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Friction and Wear of Materials

MANE 6960: Final Paper/Project

Wear Mechanisms of PTFE and PTFE Based Composites: A Summary of the Effects of Counter Surface Roughness and Properties on Friction and Wear Life

In the fields of tribology and engineering, the performance of bearing surfaces within the machinery and mechanisms that people use throughout their daily lives is a critical issue. In many cases, the most important bearing surfaces serve as a means of power transmission, such as a generator or turbine in a power plant, or the translation of motion in an application such as steering on an automobile or the actuation of landing gear or control surfaces on an aircraft. For a bearing surface in one of these high use, high load, locations, wear life and friction are critical characteristics. Many bearing surfaces utilize metal-to-metal interfaces lubricated with some type of liquid, typically oil or specially formulated synthetic lubricant. The performance of these bearings is generally sufficient, however, often times the metal surfaces wear out of their required machine tolerances and require an expensive repair or replacement process. In the search for new lubricating bearing surfaces, engineers over the last half a century have found PTFE (polytetrafluoroethylene) to be a very useful bearing material ingredient.

PTFE, when rubbed or slid along a hard metallic engineering surface exhibits a very low coefficient of friction (Biswas/Vijayan). The underlying process that creates this low coefficient of friction can be described as follows: as the PTFE surface runs against the counter metallic surface, the PTFE chain undergoes a process which creates portions of PTFE chains that are chemically reactive with the mating surface. These chains adhere to the mating engineering surface and a transfer film is created. The bulk portion of the PTFE interfaces with the transfer film, and this interaction allows the crystalline structures of both surfaces to align and shear very easily. Essentially, the transfer of the PTFE to the counter surface results in a PTFE-on-PTFE bearing surface, causing the low coefficient of friction (Biswas/Vijayan). Despite this, PTFE has been shown to have a low wear resistance, which prohibits its use in some areas. Many agree that the steady state wear rate of PTFE sliding against a hard counter surface is several orders of magnitude higher than that of other polymers. This has proved to be a counterpoint to the fact that the coefficient of friction of PTFE is an order of magnitude lower than most polymers and has required the creation of PTFE-based composites to increase the wear life. These composites offer the low friction coefficients of a pure PTFE coating due to their majority composition of PTFE, while imparting the wear life of the other fillers.

Despite having solved some of the limitations of PTFE as an engineering bearing material through the introduction of other fillers to increase wear life while maintaining low friction coefficients, there are still factors that may influence the performance of PTFE or a PTFE-based composite. It has been shown, through observation of applications and laboratory testing, that factors such as speed, temperature, contact pressure, counter surface roughness, and counter surface hardness greatly affect the friction and wear of PTFE and PTFE-based composites. The primary focus of this paper is the effect that the condition of the counter or mating surface has on the friction and wear of the PTFE and PTFE-based composites. Typically, these are the two factors that design engineers do not consider when incorporating a PTFE or PTFE-based material into their assembly as a bearing surface. While the PTFE can offer very low coefficients of friction against a metallic surface and the fillers in a PTFE composite can offer increased wear life, the condition of the counter surface can dictate whether the PTFE bearing surface performs to the low end of its friction and wear scale or towards the high of its performance rating. The PTFE-based bearing surface is only half of the entire bearing, and the counter surface must therefore be considered.

When two engineering materials of drastically different hardness run against one another in a bearing application, the surface roughness of the harder material (for the purpose of this paper, the metal versus the PTFE/PTFE -composite) can be very important. Though it is generally accepted that the roughness of the counter face surface has an effect on the friction performance of PTFE and PTFE-based composites, published reasons and mechanisms behind the phenomenon are relatively small in number. Though the wear properties of PTFE and PTFE composites have been studied, the majority of these experiments evaluated complex interactions of the various structural fillers used in PTFE composites and how they affected the friction and wear while keeping the counter surface properties constant. The following pages highlight the results of the experiments that have evaluated the effect of the counter surface roughness.

