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Polytetraflouroethylene Thin Coatings For Tribological Applications

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POLYTETRAFLOUROETHYLENE THIN COATINGS FOR TRIBOLOGICAL APPLICATIONS

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ABSTRACT

Mechanical components with lower coefficients of friction decrease the amount of energy dissipated by the system due to friction. Coating these components would decrease the coefficients of friction between surfaces without sacrificing the strength of the components. A polytetrafluoroethylene (PTFE) layer adhered through a polydopamine (PDA) layer on a steel substrate will reduce the coefficient of friction on the substrate surface. This paper discusses different methods for attempting to increase the uniformity of the PDA layer as well as decrease the PDA coating time. Methods for increasing uniformity include using a particle disperser instead of a magnet stir rod, changing the orientation of the coating surface in the solution, and changing the position of the coating surface in the solution. The PDA deposition time was decreased by increasing the temperature of the PDA solution. After applying the PDA layer onto the steel substrate, a PTFE layer was applied to the steel substrate by dipcoating. The different samples were tested for coefficient of friction and durability cycles. The method for the most uniform PDA distribution as well as highest durability of PDA/PTFE coating was the steel substrate that was in PDA solution at 90°C mixed with a particle disperser spinning at 2800 rpm for 6 hours. This sample yielded an average coefficient of friction of 0.0950 and lasting and average of 512 cycles under a 15 N normal load.

ACKNOWLEDGEMENTS

I would like to thank my research mentor, Dr. Min Zou, for her enduring support and guidance throughout my research and writing process. Thank you for providing a state-of-the-art lab and equipment that made this research project a reality. This project would not have come together were it without your direction and counseling.

To Dr. Samuel Beckford, thank you for personally training me on the technical lab equipment, explaining complicated concepts of this research, helping design experiments, and answering my questions about all aspects of the research.

To my thesis committee, thank you for taking the time out of your busy schedules to serve on my thesis defense committee.

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1. Introduction

Thin layers of a low friction coating are desirable particularly for machine components. Engines, for example, have numerous moving parts that incur friction. This friction results in an energy loss. Lowering the friction in a system such as an engine would increase the efficiency. Coatings can maintain the bulk material properties of a substrate while changing its surface properties. Polytetraflouroethylene (PTFE) is a desirable coating material because of its low coefficient of friction. However, due to its non-stick property, PTFE is also difficult to be coated onto substrate surfaces and therefore a powerful adhesive is needed. PTFE is also easily worn away which affects the durability of its thin coatings.

Dr. Zou's group of the Department of Mechanical Engineering has done prior research on developing low friction and wear resistant thin PTFE coatings. It was found that applying the PTFE coating on a stainless steel substrate reduced the coefficient of friction (COF) from 0.9 to around 0.06. However, this coating failed after about only 100 cycles under the controlled testing conditions. A polydopamine (PDA) adhesive layer was then used between the PTFE and substrate to enhance the adhesion of PTFE coating to the substrate surface (figure 1.1). The results showed that the PDA/PTFE coating lasts over 5000 cycles while under the same test condition as the previous experiment.

Figure 1.1. Cross sectional area view of film deposition.

However, the distribution of the PDA coating on the substrate surface at the macroscopic level is non-uniform. In particular, this non-uniformity is a consistent swirl pattern. This presents a problem for adhering PTFE film on the substrate uniformly. The coating will wear down at the location of most

thin PTFE coating. Although the PTFE coating will perform according to the data previously provided, this is only in the ideal case of a PTFE coating layer thick enough on the substrate. The coating will not perform well if the layering is too thin. Also, excess coating will be wasting material. Uniform coating would provide the substrate with a thick enough layer to reduce friction as well as not waste material.

With current procedures, the PDA coating time takes 24 hours for the proper amount of PDA to be deposited onto the substrates. The PTFE coating takes approximately 30 minutes to deposit and heat treat. If this frictionless PTFE coating is to be adopted by an industry, a time reduction in the process would be a desirable aspect. Previous research claims an inverse relationship between the temperature of the solution and the time required to deposit PDA onto a substrate [1].

My honors thesis project will be a continuation and expansion of this research focusing on improving PDA coating uniformity on the substrate and shorten the time required to deposit PDA. Through various experiments and testing procedures, I will identify an effective way to coat substrates uniformly as well as reduce the process time without sacrificing PDA coating thickness.

2. Experimental Details

The following procedures are based on the cleaning, PDA application, PTFE application, and friction testing procedures used in the work presented by Beckford et al. [2 - 4]. The alteration to these procedures is the use of a particle disperser, volumes of PDA solution, and the amount of applied normal load during friction testing. The full list of equipment used can be found in the appendix.

2.1 Cleaning Substrates

A large beaker was partially filled with reverse osmosis (RO) water and liquinox soap to make a 1% solution by volume heated to 60°C. Samples with the protective film peeled off were placed on a plastic tray and submerged into the solution. The beaker was then placed in the sonicator for 20 minutes. The solution was then poured down the sink and the beaker and samples were rinsed with RO water. Then beaker was then filled with acetone until the samples were completely covered. This was

ran in the sonicator for 20 minutes. This solution was then disposed of in a proper container and isopropyl alcohol was poured in the beaker until the samples were completely covered. This solution was ran for 5 minutes. The samples were rinsed with deionized (DI) water and dried with nitrogen gas before being stored in petri dishes.

2.2 Applying PDA

A 400 mL beaker was filled with 200 mL of DI water mixed with 0.242 grams of Trizma base. Substrates were inserted into the solution to where most of the sample was submerged. After reaching a predetermined temperature, 0.400 grams of dopamine hydrochloride were added to the solution. PDA application and apparatus setup can be seen in figure 1.2. Some experiments with larger steel substrates used the same 400 mL beaker but used 350 mL of DI water mixed with 0.4235 grams of Trizma base and 0.7000 grams of dopamine hydrochloride. The following experiments will identify which volume of solution was used. After a predetermined amount of time, samples were extracted from the solution. Excess PDA was removed from the substrates by being sonicated in DI water for 10 minutes, rinsed with DI water, and dried with nitrogen gas. Variables considered during experiments included position and orientation of substrate surfaces with respect to the mixer and beaker walls, type of solution mixing method, temperature of the solution, and submersion time for substrates in the solution.

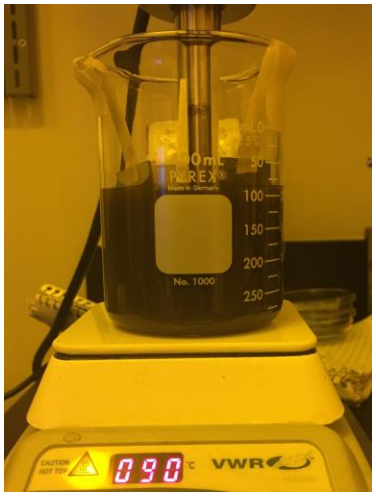


Figure 1.2. PDA application on 3 large samples at 90°C.

