High-PV Wear Study of Six High Performance Wear Grade Engineering Plastics

Abstract

A study was commissioned to examine the wear characteristics of six high performance engineering plastics currently used in tribological applications. The test consisted of a thrust bearing 3 x 3 grid High-PV wear test of each material, which was then extended through increased PV conditions until material failure for the survivors of the 3 x 3 grid.

The test materials were Celazole® TL-60, PEEK® 450FC30, Torlon® 4203L, Torlon® 4275, Torlon® 4435 and Vespel® SP-21.

The study produced valuable data on the comparative performance of these materials. The two most outstanding materials were Celazole TL-60 and Vespel SP-21. Celazole TL-60 demonstrated superior performance with its consistently low wear factor, low coefficient of friction and cool counter-surface temperatures. It was the only material to survive loads at or above 2500 psi (at speeds greater than or equal to 50 ft/min) and in fact performed at 4000 psi at a PV of 200,000 psi-ft/min. Vespel SP-21 was also remarkable in its demonstration of achieving the absolute highest PV of 400,000 psi-ft/min at a surface velocity of 800 fpm.

1. Overview

Many industrial processes and a number of consumer products require high performance materials in tribological applications. Traditionally this has been the realm of lubricated metals, but with increasing demand for performance and light weight, advancements in material science have brought engineering plastics to the forefront. These engineering plastics bring the benefit of light weight, long part life-cycles, low failures rates, and enable some applications heretofore not possible with metal. The material space in play requires wear resistance, high strength, high temperature resistance, and low creep in a non-lubricated environment. This study reviews six materials competing for this space and shows that engineering plastics exist which are up to the task.

ASTM defines wear as damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances. Wear resistance is a paramount characteristic of a material's suitability for tribological service. Technicians measure wear rate by standardized methods and commonly report wear rate as a measured change in thickness or weight loss per unit of time or distance. Since wear rate is a function of the subject material and the mating surface material, their hardness, their surface finish, the ability for the material and the system to dissipate heat, surface velocity, load, temperature, other environmental conditions, and exposure time, it is necessary to standardize test methodology and conditions to enable comparison. This study attempts to do so by measuring equilibrium wear rate, coefficient of friction and counter-surface temperature of engineering plastics in a thrust washer test configuration against a smooth mild steel surface in air. The objective is to determine which are best suited for the most demanding tribological applications with steel. Ideal materials will exhibit a low coefficient of friction and low wear rate while generating little frictional heat.

2. Experiment Design

2.1 Description of Test

The test employed was a High-PV thrust bearing wear test based on ASTM D-3702 utilizing engineering plastic thrust washer test specimens rotated against a steel counter-surface. The test specimens measured 1.0625" in diameter with 0.20 square inches of contact area. The counter-surface was annealed AISI 1018 carbon steel machined to a 16 +/- 2 micro-inch (AA) surface finish. The test specimens were rotated under load without lubrication against the stationary steel counter-surface in air at ambient conditions for fixed time periods. Wear rate, coefficient of friction, and counter-surface temperature were measured as the material progressed through a matrix of pressures and velocities.

The product of the pressure (P) on the contact area in psi and surface velocity (V) in ft/min (fpm) provides a PV value at which wear rate, counter-surface temperature, and the coefficient of friction were measured. A wear factor (K) based on measured wear is calculated and reported. K = (the measured change in specimen thickness in inches)/(PVT) where (T) is duration in hours. The coefficient of friction (*f*), a dimensionless unit, is calculated as *f* = 2Fa/(PAd), where F = the frictional Force in lbs, a = frictional arm length in inches, A = thrust washer specimen contact Area in square-inches, and d = mean annular diameter of thrust washer specimen in inches. Counter-surface temperatures were measured by a fixed thermocouple to the side edge of the counter-surface and reported in degrees Fahrenheit. Temperature readings are periodic and therefore may not represent the maximum temperature encountered.

The test battery consisted of an Initial Test of six high performance wear-grade engineering plastics and an Extended Test of those materials which survived the Initial 3 x 3 grid. All tests were conducted by Lewis Research, Inc. on a LRI-1a Thrust Bearing Tribometer.

The tests were conducted using three washer specimens (a, b, and c in Table 1 below) for each thermoplastic material. These washers were first put through a break-in test interval (designated by subscript 1 to the specimen ID in Table 1 below) at the lowest PV and middle velocity condition (PV = 50,000 psi-ft/min; Velocity = 200 fpm) for 8 hours. The specimens were then advanced through the PV grid as indicated by sequential subscripts to each specimen "a", "b" and "c". By example, after the break-in cycle specimen "a" was next tested at 50,000; then 75,000 and then 100,000 PV at a velocity of 50 fpm (respectively a_2, a_3, and a_4); broken-in specimen "b" was tested at 50,000; 75,000 and 100,000 PV at a velocity of 200 fpm (b_2, b_3 and b_4); and broken-in specimen "c" was tested at 50,000; 75,000 and 100,000 PV at a velocity of 800 fpm (c_2, c_3 and c_4). The duration of each test interval was 8 hours. This test grid is repeated in the same manner for each of the six thermoplastic materials.