In many aerospace bearing applications, mating surfaces for PTFE-based dry lubricant materials are recommended to be very smooth. It is generally accepted that the wear life of a PTFE bearing increases as the surface roughness of the mating surface decreases. To evaluate this accepted behavior, J.K. Lancaster conducted a test using PTFE fiber/glass fiber-phenolic resin composite running against four different counter surfaces, each with different a surface roughness. His results, seen in the figure below, indicate that there is a significant variation of total life depending on the counter face roughness. Only at low stresses can an adequate wear life be obtained on the roughest of the four surfaces.

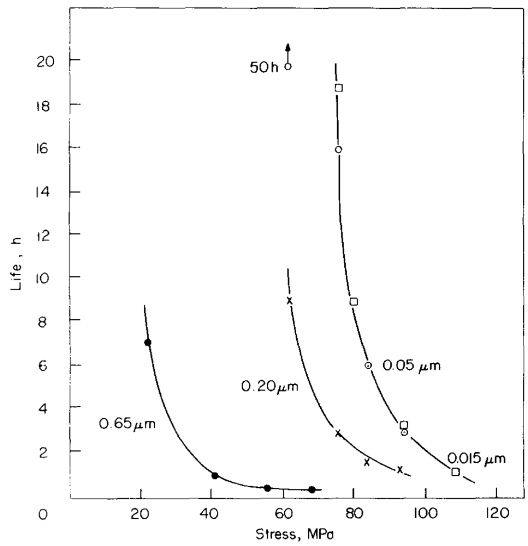

Figure 1. Effect of Counter face (tool steel) roughness on life-stress relationship of PTFE fiber based composite

Lancaster was able to generate a second plot, showing the relationship between the specific wear rate of the PTFE composite and the counter surface roughness at a given contact pressure. Paired with the curve generated by his data are two other published results that Lancaster was able to find. In general the trend of increased specific wear rate with increased surface roughness held across all three data sets.

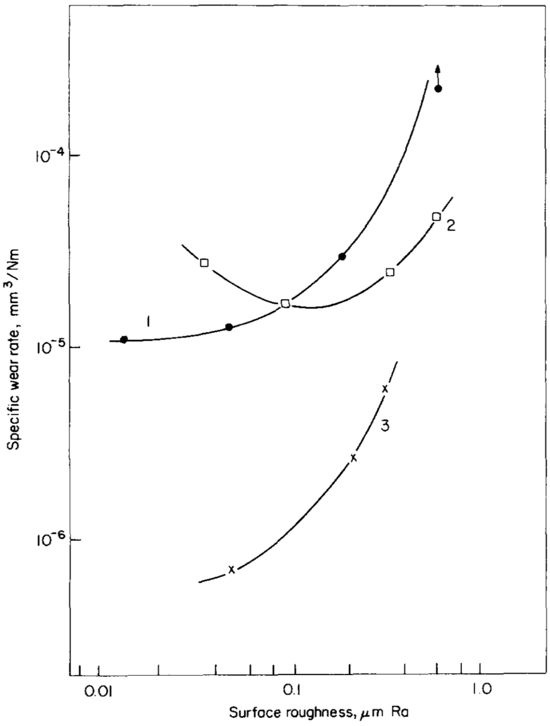

Fig 11 Variation of wear rate with counterface roughness for PTFE fibre composite, K. (1) Reciprocating line contact, 0.13m/s, 76 MPa (2) Craig[26]. Journal bearings, 25 mm x 9.5 mm; oscillatory motion ± 25°, 10 cycles/min; 10MPa. (3) Rowland and Wyles[10]. Pad on track, 0.087 m/s, 186 MPa

Figure 2. Effect of Counter face (tool steel) roughness on the specific wear rate of PTFE fiber based composite