2.3 Applying PTFE

After a sample has been coated in PDA, the PTFE coating process should begin within a few hours. Once the sample is coated in PDA, it is susceptible to contamination. The sample is coated with PTFE by using the dip coater. The sample is clipped into the stem of the dip coater. The program is run by KSV Nima (figures 2.1 – 2.2). It lowers the stem with the attached steel sample into a liquid PTFE solution and raises the sample back out. The samples are then allowed to dry, heated on a hot plate at 120°C for 3 minutes, heated in an oven at 300°C for 4 minutes, heated in a different oven at 372°C for 4 minutes, then allowed to cool to room temperature.

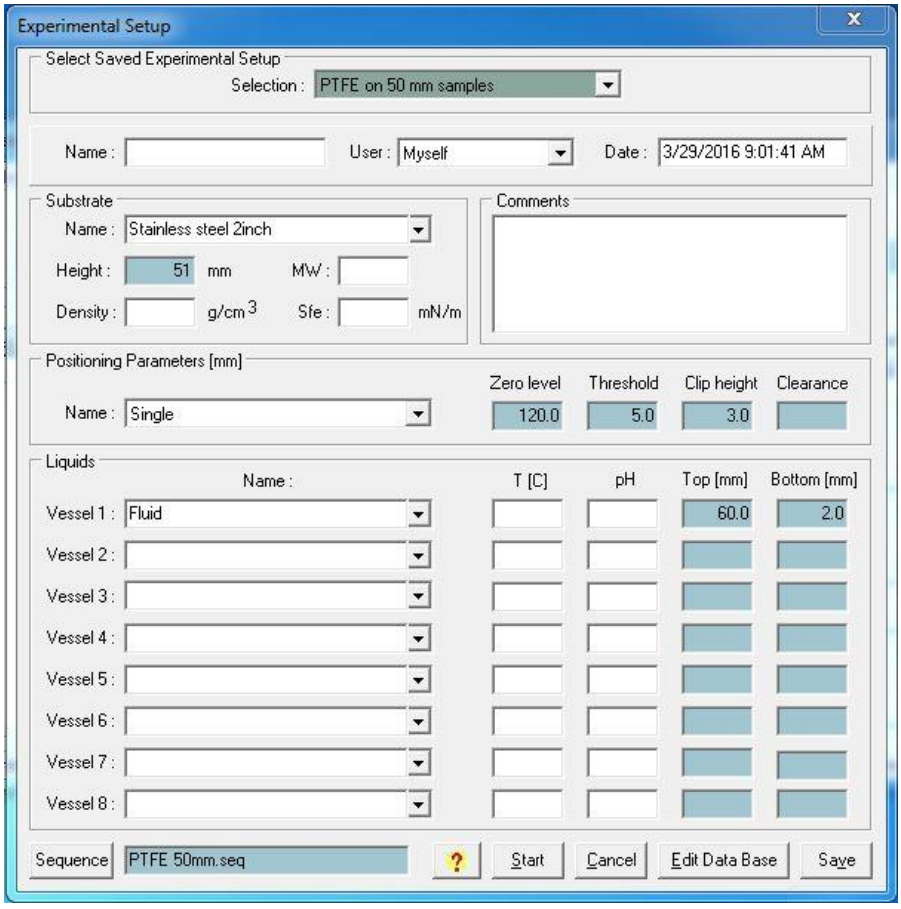


Figure 2.1. Program setup for dipcoating steel substrates into PTFE.

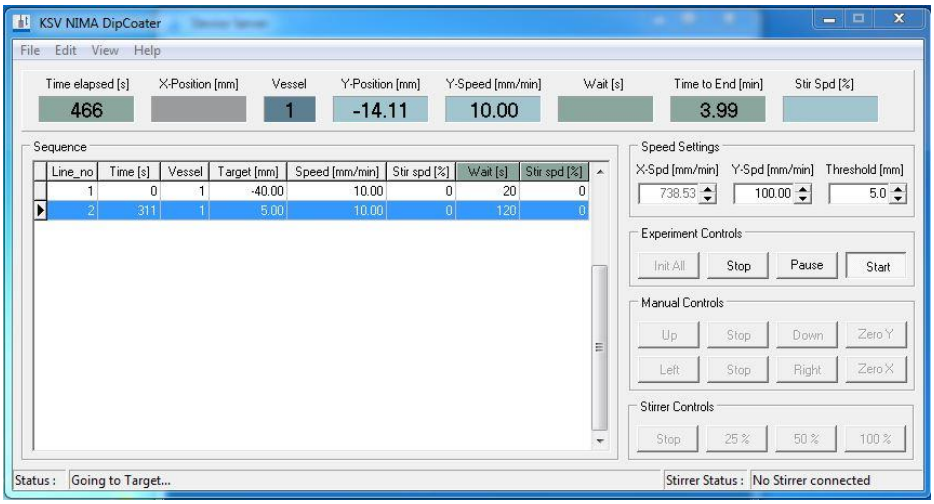


Figure 2.2. Running program screen output during dipcoating.

2.4 Friction Testing

The machine used to measure the coefficient of friction of the sample surface is a Bruker Nano Surfaces UMT (figure 2.3) with CETR UMT software (figures 2.4 – 2.5). A sample coated in PDA and PTFE was placed on the stage of the UMT. A steel ball placed on the upper unit will rub the sample. The steel balls are cleaned with the same procedure used to clean the samples before PDA coating. The upper unit would lower onto the sample with 15 N of applied load. Once the normal load is stabilized, the upper unit will move along a linear trajectory. The programmed path for the upper unit is to move 15 mm at 10mm/s with a 0.1s delay between cycles. This yields a 3.1s cycle time.

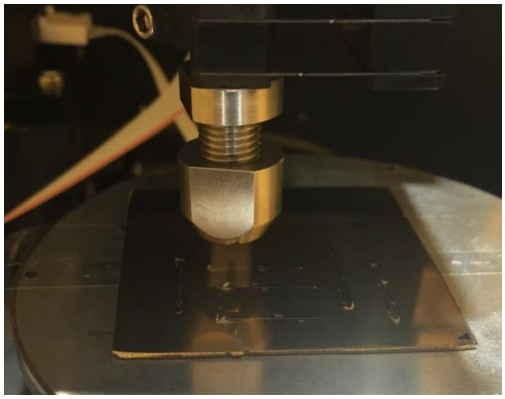


Figure 2.3. Close up of UMT testing apparatus with sample underneath ball.

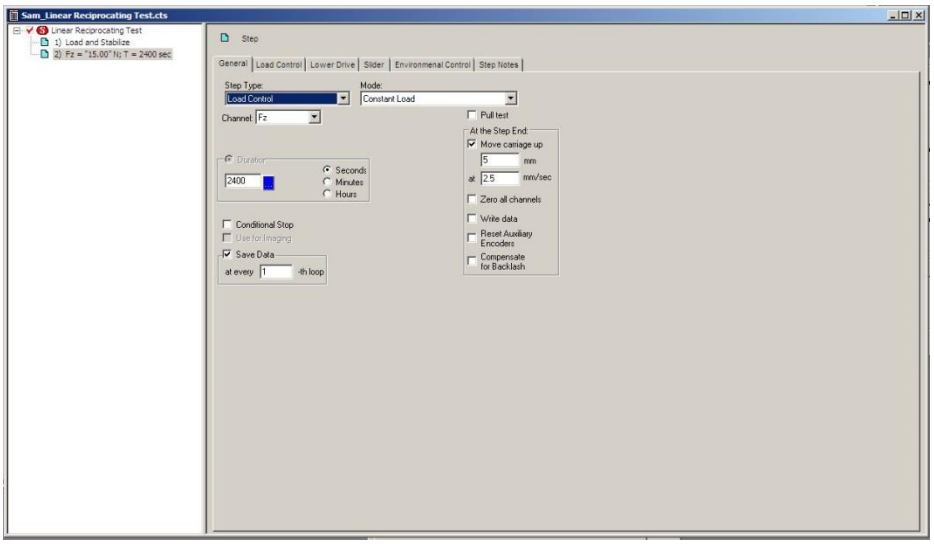


Figure 2.4. Program file for friction testing.