Three thermoplastic materials survived the Initial 3 x 3 grid and were pushed to higher PV's in increments of 25,000 psi-ft/min until failure in an Extended High-PV Wear Test. These tests were also run at 50, 200 and 800 fpm surface velocities while increasing the pressure to achieve higher PVs (subscripts 5 through 16 in Table 1). Results are presented below.

Table 1

PV (psi-ft/min)	Velocity (50 ft/min)	Velocity (200 ft/min)	Velocity (800 ft/min)	
50,000	a_2	a_1,b_1,b_2,c_1	c_2	Initial Test
75,000	a_3	b_3	c_3	
100,000	a_4	b_4	c_4	
125,000	a_5	b_5	c_5	Extended Test
150,000	a_6	b_6	c_6	
175,000	a_7	b_7	c_7	
…	…	…	…	
400,000	a_{16}	b_{16}	c_{16}	

2.2 Materials Tested and Material Preparation

Six high performance engineering plastic materials were tested. Five were aromatic thermoplastics and one was an aromatic thermoset.

Two sources of Celazole TL-60 parts were tested. This material is designed to be injection molded and used without further treatment or machining; however, since it is available in stock shape and molded part form, both machined parts (from stock shape) and injection molded parts were tested. Two approved sources for Celazole T-Series products supplied specimens. Parkway Products, Inc. molded the Injection Molded Celazole TL-60 thrust bearing specimens. These specimens were tested as molded after boring the center axis and drive holes. Piper Plastics, Inc. molded the TL-60 stock shapes and machined the respective Machined Celazole TL-60 thrust bearing specimens.

Three wear grades of Solvay Torlon Polyamide-imide (4203L, 4275 and 4435) were injection molded into part form and post cured by Parkway Products in accordance with Solvay's processing instruction. After post-curing, these specimens were bored with center axis and drive holes.

The sole aromatic thermoset wear grade material tested was DuPont's Vespel Polyimide SP-21; molded by DuPont. Thrust washers were machined from molded stock shape.

And finally, Victrex PEEK wear grade material 450FC30 was tested. Parkway Products injection molded these parts and annealed them according to Victrex's instruction. After annealing, these parts were bored with center axis and drive holes.

Reference Table 2 for further details on the Materials.

Table 2

Material		**Molding Process**	
Celazole TL-60		Injection Molded Parts	
Celazole TL-60		Piper Molded Stock Shape	
Vespel SP-21		DuPont Molded Stock Shape	
Torlon 4203L		Injection Molded & Post Cured Parts	
Torlon 4275		Injection Molded & Post Cured Parts	
Torlon 4435		Injection Molded & Post Cured Parts	
Victrex PEEK 450FC30		Injection Molded & Annealed Parts	

Product notes:

Celazole® TL-60 made with Celazole® Polybenzimidazole (PBI) and Victrex PEEK is PBI Performance Product's injection moldable, high performance, wear-grade T-Series compound.

Vespel® SP-21 is DuPont's 15% graphite filled Polyimide (PI) with enhanced wear resistance.

Torlon® 4203L is Solvay's un-reinforced all purpose-grade Polyamide-imide (PAI) compound made with 3% TiO_2 and 0.5% fluoropolymer.

Torlon® 4275 is Solvay's low-friction and low-wear Polyamide-imide compound with 20% graphite and 3% fluoropolymer.

Torlon® 4435 is Solvay's exceptionally low wear performance grade Polyamide-imide (PAI) compound made for non-lubricated applications.

Victrex PEEK® 450FC30 is Victrex's lubrication grade PEEK, with standard viscosity PEEK compound and 30% carbon/PTFE for injection molding and extrusion.

3. Results and Discussion

3.1 Initial 3 x 3 High-PV Wear Test Results

To enable the reader to obtain a more complete understanding of the test results, the wear test data is included in the attached Tables 3, 4 and 5; and Figures 1-9. The reader will find it beneficial to read this discussion in conjunction with these tables and figures.

No wear performance data could be generated for Torlon 4203L. All three specimens melted and were completely destroyed within 2.5 hours of starting the break-in interval at PV = 50,000 psi-ft/min; Velocity = 200 fpm.

PEEK 450FC30 survived just over half of the Initial 3 x 3 grid. Wear factors, coefficient of friction and running temperatures were amongst the highest. (Lower is better for all three measures.) One specimen melted during the PV = 100,000 / 200 fpm condition. Another melted at the end of the PV = 100,000 / 50 fpm condition. The third specimen, plus two additional specimens melted very early in the PV = 50,000 / 800 fpm condition; therefore, no data could be generated at 800 fpm for this material.