In a similar set of experiments, conducted by Quaglini, Dubini, Ferroni, and Poggi, the influence of counter face roughness on the friction properties of engineering plastics was evaluated. Of the many plastics tested by the group, PTFE was examined as part of the low elastic modulus category. As part of a broader set of experiments, the PTFE samples were tested against two different surfaces: one with a polished finish and the other with a mirrored finish. It was found that the PTFE exhibited a lower friction coefficient on the mirrored surface. The authors of the paper believed that this occurred because the asperities of the smooth mirrored counter face were high enough to allow the formation of an effective PTFE transfer film, while not plowing into the surface of the

PTFE enough to increase the overall friction. On the polished surface, the asperities were large enough to penetrate further into the PTFE, resulting in such an increase in friction coefficient. The plot below shows the difference in the dynamic coefficient of friction for the PTFE on the two surfaces at varying sliding velocities.

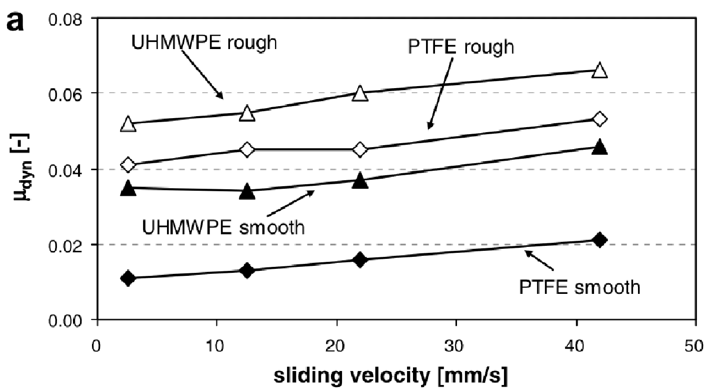

Figure 3. Effect of Counter face finish (polished or mirrored) on the dynamic coefficient of friction of PTFE

As seen in the studies mentioned above, many several studies have confirmed the overall effect of counter face surface roughness; however the specific characteristics of the surface profile that causes the changes in friction and wear have not been examined. In a series of investigative experiments conducted by W. Wieleba, several PTFE-based composite samples were tribologically tested against a steel counter face of varying surface roughness and hardness values. The main purpose of Wieleba's investigation was to expand upon previous research that described one or two parameters of roughness (e.g. R_a or R_z) on the friction and wear of mating materials, or described only the influence of hardness on the friction and wear. By conducting an experimental test, the surface roughness parameters of the mating counter face that most greatly affected the friction and wear of a polymer (in this case PTFE) composite could be identified. Wieleba chose three PTFE bases composites, Tarflen TG25, Tarflen TK25, and Tarflen TK22G3, all of which are comprised of 75% PTFE and 25% graphite and/or carbon. A tribometer (seen in the figure below), was set up with a PTFE composite specimen 2mm thick, 15mm long, and 5mm high. Several counter surfaces at varying roughness and hardness values were made from $42CrMo_4$ steel at a size of 200mm in diameter. The variations of the counter surface hardness were achieved through heat treating, and ranged from 26 to 56 HRC (Rockwell scale), while the surface roughness was characterized using a FORM Talysurf 120L profilographometer. The parameter R_a was used to describer the counter surface roughness, which varied from 0.1 to 1.5 μm.

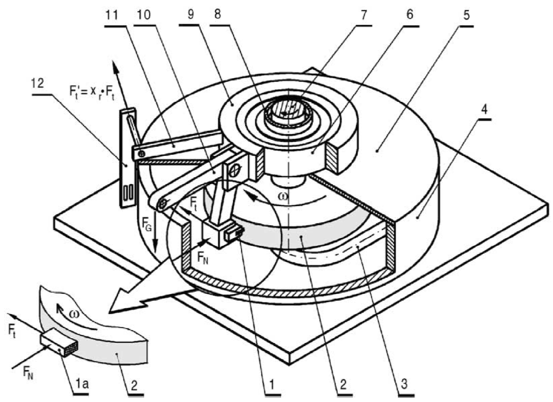

Fig. 1. Schematic diagram of experimental apparatus "Tribotester": 1, specimen encasing (1a, specimen); 2, counterface; 3, heater; 4, chamber housing; 5, cover; 6, bearing; 7, spindle; 8, spindle housing; 9, bearing housing; 10, weight lever; 11, block arm; 12, measuring beam with tensometres; F_t, friction force; F_N, normal force; F_t', reaction; F_G, dead weight.