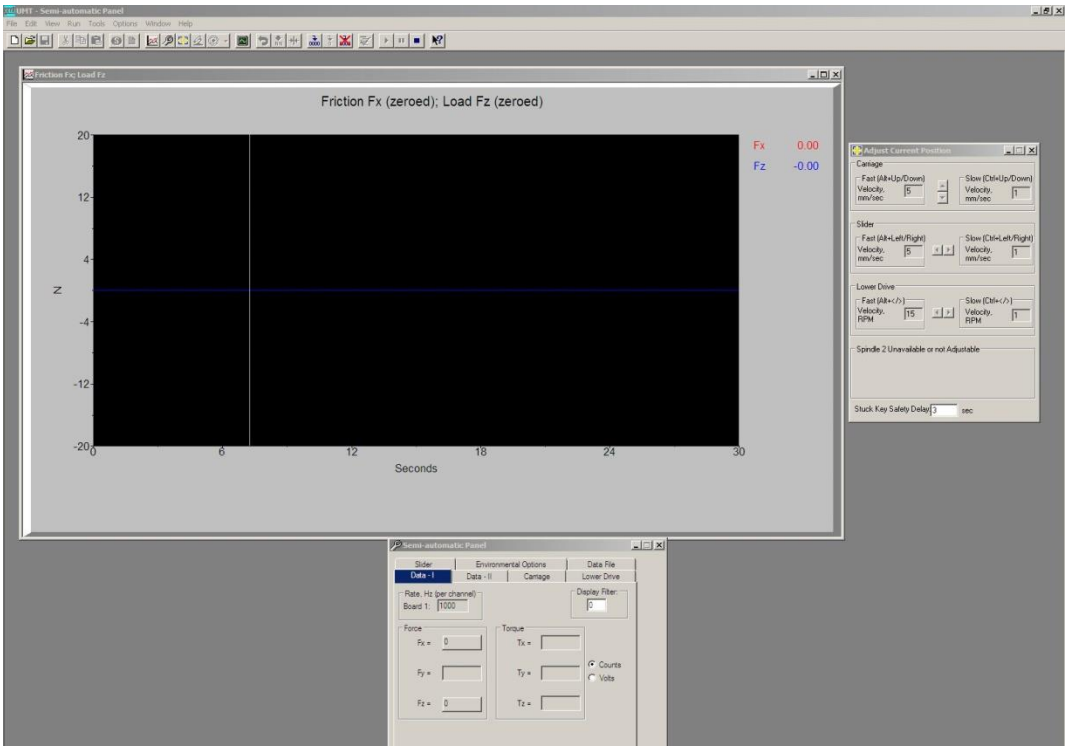


Figure 2.5. Software interface for friction testing.

3. Results

3.1 Position and orientation

The geometry of the most uniform distributive system was explored with the particle disperser. Different size beakers and substrate orientations were variable with 1 hour long tests. The shorter tests

showed the distribution of the PDA and how it would develop without a microscope. The particle disperser details are shown in figure 3.1.

Figure 3.1. Particle disperser schematic. (a) side view of particle disperser and fluid flow, (b) top view of particle disperser and fluid flow.

The variation of beaker size affected the distance between the substrate and particle disperser. It was found that more PDA was deposited onto a substrate if the distance between the particle disperser stem and the substrate was increased. The distribution of the PDA on the substrates close to the particle disperser yielded an obvious swirl pattern as seen in figure 3.2. The sample in figure 3.2 used 40 mL of DI water, 0.0484 grams of Trizma base, and 0.0800 grams of dopamine hydrochloride.

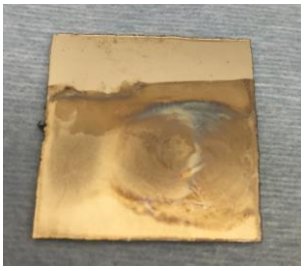


Figure 3.2. Substrate close to particle disperser during PDA application. Substrate with central swirl pattern.

The orientation of the substrate was either such that the substrate surface directly faced the particle disperser or faced the beaker wall. This was to determine if a close proximity to the disperser could be achieved without shearing off the PDA. This method proved to not be useful because the PDA deposited resulted in a non-uniform, speckled pattern as seen in figure 3.3. The sample in figure 3.3 used 40 mL of DI water, 0.0484 grams of Trizma base, and 0.0800 grams of dopamine hydrochloride.

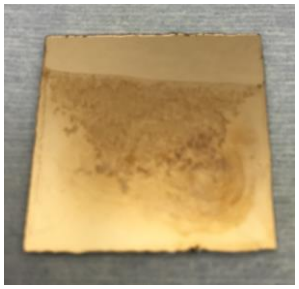


Figure 3.3. Substrate surface facing away from particle disperser. Substrate with speckled and swirl pattern.

3.2 Mixing Methods

Mixing methods considered were that with a magnet stir rod, an immediate stir, and a particle disperser. The magnet stir rod has been the method used in previous research by Dr. Zou's lab and can be seen as the control for this set of experiments.

The magnet stir rod experiments yielded consistent results with what Dr. Zou's previous work. The swirl in figure 3.4 demonstrates the PDA coating distribution in this experiment. There is a visible slope at the upper left corner of the PDA on the substrate as well as a speckled distribution on the right side of the substrate. The sample in figure 3.4 used 200 mL of DI water.

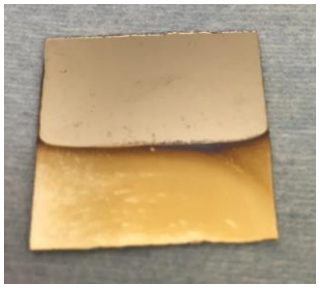


Figure 3.4. PDA deposited onto substrate with magnet stir rod.

The immediate stir experiment evaluated how PDA would apply to a sample without constantly stirring the solution. In order to ensure the dopamine hydrochloride completely dissolved, the solution was stirred until no more dopamine hydrochloride particles could be identified. This experiment showed a speckled pattern and did not achieve uniformity as seen in figure 3.5. This suggests that stirring is needed for proper PDA deposition. The sample in figure 3.5 used 40 mL of DI water, 0.0484 grams of Trizma base, and 0.08 grams of dopamine hydrochloride.