Torlon 4275 demonstrated measurable improvement relative to the first two materials. It performed well at the lower PV level (50,000 psi-ft/min/) under the conditions of low surface velocities 50 and 200 fpm. Nevertheless, its wear rate was twice that of the best material. It melted or showed signs of melt at

Table 3 -- Wear Factor Data

Wear Factor K at 50 fpm (in^3-min/ft-lb-hr x 10^{-10})

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	41	48	50	104	26	25	
75000	42	46	46	129^	21	16~	
100000	19	41	broke	183*	20	13~	
125000	melted				test end; no failure	23~	
150000						36~	
175000						6	
200000						19^	
225000							

Wear Factor K at 200 fpm (in^3-min/ft-lb-hr x 10^{-10})

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	47	70	49	79	39	47	melted
75000	43	195*	40	78	30	30	
100000	63	melted	30	melted	23	26	
125000	melted		28		test end; no failure	18	
150000			25			13	
175000			20			12	
200000			17			10	
225000			24			12^	
250000			11				
275000			18				
300000			12				
325000			8				
350000			10				
375000			broke				

Wear Factor K at 800 fpm (in^3-min/ft-lb-hr x 10^{-10})

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	88	89	31	melted	20	24	
75000	70	76	39		17	23	
100000	46	194*	22		13	20	
125000	melted		43		test end; no failure	15	
150000			38			27	
175000			27			40^	
200000			26				
225000			24				
250000			22				
275000			20				
300000			17				
325000			20				
350000			23				
375000			28				
400000			29				

Notes: ^ slight melting
* melting
~ slight mushroom

Table 4 -- Coefficient of Friction Data

Coef. Friction at 50 fpm

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	0.18	0.18	0.19	0.16	0.09	0.10	
75000	0.08	0.10	0.27	0.07^	0.07	0.07~	
100000	0.08	0.09	broke	0.1*	0.04	0.06~	
125000	melted				test end; no failure	0.05~	
150000						0.06~	
175000						0.05	
200000						0.07^	
225000							

Coef. Friction at 200 fpm

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	0.13	0.24	0.14	0.16	0.10	0.11	melted
75000	0.09	0.17*	0.10	0.11	0.08	0.08	
100000	0.07	melted	0.08	melted	0.07	0.07	
125000	melted		0.07		test end; no failure	0.06	
150000			0.06			0.05	
175000			0.06			0.05	
200000			0.05			0.04	
225000			0.05			0.04^	
250000			0.05				
275000			0.05				
300000			0.04				
325000			0.04				
350000			0.04				
375000			broke				

Coef. Friction at 800 fpm

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	0.11	0.20	0.12	melted	0.09	0.06	
75000	0.10	0.21	0.11		0.07	0.07	
100000	0.08	0.13*	0.07		0.08	0.05	
125000	melted		0.09		test end; no failure	0.06	
150000			0.08			0.05	
175000			0.06			0.05^	
200000			0.07				
225000			0.07				
250000			0.05				
275000			0.04				
300000			0.05				
325000			0.04				
350000			0.04				
375000			0.06				
400,000			0.05				

Notes: ^ slight melting
* melting
~ slight mushroom

Table 5 -- Counter-Surface Temperature Data

Counter-Surface Temp at 50 fpm (F)

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	360	390	422	355	273	277	
75000	350	375	343	308^	286	293~	
100000	316	360	broke	442*	423	301~	
125000	melted				test end; no failure	331~	
150000						333~	
175000						327	
200000						371^	
225000							

Counter-Surface Temp at 200 fpm (F)

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	314	398	314	410	269	283	melted
75000	312	484*	335	414	301	295	
100000	314	melted	366	melted	303	323	
125000	melted		384		test end; no failure	323	
150000			383			344	
175000			391			340	
200000			409			346	
225000			398			370^	
250000			417				
275000			420				
300000			426				
325000			432				
350000			428				
375000			broke				

Counter-Surface Temp at 800 fpm (F)

PV	Torlon 4435	Torlon 4275	Vespel SP-21	PEEK 450FC30	Celaz TL-60 Mach'd	Celaz TL-60 Inj'n	Torlon 4203L
50000	302	423	279	melted	213	235	
75000	329	483	330		240	278	
100000	350	449*	305		259	293	
125000	melted		442		test end; no failure	303	
150000			447			304	
175000			432			357^	
200000			447				
225000			464				
250000			486				
275000			488				
300000			506				
325000			519				
350000			580				
375000			638				
400,000			590				

Notes: ^ slight melting
* melting
~ slight mushroom

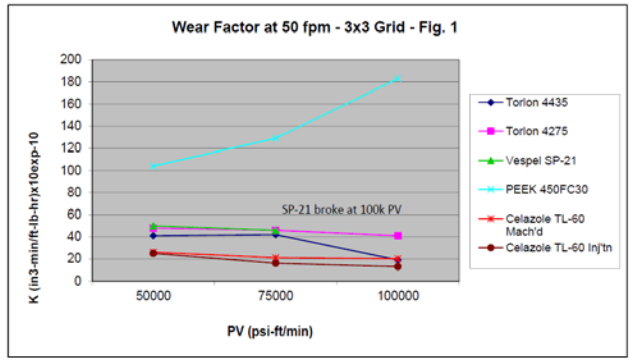
100,000 PV for all three velocities, performing best at low speed (50 fpm). Its coefficient of friction was notably high, thereby exhibiting high counter-surface temperatures. Due to melting, it could not continue to the Extended High-PV test.