Figure 4. Tribometer Schematic

Thirteen separate tests were conducted for each of the composite samples chosen by the author, against the varying roughness and hardness counter surfaces. The load applied to the samples was 2 MPa, while the sliding velocity and distance were v= 3 m/s and L=10 km, respectively. The friction force and the amount of wear on the PTFE composite pin were measured through the testing and the following results were generated.

The results of tribological investigations of PTFE composites sliding against steel under dry friction conditions

Experiment no.	Disc no.	$T_0 = 60\,°C$						$T_0 = 110\,°C$					
		TG25		TK25		TK22G3		TG25		TK25		TK22G3	
		μ	I_h (μm/km)	μ	I_h (μm/km)	μ	I_h (μm/km)	μ	I_h (μm/km)	μ	I_h (μm/km)	μ	I_h (μm/km)
1	1	0.129	12.3	0.176	1.1	0.180	1.3	0.120	10.7	0.205	1.4	0.280	2.2
2	2	0.147	1.6	0.217	1.4	0.215	1.4	0.119	2.0	0.225	1.8	0.260	1.6
3	3	0.127	26.0	0.189	1.2	0.180	2.0	0.118	18.7	0.240	2.1	0.180	2.3
4	4	0.138	1.2	0.340	3.8	0.340	3.5	0.134	0.8	0.215	2.3	0.440	4.4
5	5	0.121	22.1	0.169	1.1	0.177	1.7	0.113	22.2	0.229	2.5	0.430	2.2
6	5	0.122	19.9	0.165	1.2	0.176	1.9	0.113	20.8	0.255	3.1	0.420	2.8
7	5	0.122	15.7	0.171	1.6	0.175	1.3	0.115	18.8	0.238	2.8	0.420	2.8
8	5	0.123	14.2	0.171	1.5	0.171	1.6	0.115	21.3	0.243	2.9	0.410	3.0
9	5	0.122	12.6	0.171	1.6	0.175	1.9	0.117	18.4	0.230	2.5	0.411	3.0
10	6	0.126	47.0	0.188	3.7	0.179	8.5	0.124	37.8	0.214	5.0	0.210	11.2
11	7	0.150	1.9	0.194	1.6	0.195	1.3	0.127	1.8	0.275	2.8	0.425	3.5
12	8	0.120	28.0	0.173	1.2	0.181	1.5	0.108	28.5	0.255	3.4	0.360	2.3
13	9	0.122	16.0	0.188	1.4	0.178	1.3	0.112	11.9	0.290	2.9	0.440	2.3

$p = 2$ MPa, $v = 3$ m/s (TG25, PTFE + 25 wt.% graphite; TK25, PTFE + 25 wt.% carbon; TK22G3, PTFE + 22 wt.% carbon + 3 wt.% graphite).

Table 1. Experimental Results of Wieleba's Experiment

From these results, Wieleba defined a multi-dimensional function to describe the dependence of the coefficient of friction and the wear of the PTFE composite on hardness and selected counter surface roughness parameters. The final regression function created was:

$$Y = a_0 + a_1 R + a_2 H + a_3 R^2 + a_4 H^2 + a_5 RH$$

Where: Y = coefficient of friction μ or specific linear wear rate, I_h

$a_0 ... a_5$ = the polynomial coefficients

R = variable describing surface roughness

H = variable describing surface hardness, Rockwell scale

Once the coefficients were calculated using the least squared method, a statistical analysis of the test was carried out to create a comparison to the experimental data.