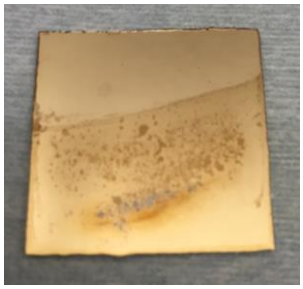
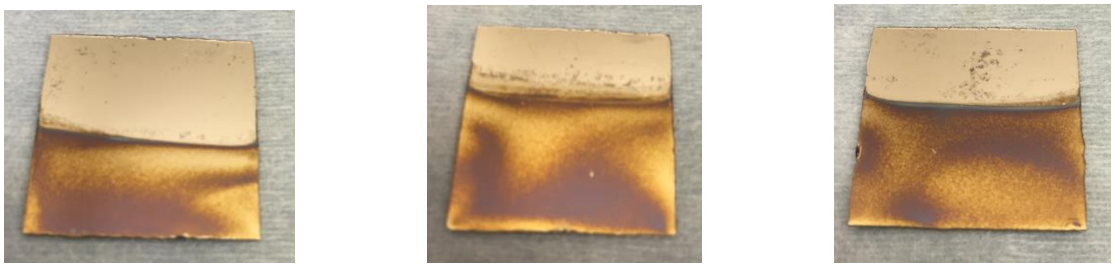


Figure 3.5. Speckled pattern seen at the top of the PDA layer on the substrate for immediate stir test.

The particle disperser with the 400 mL beaker with the substrate surface of interest facing the disperser stem yielded the most PDA as seen in figure 3.6. There is not an apparent swirl pattern, but there is a distinct non-uniformity that is different for each sample. The samples in figure 3.6 used 200 mL of DI water.



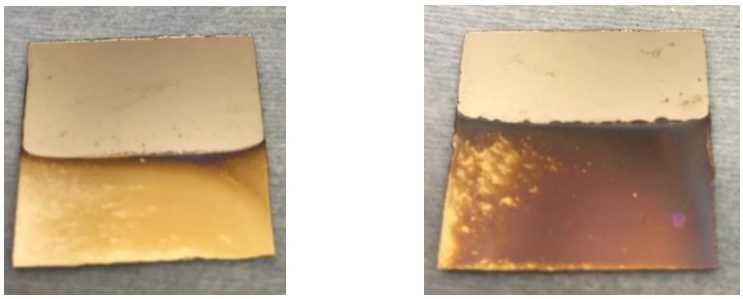
(a) (b) (c)

Figure 3.6. Particle disperser samples. (a), (b), and (c) are from the same test.

3.3 Temperature

An increase in temperature was expected to decrease the required time needed to deposit a sufficient amount of PDA.

Environments at 60°C could deposit more PDA than environments at room temperature. This was shown in both the magnet stir rod apparatus and the particle disperser apparatus. Figure 3.7 shows samples from the magnet stir rod test; one with a heated solution and one at room temperature. Figure 3.8 shows samples from the particle disperser experiments; one with a heated solution and one at room temperature. All samples were kept in 200 mL of solution for 12 hours. A darker PDA deposit suggests that more PDA is present.



(a) (b)

Figure 3.7. Magnet stir rod samples with 6 hour submersion time. (a) solution kept at room temperature and (b) solution heated to 60°C.

(a) (b)

Figure 3.8. Particle disperser samples. 6 hour submersion time. (a) solution kept at room temperature and (b) solution heated to 60°C.

The solution was then heated to 90°C for PDA deposition. In order to see the effect of PDA application dependent on time, samples were extracted from the solution every 2 hours. Once again, an increase in temperature shows a faster deposition of PDA. Figure 3.9a shows only a light colored layer that grows darker until figure 3.9c. Afterwards, the coating begins to fade in color. The figures 3.8b and 3.9c show similar coating color but the difference between the two is 3 hours of time and 30°C of temperature in the solution. The edge of the coating in figures 3.9d – 3.9f shows a distinct non-uniformity due to the evaporation of the solution. The solution could have evaporated in the later times because of a leak in the seal of the system.

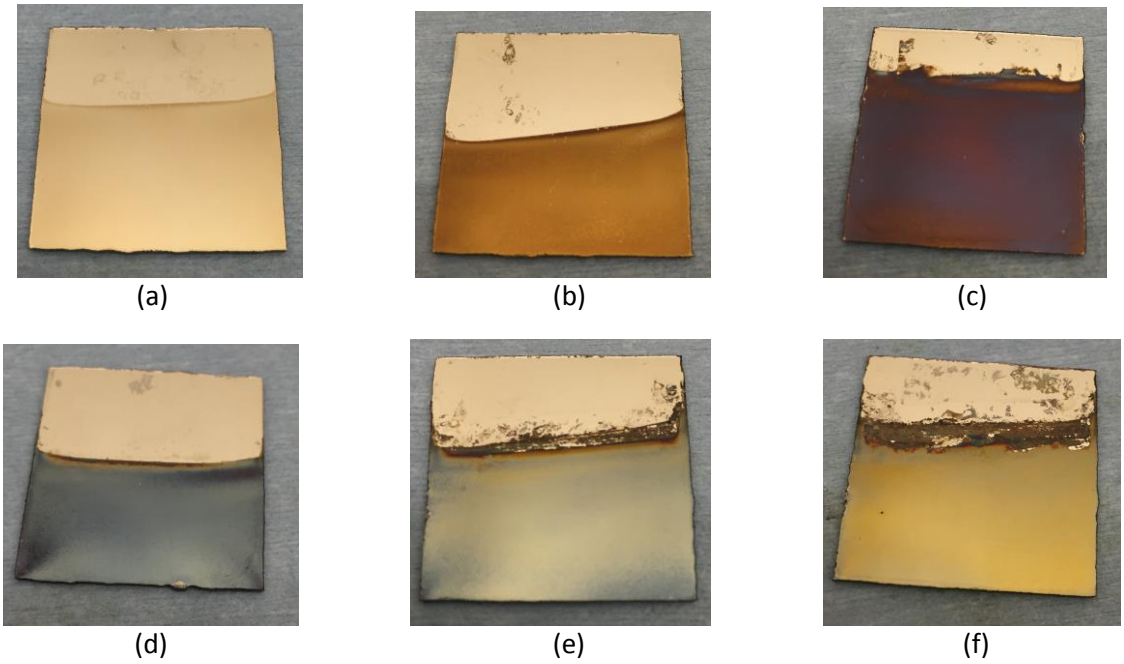


Figure 3.9. Samples with solution at 90°C. (a) 2 hour deposition. (b) 4 hour deposition. (c) 6 hour deposition. (d) 8 hour deposition. (e) 10 hour deposition. (f) 12 hour deposition.

3.4 Sample Size

The surfaces of experimentation so far in this paper have been 1 in. X 1 in. Since the end goal of the research is beyond small surfaces, it must be shown that the method of PDA coating can apply to larger surfaces as well. A 2 in. x 2 in. surface of the same material was used for a trial of 6 hours. The purpose of this experiment was to replicate the uniformity and color of figure 3.9c even though the surface size changed. Figure 3.10 shows that the color of the PDA coating is similar to figure 3.9c outside of the light colored patches. These patterns are due to the proximity of the surfaces and the disperser outlet. This pattern was not present in the smaller samples because they were not submerged as far as the large samples were.