Torlon 4435 survived the entire Initial 3 x 3 grid. Its frictional coefficient was very similar to Vespel SP-21, or perhaps slightly lower. At 50 and 200 fpm surface velocities its wear factor was similar to SP-21, but was nearly twice SP-21 at 800 fpm, and its wear factor was nearly twice Celazole TL-60 under almost any condition. At the 800 fpm condition, its counter-surface temperatures were 50 to 90F hotter than Celazole TL-60.

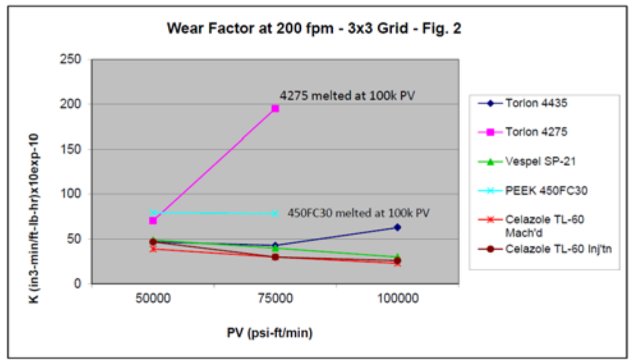
Vespel SP-21 had difficulty with tests at high load and low speed, but performed well at moderate and high speeds despite increasing temperature due to friction. One of the Vespel SP-21 specimens broke during the break-in cycle under the 50,000 PV / 200 fpm condition (250 psi), so a substitute specimen was broken in and introduced to fill this space in the grid. A second specimen broke during testing under the 100,000 PV / 50 fpm condition (2000 psi). The other two specimens completed the 3 x 3 test grid. Wear factors for SP-21 in this 3 x 3 grid were about twice that of the Celazole TL-60 at the lower velocity and measurably higher at the middle and upper velocity conditions. The Vespel SP-21 frictional coefficient was notably higher than Celazole TL-60; therefore, counter-surface temperatures were also higher – by about 50F.

Celazole TL-60 exhibited the lowest wear factors, the lowest coefficients of friction and the coolest counter-surface temperatures of the group. At the highest surface velocity (800 fpm) the differences in counter-surface temperatures were dramatic. Celazole TL-60 ran about 50F cooler than the next lowest material – Vespel SP-21, and about 200F cooler than the highest – Torlon 4275.

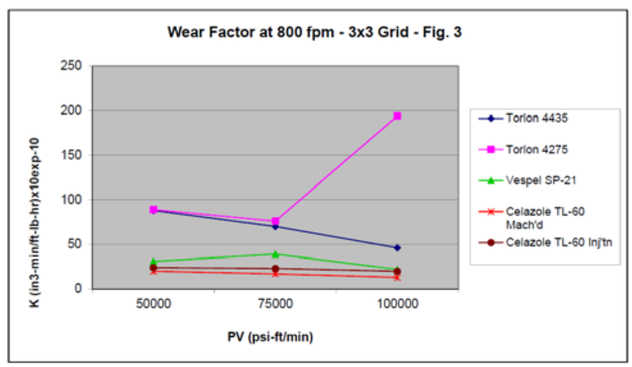
Overall, Machined Celazole TL-60 parts from stock shapes produced almost identical results to the Injection Molded TL-60 parts. At several conditions, the numbers were slightly better for the machined parts, but within the variability seen at the replicate point (+/- 20%) the results were the same. A difference was observed, however, at 800 fpm, where the counter-surface temperatures for Machined TL-60 parts ran about 30F cooler than those coupled with their injection molded cousins. Also, the Injection Molded TL-60 parts showed some slight mushrooming beginning at 1500 psi loading in



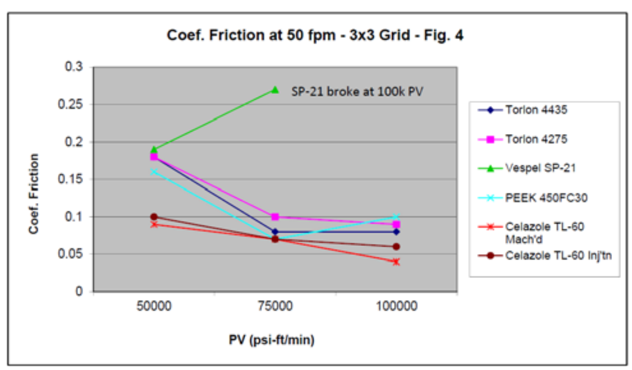
Wear Factor at 50 fpm - 3x3 Grid - Fig. 1



