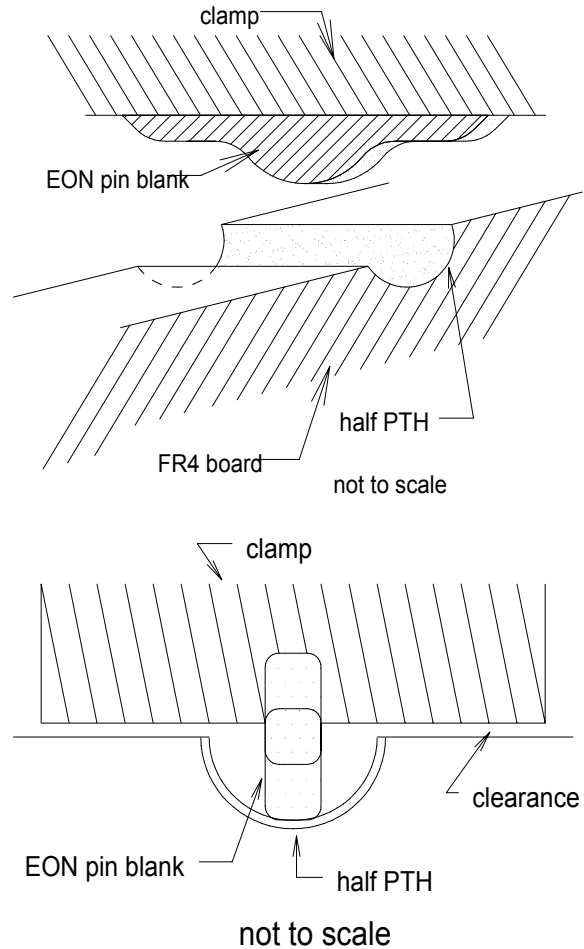


Figure 2. Fixturing Schematic

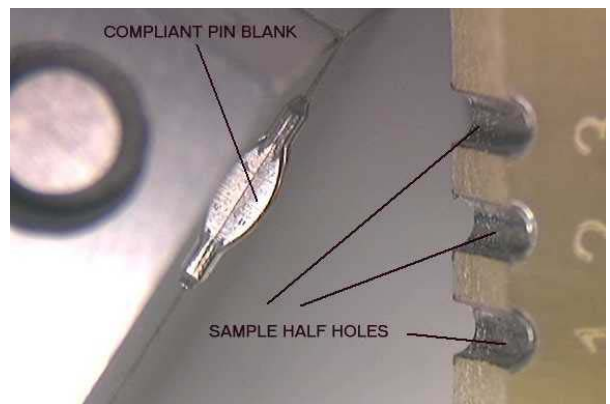


Figure 3. Clamp, Compliant Pin Blank and PCB half PTH

The friction apparatus is shown in Fig. 4. A reciprocating motion is produced using a micrometer adjustable eccentric cam driven by a DC motor. The variable speed DC motor and

reduction gear provide a smooth motion not affected by the high loads. Adjustment of the eccentric cam allows the sliding distance to be set between 0.125mm (0.005 in) and 12.7 mm (0.5 in). Rotational speeds between 0.5 cycle/sec. (2 sec. for 1 revolution) and 0.062 cycle/sec. (16 sec. for 1 revolution) are possible using the continuously variable speed control.

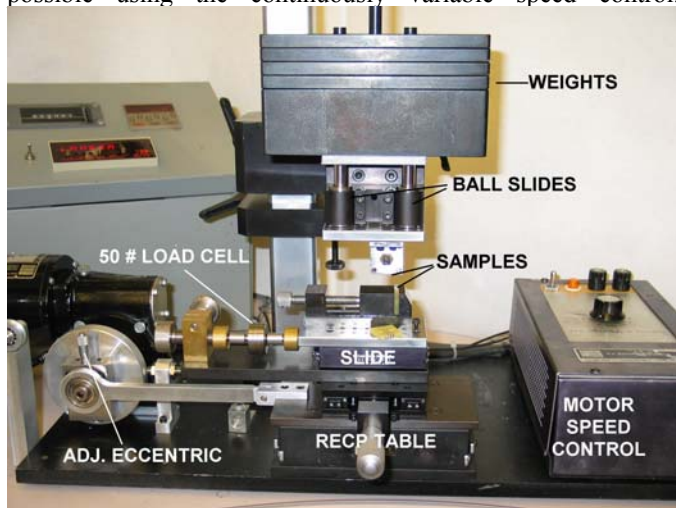


Figure 4. Friction Apparatus

Since the reciprocating motion is simple harmonic in nature, the rotational speed translates into a variable sliding velocity as defined by the simple harmonic motion equations. While this continuously varying velocity may complicate the data analysis, it is representative of many contact mating situations. The variable velocity also highlights the variability of measured friction coefficients. Root mean square (RMS) velocities of 0.017mm/sec (0.007 in/s) to 14.7mm/sec (0.58 in/s) are possible depending on the sliding distance and rotational speed selected.