(a) (b)

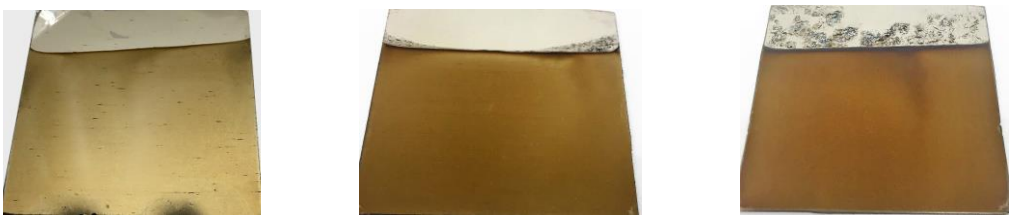
Figure 3.10. Large samples in solution at 90°C. (a) and (b) are from the same test.

In order to increase uniformity on the large samples, the vertical distance was increased between the bottom of the sample and the discharge of the particle disperser. This was achieved by adding a larger volume of solution to the same beaker. This yielded the samples in figure 3.11. The color is not as dark as previous samples because the temperature of the PDA solution was lower due to a larger volume and mass of solution that had to be heated.

(a) (b) (c)

Figure 3.11. Large samples in solution at 90°C. (a) 4 hours in solution, (b) 6 hours in solution, and (c) 8 hours in solution.

The PDA solution is heated in order to accelerate the PDA deposition. The apparatus for a larger amount of solution was adjusted by insulating the beaker of solution and allowing a longer pre-heat time for the buffer solution. Repeating the above experiment with the adjusted experimental apparatus yields figure 3.12. The color of each sample is darker for each correspondent to figure 3.11. This indicates more PDA deposited on the surface.



(a) (b) (c)

Figure 3.12. Large samples in solution at 90°C with insulation. (a) 4 hours in solution, (b) 6 hours in solution, (c) 8 hours in solution.

3.5 Friction Test Results

The samples from figure 3.12 were each coated in PTFE and friction tested. Each sample was tested six times. Three tests ran parallel to the polish lines of the steel substrates; the other three tests ran perpendicular to the polish lines. A picture of each test result image, 3-D image, and steel ball can be found in figures 3.13 – 3.17. The ball rubbing on the sample during friction testing shows a wear track. Each sample shows the center wear track is the lowest area on the sample. Just outside the center wear track, the surface raises up. The outer wear track is shown to be slightly lower than the area outside of the wear track. The center wear track shows penetration through the PDA/PTFE coating to the steel substrate itself. The 3-D images show the contour of the wear track and delamination of the PTFE coating. The scratches on the steel balls show different scratch patterns and the removal of the PDA/PTFE coating from the steel substrate and onto the ball.

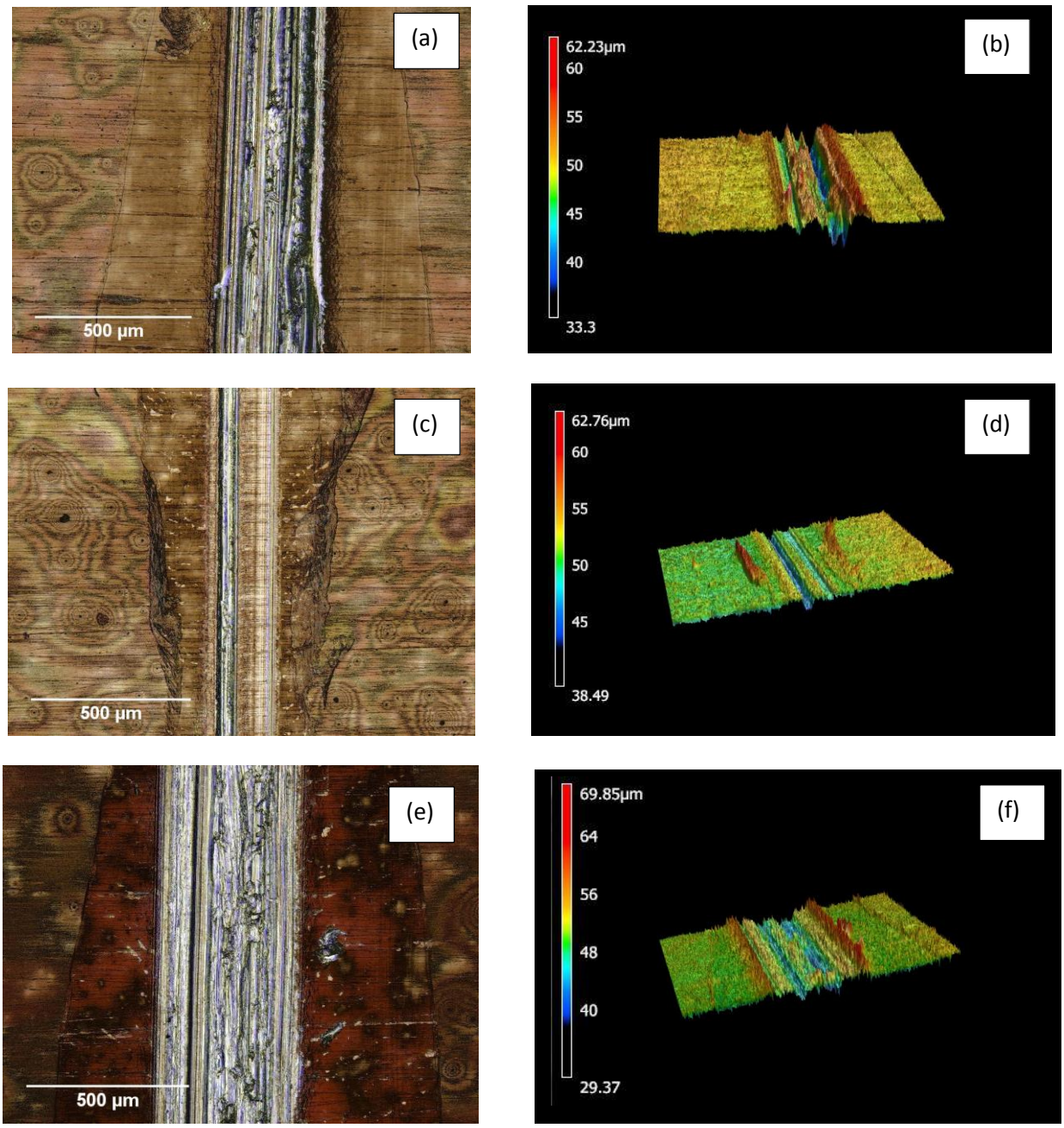


Figure 3.13. Samples heated at 90°C and friction tested perpendicular to polish lines with a 15 N normal load. (a) image of 4 hour sample (406 cycles), (b) 3-D image of 4 hour sample, (c) image of 6 hour sample (546 cycles), (d) 3-D image of 6 hour sample, (e) image of 8 hour sample (258 cycles), (f) 3-D image of 8 hour sample.