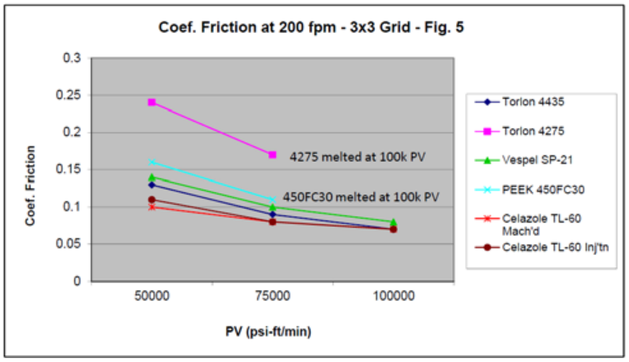
Wear Factor at 200 fpm - 3x3 Grid - Fig. 2

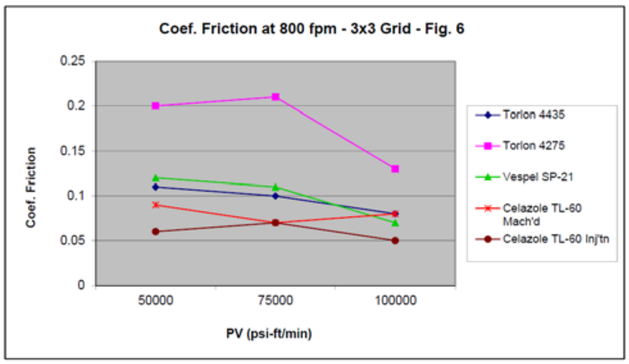


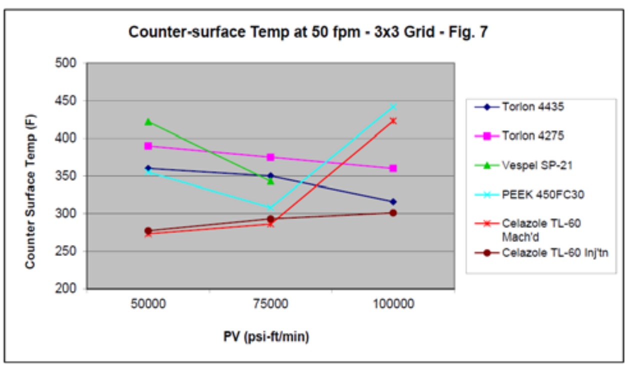
Wear Factor at 800 fpm - 3x3 Grid - Fig. 3

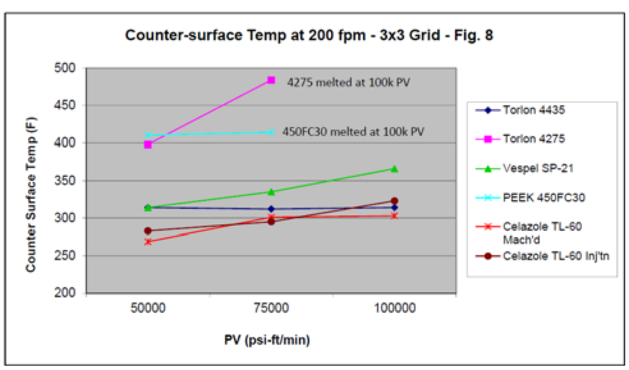


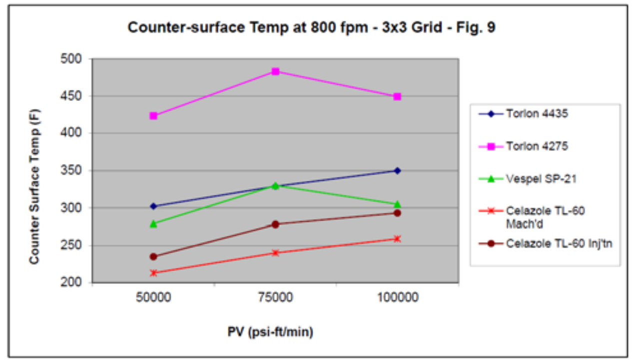
Coef. Friction at 50 fpm - 3x3 Grid - Fig. 4











the 50 fpm tests; whereas, the Machined TL-60 parts from stock shapes did not. The slight mushrooming of the Injection Molded TL-60 parts did not change through 3500 psi. Scanning Electron Microscope images of untested Injection Molded TL-60 parts showed filling fibers horizontal to the thrust surface, supporting a view that filler orientation in injection molded parts could allow mushrooming. Parts with more randomly oriented fibers would benefit from added structural reinforcement.