The results of test F calculated for the regression functions which describe μ and I_h as a function of the roughness parameters (measured perpendicularly to the direction of sliding) and hardness of the steel counterface

Composite	T_0 (°C)	Roughness parameters (μm)														
		R_a	R_z	R_{3z}	R_t	R_q	R_p	R_v	Ku	R_k	R_{pk}	R_{vk}	S_m	S	$\Delta\alpha$	Δ
Friction coefficient (μ)																
TG25	60	**5.01**	3.53	3.89	**4.93**	***5.72***	**3.98**	**5.66**	1.09	3.70	**4.61**	2.99	1.13	1.82	**4.52**	***7.63***
	110	***31.50***	***16.99***	***33.44***	***16.23***	***22.33***	***36.04***	***12.46***	2.10	***12.67***	***12.44***	***7.66***	***5.71***	***17.91***	***7.96***	***17.30***
TK25	60	**4.18**	***6.78***	***5.83***	2.92	3.31	3.82	2.60	***28.19***	***5.69***	3.96	1.42	***17.00***	***5.76***	***13.44***	2.76
	110	**4.98**	***5.21***	***5.80***	**4.59**	**4.75**	**4.80**	**4.48**	***6.41***	**4.64**	**5.21**	**4.87**	***10.18***	***7.61***	***5.75***	**4.64**
TK22G3	60	**4.04**	***6.84***	**5.54**	2.66	3.12	3.60	2.34	***42.45***	***6.07***	3.93	1.43	***20.34***	***4.68***	***18.23***	2.70
	110	**4.12**	3.27	3.33	**4.60**	**4.27**	**4.20**	4.79	***6.45***	3.79	***5.96***	**4.57**	3.44	2.45	1.52	**4.31**
Specific wear rate (I_h)																
TG25	60	***15.26***	***13.71***	***14.30***	***15.07***	***14.60***	***14.50***	***14.16***	**4.37**	***14.82***	***14.44***	***27.91***	2.93	3.32	4.06	***16.52***
	110	***107.0***	***94.77***	***118.0***	***107.1***	***101.7***	***61.40***	***101.6***	**4.40**	***66.52***	***14.49***	***31.81***	**4.31**	**4.02**	***19.76***	***151.9***
TK25	60	**5.25**	**3.98**	**6.81**	**4.90**	**5.09**	***6.27***	4.34	**4.63**	2.86	***6.26***	3.84	***10.56***	***19.97***	1.97	**4.03**
	110	***27.78***	***7.58***	***16.15***	***42.32***	***41.52***	***40.07***	***41.14***	**5.63**	***6.76***	***13.37***	***37.22***	***6.89***	2.30	2.42	***36.04***
TK22G3	60	***11.58***	3.15	***8.40***	***25.25***	***23.32***	***33.13***	***21.30***	2.15	2.46	***24.85***	***26.81***	3.80	2.29	0.70	***14.01***
	110	***17.35***	3.02	***8.97***	***74.45***	***60.20***	***104.5***	***59.16***	1.57	2.38	***11.40***	***60.28***	3.24	1.77	0.65	***27.13***

The numbers in italics highlight these results of test F which are greater than $F_{kr} = 5.67$ (for $\alpha = 0.01$), bold numbers represent the results of test F greater than $F_{kr} = 3.97$ (for $\alpha = 0.05$).