The reciprocating table holds a load cell attached to a precision slide. Lateral forces on the precision slide result in deflection of the load cell. The moving half of a test sample (half PTH) is fixed on the precision slide. The stationary half of a test sample (EON pin blank) is fixed on a platform supported by two vertical ball slides. Normal force is applied to the test sample by adding weights to this vertically movable platform.

The load cell is calibrated by hanging a known weight using a pulley arrangement. This is shown in Fig. 5. Typical output from the load cell amplifier can be plotted and digitally analyzed.

Fig. 6 shows a typical result of 1 reciprocating cycle where the sliding distance used is 1mm (0.0394 in), and the peak velocity is 0.2 mm/s with a RMS velocity of 0.14 mm/s. Fig. 6 emphasizes the fact that the lateral force and the resulting calculated μ are not constant. The velocity dependence of the μ as the velocity approaches zero is evident from the trace. The values of $F_{friction}$ as the velocity transitions through zero (while changing direction) were excluded from the μ calculations. The positive and negative peak values were identified and the data clipped to include only values greater than or equal to 80% of the respective peak. The RMS value of

the remaining data set was used to calculate the coefficient of friction.



Figure 5. Calibration

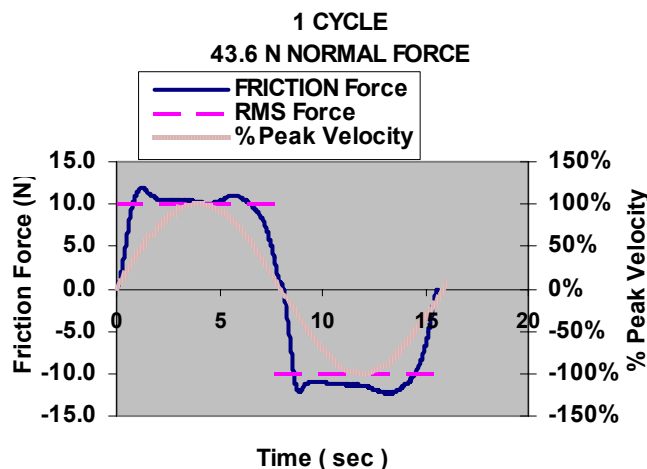


Figure 6. Typical Output

III. RESULTS AND DISCUSSION

A. Samples and data

A combination of two different EON pin finishes were evaluated against six different PTH finishes. There were two different pin thicknesses (0.5 and 0.25 mm) and two different PTH diameters (1.0 and 0.55mm) All measurements were made with a sliding distance of 1 mm and 0.2 mm/sec. peak velocity. At this velocity, frictional heating of the interface is not a concern [1].

The results of the EON friction testing are split into two subsets, Fig. 7 and 8. Fig. 7 shows the results for three board

finishes that usually exhibit higher μ values (~ 0.5 and greater) in the load range used with non press fit separable interfaces ($F_N \sim 10$ N). Fig. 8 shows the results for the three board finishes that usually exhibit lower μ values (~ 0.5 and lower) in the load range more typical of non press fit separable interfaces ($F_N \sim 10$ N). These graphs contain all the data for the 12 combinations of pin blank and PTH finishes. The thin pin, small diameter PTH combinations were tested at a low load range (10-30 N). The thick pin, large diameter PTH combinations were tested at a higher load range (20-70 N).