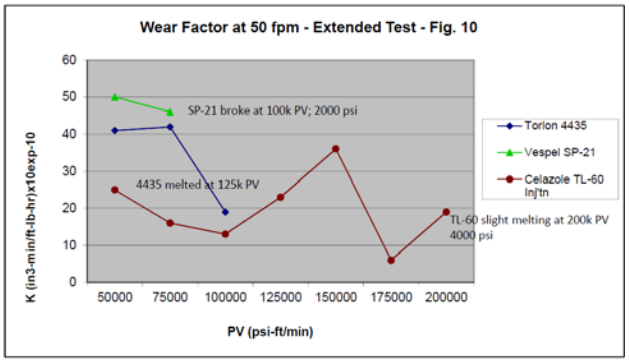
3.2 Extended High-PV Wear Test Results

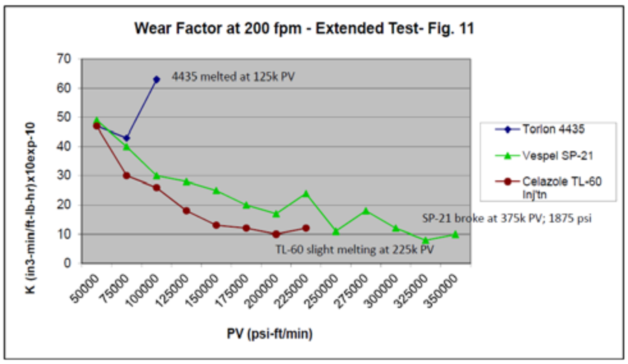
To enable the reader to obtain a more complete understanding of the test results, the wear test data is included in the attached Tables 3, 4 and 5; and Figures 10-18. The reader will find it beneficial to read this discussion in conjunction with these tables and figures.

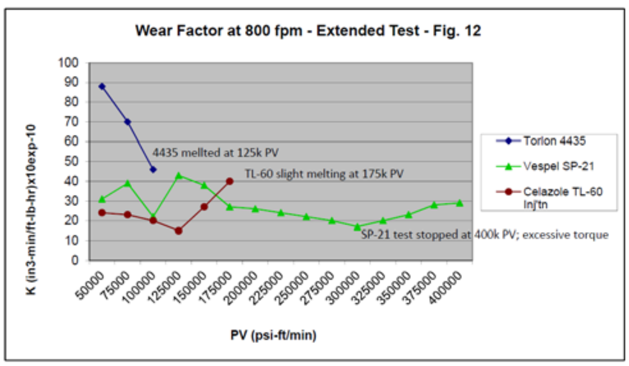
The specimens which were continued to the Extended High-PV grid included: Celazole TL-60 Injection Molded parts from Parkway, Torlon 4435, and Vespel SP-21. Note that the Machined TL-60 parts could have undergone the extended test, but in the interest of efficiency, and because the Injection Molded parts represented the most conservative and critical review of the material, only the Injection Molded TL-60 parts were carried forward. The Torlon 4203L, Torlon 4275 and PEEK 450FC30 did not survive the Initial 3 x 3 grid and therefore, could not be extended.

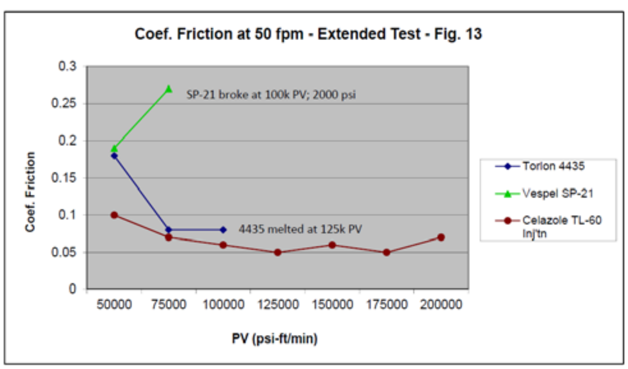
All three Torlon 4435 specimens failed at the first interval beyond the initial 3 x 3 grid at 125,000 PV at all three velocities by melting within the first hour.

Celazole TL-60 continued to do well up to 200,000 PV at 50 fpm, 225,000 PV at 200 fpm, and 175,000 PV at 800 fpm. Without exception, the Celazole TL-60 exhibited the lowest wear factors, the lowest









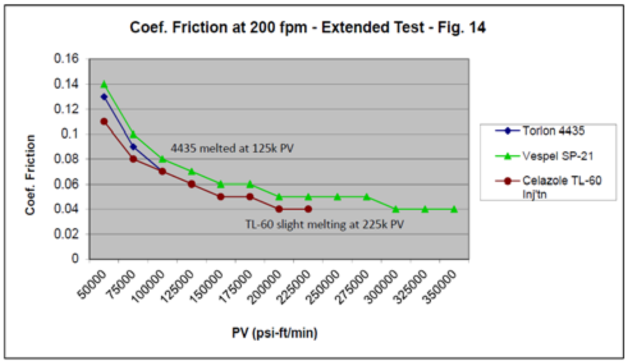
frictional coefficients and the lowest counter-surface temperatures at a given PV throughout the Extended High-PV test, until failure.