Tables 2 . Results of Wieleba's Statistical Analysis

The results of test F calculated for the regression functions which describe μ and I_h as a function of the roughness parameters (measured parallelly to the direction of sliding) and hardness of the steel counterface

Composite	T_0 (°C)	Roughness parameters (μm)															
		R_a	R_z	R_{3z}	R_t	R_q	R_p	R_v	Ku	R_k	R_{pk}	R_{vk}	r	S_m	S	$\Delta\alpha$	Δ
Friction coefficient (μ)																	
TG25	60	3.96	1.15	**4.14**	***46.24***	***9.83***	***38.02***	***31.59***	1.03	2.71	***9.22***	***67.05***	1.70	0.45	2.48	***10.31***	***6.28***
	110	***11.44***	***7.61***	**5.03**	2.16	***11.11***	1.39	2.94	2.10	**4.89**	***13.81***	2.28	**5.58**	2.07	0.76	***10.56***	***9.40***
TK25	60	***5.67***	1.51	**4.73**	0.77	2.23	0.33	1.08	***23.18***	***7.66***	2.50	0.37	***9.08***	**5.47**	0.04	2.15	2.91
	110	3.73	**5.02**	**4.00**	3.00	3.91	3.49	3.15	***7.26***	***3.97***	***5.67***	3.44	***9.25***	***13.46***	**4.68**	**5.48**	**5.66**
TK22G3	60	**5.49**	1.08	**5.28**	0.80	2.21	0.40	1.09	***48.84***	**9.17**	2.38	0.38	***6.41***	**4.73**	0.07	2.33	**3.99**
	110	3.66	1.74	2.19	2.36	**4.01**	**5.37**	1.28	1.40	2.48	1.95	2.87	**4.46**	***15.60***	**5.30**	1.20	1.81
Specific wear rate (I_h)																	
TG25	60	***7.72***	0.15	2.09	3.40	***10.22***	***6.54***	1.59	0.58	2.46	3.95	3.90	0.11	**4.12**	**4.20**	1.85	1.90
	110	***24.36***	0.43	***5.97***	***11.24***	***51.07***	***8.91***	**5.62**	1.10	***6.60***	***9.98***	***8.65***	0.47	**4.46**	3.28	**5.39**	3.87
TK25	60	1.94	**4.90**	0.71	0.28	2.01	0.27	0.35	2.03	0.73	**5.34**	0.56	***8.18***	***10.32***	1.11	1.60	1.72
	110	3.76	1.14	1.42	2.22	***7.29***	3.20	1.41	1.21	1.57	***10.07***	***5.07***	1.78	***13.33***	***19.96***	3.05	**4.53**
TK22G3	60	1.24	1.42	0.16	0.29	2.42	0.66	0.17	0.36	0.17	***13.50***	1.19	1.33	**7.16**	***8.49***	1.54	2.20
	110	1.16	1.72	0.17	0.35	2.76	0.70	0.22	0.27	0.17	***28.49***	1.78	1.48	**5.47**	***14.92***	2.54	3.62

Numbers in italics highlight the results of test F which are greater than $F_{kr} = 5.67$ (for $\alpha = 0.01$), bold numbers represent the results of test F greater than $F_{kr} = 3.97$ (for $\alpha = 0.05$).

Tables 3. Results of Wieleba's Statistical Analysis

Analyzing Wieleba's results showed that there was a much stronger dependency on surface roughness for the linear wear rate I_h than there was for the coefficient of friction μ. Overall, it was determined that the roughness parameters S_m, $\Delta\alpha$, and R_k had the strongest influence on value and magnitude of the coefficient of friction. These parameters were all related to the shape of the counter surface's asperities. According to Wieleba, the influence of the S_m parameter is related to the hardness of the counter face material. The S_m parameter itself described the mean distance between the asperity peaks of the steel counter face, so as the S_m value increases, the asperities are spread further apart. When the hardness of the steel counter face was above 48 HRC, the influence of S_m was minimized, while below 48 HRC, the coefficient of friction rises along with the value of S_m. This correlates with previous conclusions that wider spread asperity peaks on the counter face prevents the creation of the PTFE transfer film, increasing the coefficient of friction.