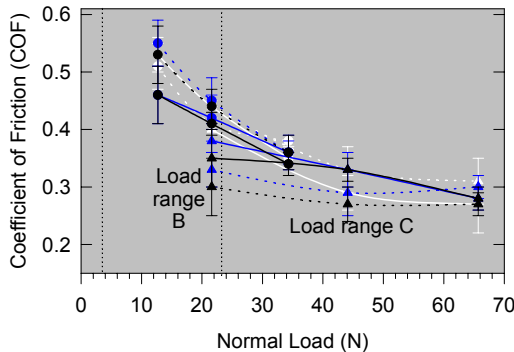


Figure 7. Higher μ coatings (as used in non-press fit separable interface applications at loads < 10 N)

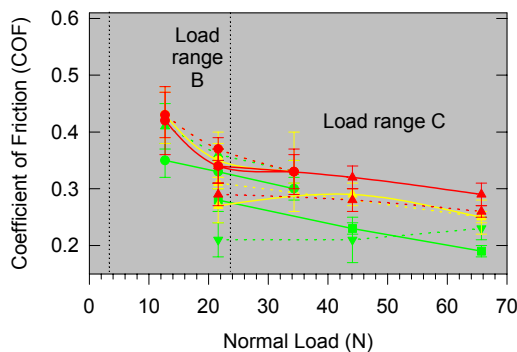


Figure 8. Lower μ coatings (as used in non press fit separable interface applications at loads < 10 N)

Each datum point on the graphs represents the median μ of 9 cycles. The 9 cycles were distributed over 3 half PTHs using 9 EON pin blanks. A fresh pin blank was used for each cycle. Each half PTH received 3 cycles. This was done to simulate an initial pin insertion and two reworks, involving the removal of a pin and replacement with a new pin. The standard deviation is included with the median value. The analysis of the data excludes the ‘turn-around’ and ‘static’ components, which are not representative of EON insertion.

In all cases, μ decreases with increasing load. The rate at which μ decreases is dramatic until the normal force, F_N , is above about 22 N. Basic frictional theory can be used to understand this trend.

B. EON Frictional Behavior

Friction behavior is not a fundamental parameter of a material such as crystalline structure, Young’s modulus, or hardness. It is an energy dissipation process; a function of how two impinging surfaces (free surface, surface films, applied surface coatings, substrates, supporting bulk volume of material) with specific surface morphologies (geometry and asperity distribution) and microstructural profiles (surface affected zone) interact mechanically (elastic/plastic), chemically (adhesion), and thermally. It is also a function of the combination of bulk and surface features that are affected by the history of the surfaces.

In these EON applications, the sliding velocity, surface roughness, and frictional heating are in the range where frictional behavior is independent of them. How the composite properties of the impinging surfaces dissipate frictional energy during tangential sliding determines the frictional behavior of the system. With greater applied normal load, more surface materials plastically deform, larger bulk material volumes interact, and more supporting sub surface and bulk materials influence the frictional behavior of the system.

Friction is quantified as the coefficient of friction μ – the ratio of the force required to slide the two surfaces against one another (F_{friction}) and the applied normal force (F_N). μ is a function of the force required to shear the formed junctions (F_S) and plough (plastic/elastic flow) material (F_P) within the deformation zones of either surface. F_S is proportional to the real area of contact ($A_r = \Sigma$ asperity contact areas) and the shear stress required to break the asperity junctions between the two surfaces (s_j). A_r is the ratio of F_N over the yield pressure of the junctions (p). F_P is a function of the how the two impinging geometries interact, i.e. the depth, width, and shape (cross-sectional area (A')) of the wear track, and the stress required to plough the material away from the interface (p'). Ploughing is more important for softer materials than harder materials.

$$\mu = [F_{\text{friction}}]/F_N = [F_S + F_P]/F_N = [s_j/p] + [A'p'/F_N]$$

μ is generally independent of F_N (Amonton’s laws) for sliding monolithic materials (except for limiting cases, i.e. extremely high or low loads). This is attributable to the fact that the A_r increases linearly with load F_N [2].

EON applications are a case of composite sliding surfaces, not monolithic sliding surfaces. The F_N ’s applied at EON interfaces are high enough so there is significant ploughing and displacement of material away from the wear track. The substrate interface, substrate, and supporting bulk (i.e. FR4 board) are all involved in the deformation zone between the two sliding surfaces. The sliding interface becomes a thin layer of soft metal between two sliding harder substrates. A frictional situation where it is known that Amonton’s classical friction laws do not apply and μ decreases with load. Both F_S (s_j , p) and F_P (A' , p') cannot be considered linearly related to F_N

and are a function of how the composite surface morphology/properties react to increasing F_N . [3].

C. Extension of the Data

Fig. 9 is a graph of data similar to Fig. 7 and 8. It extends the load range to less than 10 N typically used with separable contact interfaces. The data are for only the first friction cycle for 0.5 mm thick EON blanks used against 1.0mm diameter half hole boards and comparably finished flat Cu alloy coupons. Data for two different board finishes, one representative finish from Fig. 7 (circle symbol) and one representative finish from Fig. 8 (triangle symbol), are shown.