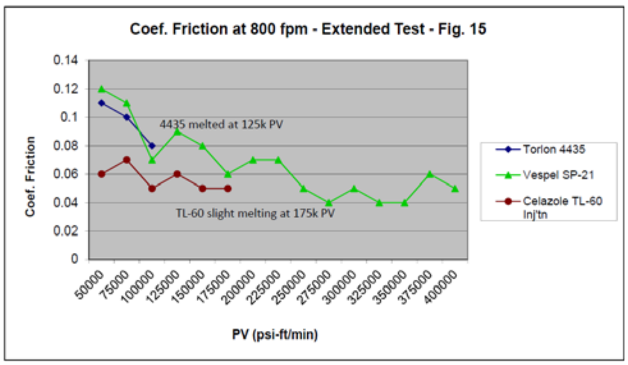
At the 125,000 PV / 50 fpm condition (2500 psi), only Celazole TL-60 survived; all other materials had either broken or melted by this point. Celazole TL-60 not only survived this condition, but went on to 200,000 PV / 50 fpm, a 4000 psi load.

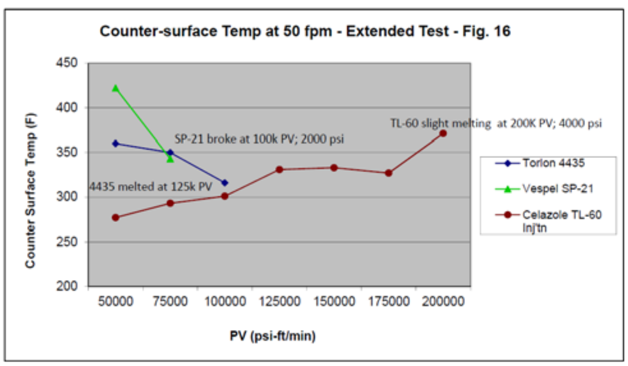
Vespel SP-21 achieved the absolute highest PV in the group. It did very well at high speeds and in fact achieved 400,000 PV at 800 fpm and 350,000 PV at 200 fpm. Above 250,000 PV, the 800 fpm specimen needed help to get started, however. That is, when the test first started the friction was too high for the ¾ hp motor to turn the specimen so the load was partially lifted off the arm until the counter-surface heated enough to drop the friction. This took between 15 seconds and 2 minutes to level out, after which it was stable. This is not unexpected for Vespel SP-21 as its static coefficient of friction at ambient temperature is about 0.3, but drops substantially when the surface temperature reaches 300F.

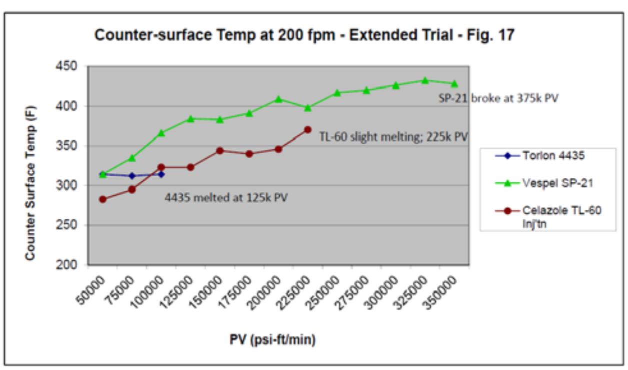
The high velocity (800 fpm) Vespel SP-21 specimen was stopped when the torque within a test became too great for the test machine to maintain the proper speed. The final test condition (400,000 PV/ 800 fpm) duration and wear factor are approximate as the torque became too high during the test and stopped the machine. This duration of this test was limited to about 3 hours.