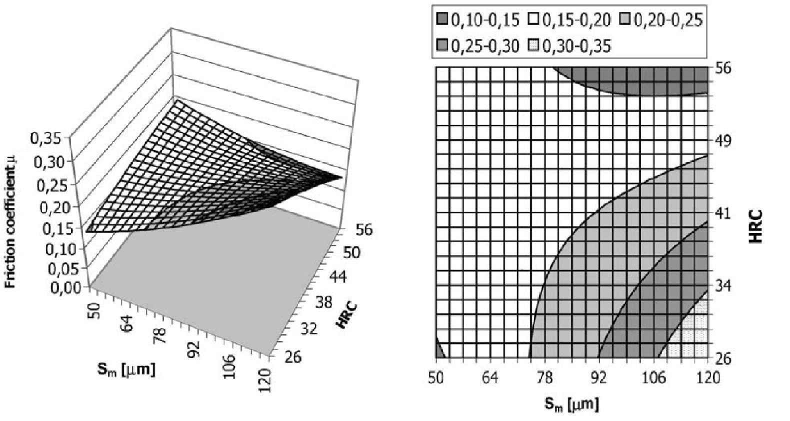

Fig. 3. The effect of roughness parameter S_m and hardness HRC of a steel counterface on the coefficient of friction μ for PTFE + 25 wt.% carbon ($p = 2$ MPa, $v = 3$ m/s, $T_0 = 60\,°C$).

Figure 5. Effect of S_m and Hardness on Coefficient of Friction

The parameter $\Delta\alpha$, or the average profile slope of the counter surface profile, causes the friction coefficient to vary regardless of the steel surface's hardness. For smaller profile slope values ($\Delta\alpha$), the contact area between the PTFE and the steel counter surface is large, causing relatively strong adhesive interactions, driving the friction forces up. Additionally, the lower surface profile slopes prohibit the formation of the PTFE transfer film, which also promotes higher friction forces. Wieleba determined that there is an optimal slope value at which the coefficient of friction is the lowest; this occurred in his testing around $\Delta\alpha \approx 4$.

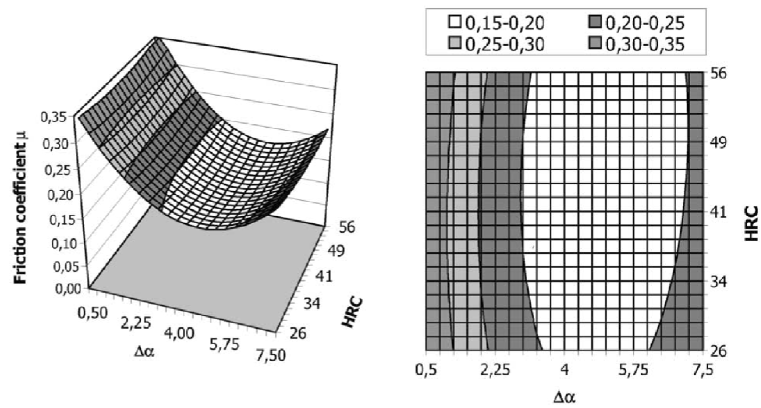

Fig. 2. The effect of roughness parameter $\Delta\alpha$ and hardness HRC of a steel counterface on coefficient of friction μ for PTFE+25 wt.% carbon ($p = 2$ MPa, $v = 3$ m/s, $T_0 = 60\,°C$).

Figure 6. Effect of $\Delta\alpha$ and Hardness on Coefficient of Friction

The final surface roughness parameter, R_k (core roughness depth), along with the parameters S_m and $\Delta\alpha$ are related to the number of contact points between the PTFE composite and the metal counter surface, as well as the size and shape of the actual contact areas. As the size of the real contact area between the two surfaces varies, the amount of adhesion and mechanical forces occurring between the two surfaces also varies, creating variations in the overall friction forces/coefficients.   The author of the paper believes that the surface hardness is not directly related, but rather indirectly related to the coefficient of friction.