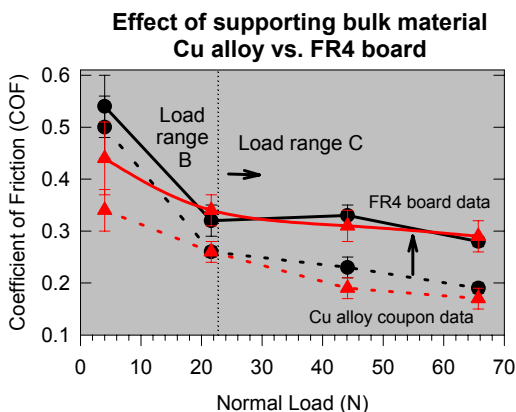


Figure 9. EON pin blank on FR4 half PTH (solid lines) vs. comparable plated Cu alloy coupon (dashed lines)

Fig. 10 is a similar graph for the same finishes using different sample types. For this test, 6.35 mm (0.25 in.) diameter hemispherical caps were used instead of a sheared edge EON pin blanks against comparably finished Cu alloy coupons. These are not EON product samples but they further illustrate the effect of geometry differences (i.e. 0.25 vs. 0.5 mm thick pin, sheared vs. formed surface), the effect of the differences in finish frictional behavior, as well as the differences in frictional behavior across the load ranges as discussed below.

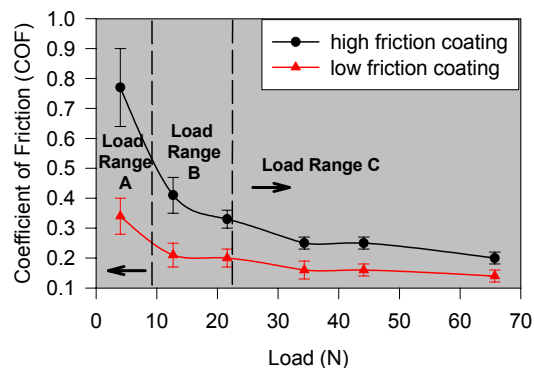


Figure 10. Frictional behavior of plated formed surface hemispherical cap on plated Cu alloy coupon

All coating material combinations tested had similar trends.

1) Effect of FR4 board vs. Cu alloy supporting bulk (Fig. 9)

The μ values for the two different samples, half hole boards and Cu alloy coupons, vary by about 0.1. The surface finishes were the same. The major difference between the samples was the supporting base materials (FR4 vs. Cu alloy). This effect is most notable at higher values of normal force F_N .

2) F_N Ranges

a) F_N range A (Fig. 10) – Amonton’s friction [$F_N < \sim 10$ N]

As long as F_N is low enough and the soft surface coatings are thick enough, the elastic/plastic deformation zones within the two sliding surfaces do not approach the interfaces between the softer surface coatings and the harder substrates of the two impinging geometries. No portion of the wear track is converted to a thin soft coating on a hard metal substrate. Within load range A, μ is independent of the interacting geometry’s of the two surfaces: a situation where Amonton’s laws applies [2,4]. An example of load range A is shown in the 4 N data in Fig. 10 for hemispherical cap on coupon geometry. A corresponding wear track is represented by the 4N hemispherical cap wear track in Fig. 11.

The EON applications studied here (Fig. 7-9) do not operate in this F_N range A.

b) F_N range B (Fig. 7-10) – Transitional friction [~ 10 N $< F_N < \sim 22$ N]

As F_N is increased, plastic flow of the surface coatings causes the deformation zone and wear track depth to approach the thickness of the coatings. The pile up of surface coating material at the end of the 4 N 0.5 mm thick EON pin blank and the 66 N wear tracks show this [Fig. 11]. The interface between the softer coatings and the harder substrates starts to be involved in the elastic/plastic deformation zones within the two sliding surfaces. Amonton’s friction laws stop being valid. μ

starts to decrease with increasing F_N as more of the load is supported by the harder substrate materials and the interface between the softer surface coating and the harder substrate constrains the plastic flow of the softer surface metal and pile-up occurs [5].