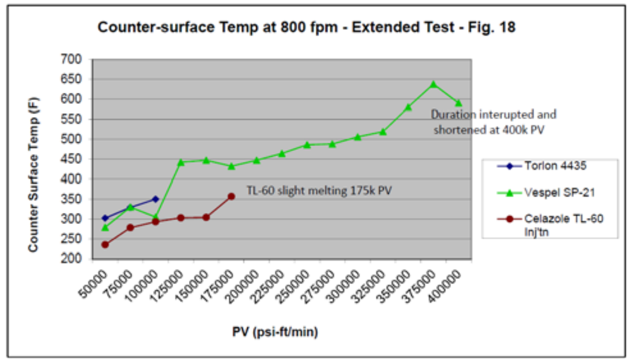
While Vespel SP-21 demonstrated excellent extension of PV range, it consistently demonstrated a high coefficient of friction, high counter-surface temperature, and a high wear rate relative to Celazole TL-60. At any given PV the counter-surface temperatures were higher by about 50F. In the extreme, the counter-surface temperature in the Vespel SP-21 test reached 638F. It is impressive from the standpoint that it ran without melting, but more notable for that fact that the high temperature was induced by its high coefficient of friction. Vespel SP-21 also did not tolerate the high-load/ low-speed conditions as well as Celazole TL-60 since it is inherently lower strength. Compare (ambient) Flexural Strength – 16 ksi for Machined SP-21 vs. 23 ksi for Injection Molded TL-60. This was exhibited by three Vespel SP-21 washer fractures – two in the Initial 3 x 3 grid (250 and 2000 psi) and the third in the Extended grid (at 1875 psi). Had the Vespel SP-21 been Direct Formed, Flexural Strength would be lower still at 12 ksi.











4. Conclusions

1. Injection Molded Torlon 4203L melted due to frictional heat created at PV of 50,000 psi-ft/min; 200 fpm velocity during the break-in cycle, making it ineligible for comparison in this High-PV test. And while Injection Molded PEEK 450FC30 did survive several conditions of the initial 3 x 3 PV grid, its wear factor and counter-surface temperatures were quite high.

2. Injection Molded Torlon 4275 performed reasonably at low velocity (50 fpm) for the initial 3 PV's: 50,000; 75,000 and 100,000; however, it generated a significant amount of heat and the wear rate was high in comparison with the rest of the field.

3. Injection Molded Torlon 4435 reached a PV of 100,000 psi-ft/min (for all three velocities) – which is high for most engineering plastics; however, its wear rate was measurably higher than the best. At PV's of 50,000 and 75,000 with surface velocities of 50 and 200 fpm its wear factor was about equal to Vespel SP-21. Its wear rate was very high at 800 fpm. Beyond 100,000 PV (at all three velocities) it melted.

4. Interestingly, all three Torlon materials and PEEK 450FC30 failed by melting, yet the highest counter-surface temperatures recorded prior to melt and/or destruction were well below the test specimen's respective melt points. Therefore it should be noted that the counter-surface temperature recorded may not reflect the peak temperature of the specimen at the time of failure. Also, the samples are under considerable load, so damage can be expected to occur much nearer to the glass transition temperature. So, while these materials failed relatively early in this test as compared with SP-21 and TL-60, they are known wear grade materials and their widespread use in lower PV situations

As an illustration of what the thrust washers look like after completing a segment of the test grid, a photo was taken of each of the test specimens upon completing their final run at the 200 fpm (middle velocity) condition. This is the failure PV condition for these specimens at 200 fpm.

Torlon 4435 -- melted at 125K PV (200 fpm)

Torlon 4275 – melted at 100K PV (200 fpm)

Vespel SP-21—broke at 375K PV (200 fpm)

PEEK 450FC30 – melted at 100K PV (200 fpm)

Celazole TL-60 – slight melt at 225K PV (200 fpm)

Torlon 4203L – melted during break-in at 50K PV (200 fpm)

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indicates they provide value in less demanding applications.

5. Machined Vespel SP-21 was capable of the highest operating PV's of the group; reaching a PV of 400,000 psi-ft/min. The final condition, 400,000

PV / 800 fpm had to be stopped, however, as the torque became too high to maintain the speed. SP-21's wear rate and counter-surface temperatures were not all that low, however. In fact, Vespel SP-21's counter-surface temperature typically ran 50F hotter than Celazole TL-60 and wear rates were frequently 50-100% higher than TL-60 at any given condition. Vespel SP-21 was also prone to failure under load as exhibited by washer fractures at 250, 1875 and 2000 psi. It did best with low loads and was the only survivor beyond a PV of 225,000 psi-ft/min.

6. Celazole TL-60 is an exceptional wear grade material reaching a PV of 225,000 psi-ft/min at 200 fpm. It exhibited the lowest wear factors, the lowest coefficients of friction and the lowest counter-surface temperatures of the group. At the highest surface velocity (800 fpm) the differences in counter-surface temperature were dramatic; as it ran about 50F cooler than the next lowest material – Vespel SP-21, and about 200F cooler than the highest – Torlon 4275. The value of low operating temperature should not be discounted, since the temperature of a bearing surface frequently determines the PV limit as long as mechanical strength is sufficient. And since engineering plastics lose strength with increasing temperature, it frequently comes back to this point.

7. Choice of a bearing material requires a match between the conditions of the application and the attributes of subject materials. And as the empirical evidence within this study shows, it is not sufficient to look only at PV. It is important to consider wear rate, operating temperature and strength requirements. And when looking at PV, both the velocity and pressure components should be considered because some materials are better at high speed/ low load and vice versa. Opening one's mind to consider all the repercussions will result in the best material choice.

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