Delamination of the PTFE coating only appears in figures 3.13b and 3.13c. This delamination is shown in the optical image as dark material in the outer wear track and as a raised surface in the 3-D image. In figure 3.13e, the PDA/PTFE coating wore off in both the center wear track and the outer wear

track. This removal of PDA/PTFE coating in the outer wear track can be seen to begin developing in figure 3.13c.

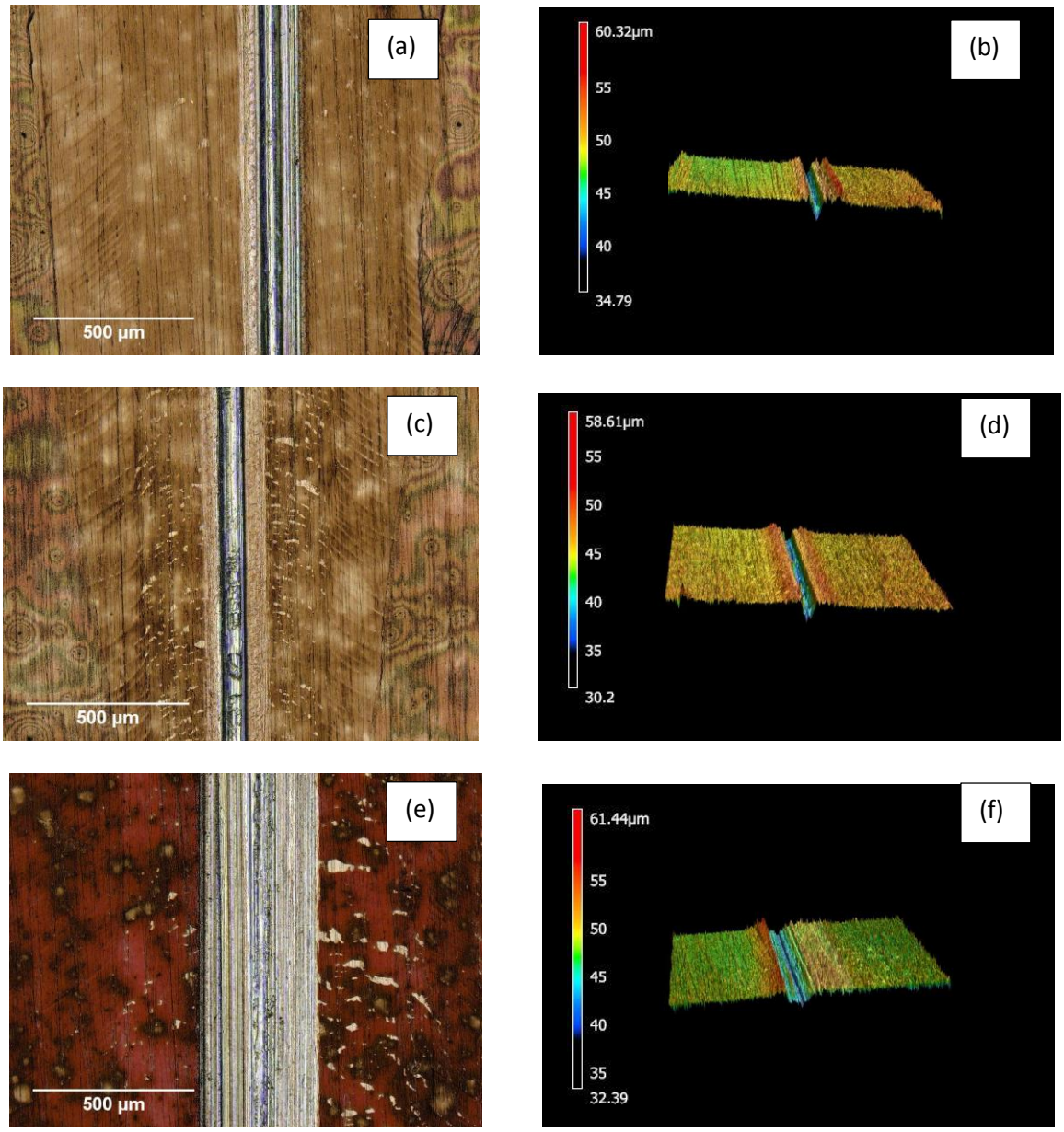


Figure 3.14. Samples heated at 90°C and friction tested parallel to polish lines with a 15 N normal load. (a) image of 4 hour sample (55 cycles), (b) 3-D image of 4 hour sample, (c) image of 6 hour sample (41 cycles), (d) 3-D image of 6 hour sample, (e) image of 8 hour sample (46 cycles), (f) 3-D image of 8 hour sample.

Delamination of the PTFE coating is only apparent in figure 3.14a. The detachment of the PDA/PTFE coating in the outer wear track can be seen in figure 3.14e and developing in figure 3.14c.