This F_N range represents the transition of the friction/wear mechanism from classical Amonton's to that of a hard substrate coated with a thin soft material that does not follow Amonton's friction laws [2]. At the lowest level of load range B, the majority of the interface can be described by Amonton's law and only a small fraction of the interface behaves as a composite of thin soft surface coatings over hard substrates. Thus the behavior is roughly equivalent to F_N range A. As F_N increases, the percent of the interface area 'obeying' Amonton's law approaches zero as the balance of the interface area is converted to a thin layer of soft material over a hard substrate which does not obey Amonton's laws. Effectively, F_N range C has been reached.

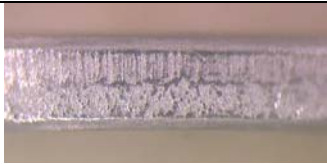


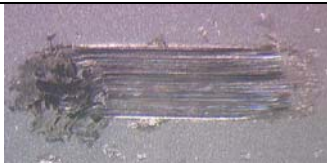
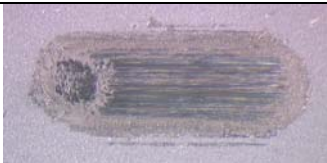
Sliding surfaces	
	← Shear to break transition line of sheared sliding surface.
0.5 mm thick EON pin blank sheared edge sliding surface	
4 N load: Some part (EON pin blank) or none (cap) of the wear track is a thin soft coating on a harder substrate	
	
0.5 mm thick EON pin blank wear track on coupon surface	6.35 mm hemispherical cap wear track on coupon surface
66 N load: Most to all of wear track is a thin soft coating on a harder substrate	
	
0.5 mm thick EON pin blank wear track on coupon surface	6.35 mm hemispherical cap wear track on coupon surface

Figure 11. Wear track micrographs

c) F_N range C (Fig. 9) – thin soft metallic layer on a harder substrate [$F_N > \sim 22N$]

The transition of the interface to one that does not obey classical Amonton's friction laws is complete as the depth of the wear track approaches the finite depth of the softer

coating(s) [Fig. 7-10, 66 N data in Fig. 11]. The majority of shearing still occurs within the softer thin film of coating material(s). Increases in A_r (and A') are severely limited and follow any deformation behavior of the harder substrate material as the impinging geometries increase load contact pressure.

3) Geometry effects

The force where the load range A transitions to load range B, and then to C, as F_N is increased is dependent on both the coating material response to normal load/lateral motion (e.g. COF and tendency to plastically flow) and how the two impinging geometries interact. The vertical lines separating load ranges A, B, and C are visual guides which are dependent on the interaction between the coatings and geometries of the two impinging surfaces.

For higher μ coatings, geometry differences are more significant. This is due to the greater tendency of the coating material to flow. The relatively 'sharp' peak at the 'shear to break' transition (Fig. 11) within the sheared edge surface (e.g. EON pin blank) interacts with an opposing surface very differently than a relatively smooth formed surface (e.g. hemispherical cap).

From Fig. 9, the 4 N EON pin blank 'sheared edge on coupon' data exhibits μ values typical of sheared edge separable connector. From Fig. 10, the 4 N '6.35 hemispherical cap on coupon' data exhibits μ values typical of formed surface separable connectors. The differences in the wear tracks can be seen in the 4 N wear tracks in Figure 11.

The frictional value is lower for sheared edge wear. This is because a portion of the wear track supporting part of the normal load has been converted to a thin soft coating material on a harder substrate. This does not occur within the 4 N hemispherical wear track. The differences are due to geometry interaction.

4) Wear Tracks

With the samples and F_N ranges used in this EON study, plastic deformation of the Cu (or Ni over Cu) substrate did occur, but not enough to completely remove the more ductile surface coating from the wear track. Complete film breakdown did not occur. There was always a thin layer of a more ductile coating material left on substrate. In all the EON pin blank on half PTH samples tested, at least some part of the wear tracks have been converted to a thin layer of the soft metallic coating on the harder substrate (i.e. Cu or Ni over Cu). The higher the load, the more this effect is seen.

IV. CONCLUSIONS

- The proposed apparatus and methodology provide a metric for the frictional behavior between a EON pin and a PTH hole.
- At lower press fit application normal forces (in the range of $10 N < F_N < 20 N$), there is more variation in the friction behavior with respect to the different EON/PTH surface finishes.

- At higher press fit application normal forces ($F_N > 20$ N); with increasing F_N
 - the supporting bulk material (i.e. FR4 board vs. Cu alloy) has greater impact on the coefficient of friction values than the surface finishes.
 - coefficient of friction values, for all the surface finish combinations tested, decreased to between 0.2 – 0.3 irrespective of the actual coating material properties.

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