The author also determined that the parameters related to the height of the counter surface asperities, R_p and R_{pk}, as well as the non-dimensional complex coefficient Δ, had the greatest influence on the wear of the PTFE composite. The coefficient Δ depends on the average radius of curvature of the peaks r and on the maximum roughness R_y.   All of these parameters, being related to the height of the steel counter face profile, have a direct influence on the mechanical interactions of the micro irregularities of the steel and the PTFE composite. The following figure, generated by Wieleba, shows the dependence of wear of the PTFE composite on surface roughness and hardness of the steel counter face.

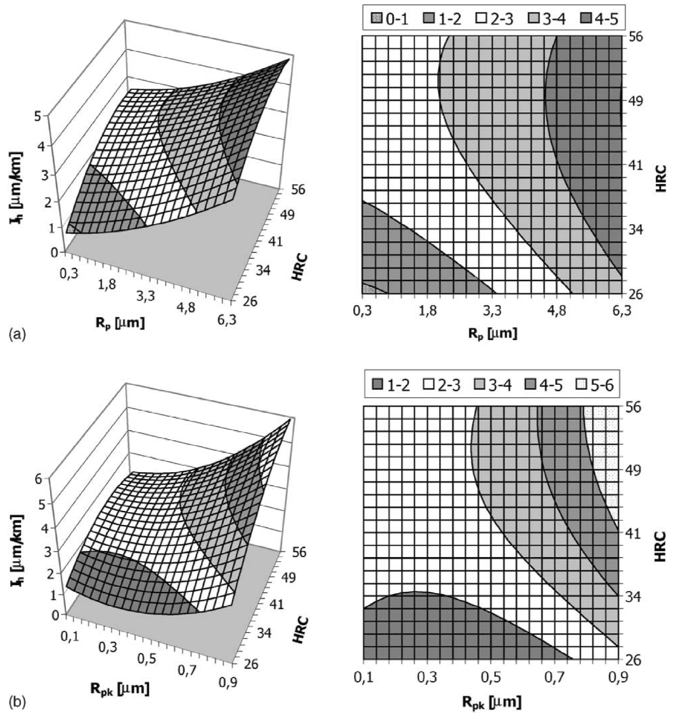

Fig. 4. The effect of roughness parameter R_p (a) and R_{pk} (b) and hardness HRC of a steel counterface on the specific linear wear ratio I_h for PTFE+25 wt.% carbon ($p = 2\,\mathrm{MPa}$, $v = 3\,\mathrm{m/s}$, $T_0 = 110\,°\mathrm{C}$).

Figure 7. Effect of Counter Face Surface Roughness and Hardness on Wear of PTFE Composite

Overall, Wieleba was able to determine which characteristics of a counter face that may cause the trends in friction and wear seen in other studies through comparisons of his statistical models and his own experimental results.

As a bearing material, PTFE and PTFE-based composites have been invaluable engineering tools. In using this material, one must understand the effects of the counter surface's properties on the performance of the PTFE and PTFE based composites. Particularly, the surface roughness and in some cases the hardness of the counter face can drastically influence the friction of a PTFE based composite. Through various studies, it has been shown that generally smoother surfaces extend the wear life of PTFE based composites, while the secondary parameter of hardness acts as an indirect influence on the friction and wear of PTFE. Though these studies have found general trends and possible specific characteristics of a counter surface's profile that affect the friction and wear of PTFE and PTFE based composites, there is still much to be learned about its behavior. It would be worth while to continue the experiments, possibly using different counter face materials than steel, such as ceramics, chrome plating, titanium, Inconel, or Monel. Temperature, sliding velocity, and other environmental variables could be introduced as well, as they have been shown to greatly influence the performance of PTFE-based bearing materials.

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For additional references not directly used in this paper, see: http://www.ewp.rpi.edu/hartford/~peetrm/FWM/Project/Reference%20Papers/