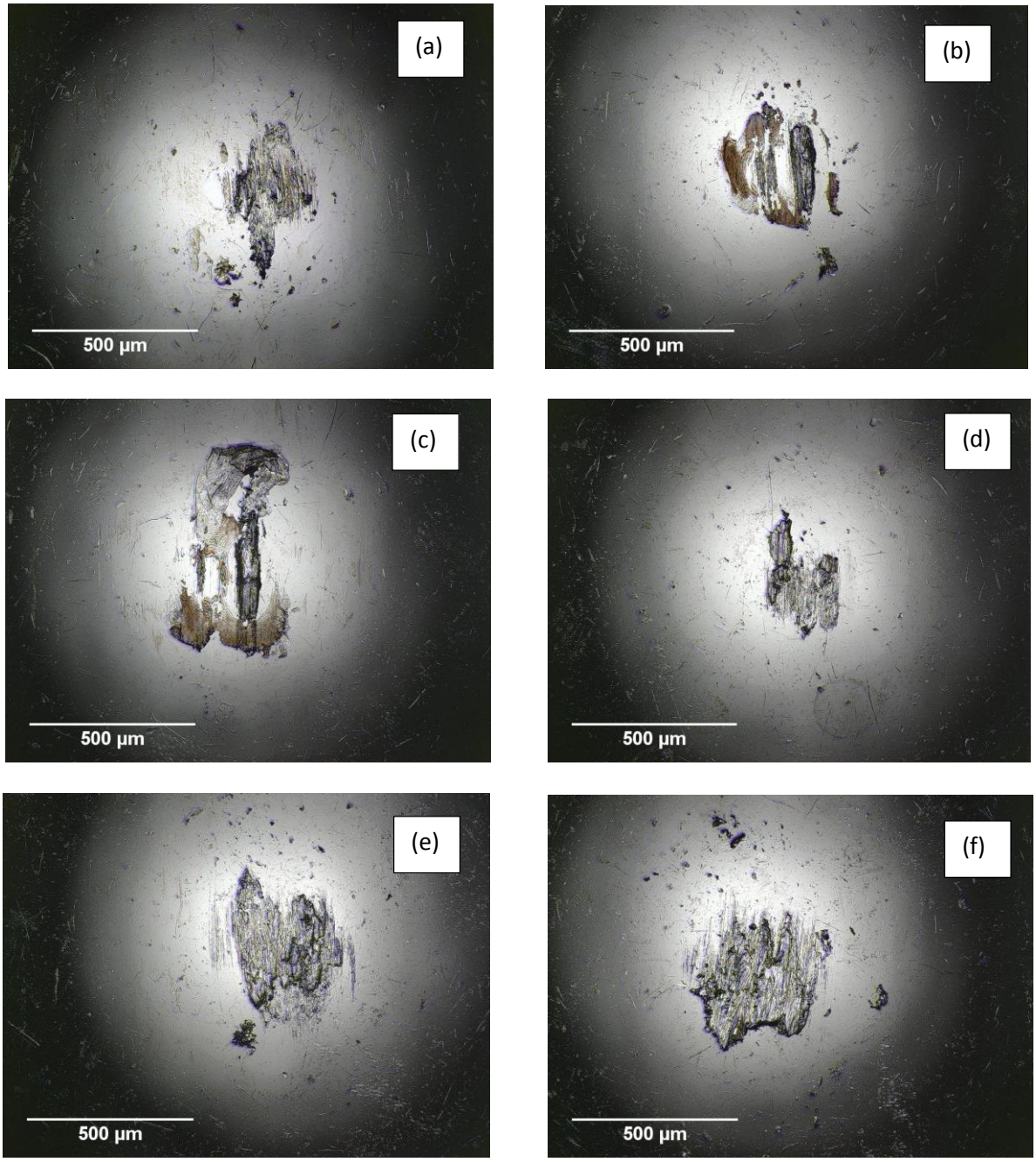


Figure 3.15. Steel balls used to friction test the samples in figures 3.13 and 3.14. (a) ball used on 4 hour sample perpendicular to polish lines, (b) ball used on 4 hour sample parallel to polish lines, (c) ball used on 6 hour sample perpendicular to polish lines, (d) ball used on 6 hour sample parallel to polish lines, (e) ball used on 8 hour sample perpendicular to polish lines, (f) ball used on 8 hour sample parallel to polish lines.

The scratches on the steel balls correspond to scratches on PDA/PTFE coated substrates in figures 3.13 – 3.14. The scratch patterns differ in width and amount of PDA/PTFE coating adhered to the steel ball.

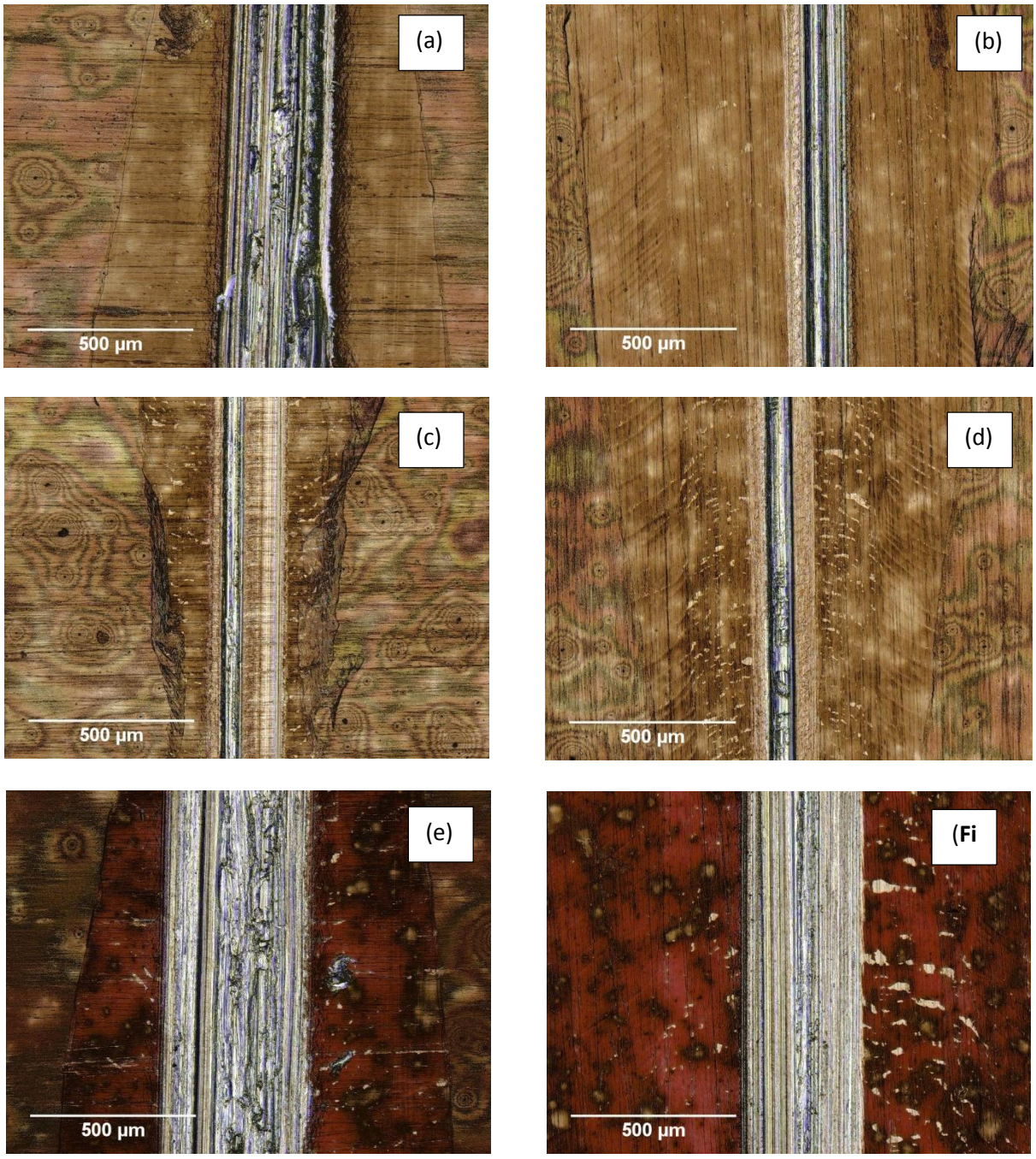


Figure 3.16. Samples heated to 90°C and friction tested with a 15 N normal load. (a) friction testing perpendicular to polish lines on 4 hour sample (406 cycles), (b) friction testing parallel to polish lines on 4 hour sample (55 cycles), (c) friction testing perpendicular to polish lines on 6 hour sample (546 cycles), (d) friction testing parallel to polish lines on 6 hour sample (41 cycles), (e) friction testing perpendicular to polish lines on 8 hour sample (258 cycles), (f) friction testing parallel to polish lines on 8 hour sample (46 cycles).

For friction testing both parallel and perpendicular to the polish lines, the PDA/PTFE coating in the outer wear track begins to wear off in samples in PDA solution for 6 hours (figures 3.16c – 3.16d) and shows a progression of that wear in samples in PDA solution for 8 hours (figures 3.16e – 3.16f).

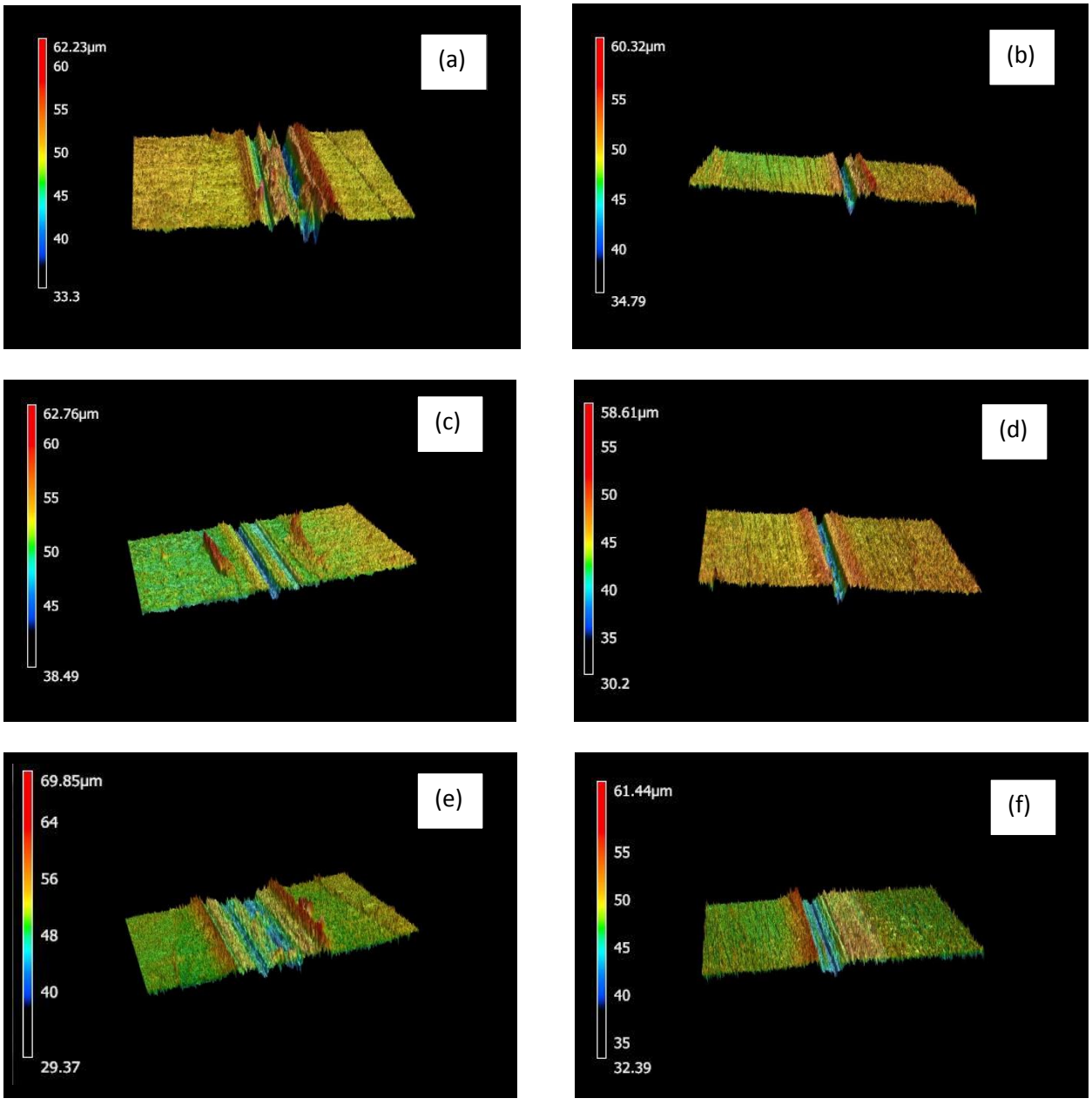


Figure 3.17. 3-D images of the friction tests found in figure 3.16. (a) friction testing perpendicular to polish lines on 4 hour sample, (b) friction testing parallel to polish lines on 4 hour sample, (c) friction testing perpendicular to polish lines on 6 hour sample, (d) friction testing parallel to polish lines on 6 hour sample, (e) friction testing perpendicular to polish lines on 8 hour sample, (f) friction testing parallel to polish lines on 8 hour sample.

The 3-D images in figure 3.17 all show the center wear track as the lowest area of the scratched substrate and the raised edge between the center wear track and the outer wear track. This topography is consistent for both samples friction tested parallel and perpendicular to the polish lines.

The detachment of PDA/PTFE coating on the outer wear track of samples is due to the fact that the PDA will form aggregate particles if the sample is left in solution for too long. The aggregate particles have lower adhesion to the steel substrate than a uniform PDA coating. The ideal PDA coating will have enough thickness without aggregate particles.

The optical images and 3-D images for the wear tracks for the friction tests parallel and perpendicular to the polish lines look similar but the test results are significantly different. The higher durability found when the friction tests are perpendicular to the polish lines is because the polish lines keep the PDA/PTFE coating less susceptible to shearing away. When the friction test is parallel to the polish lines, the PDA/PTFE coating is sheared away faster and will not last as many cycles as the perpendicular tests.

The normal force and friction force were recorded by the testing software every 0.1s. A coefficient of friction was then calculated based on their ratio. Figures 3.18 – 3.23 show the coefficient of friction vs time for the various friction tests. All of the tests had the same programmed normal load of 15 N, rubbing speed of 10 mm/s, rubbing length of 15 mm, and delay time of 0.1 s.

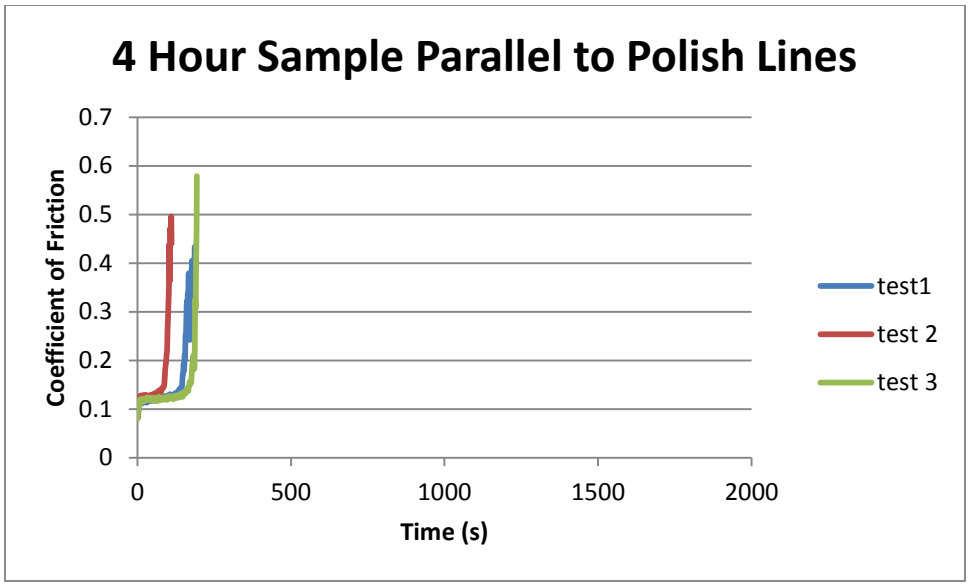


Figure 3.18. Sample extracted from solution after 4 hours, friction tested parallel to polish lines.

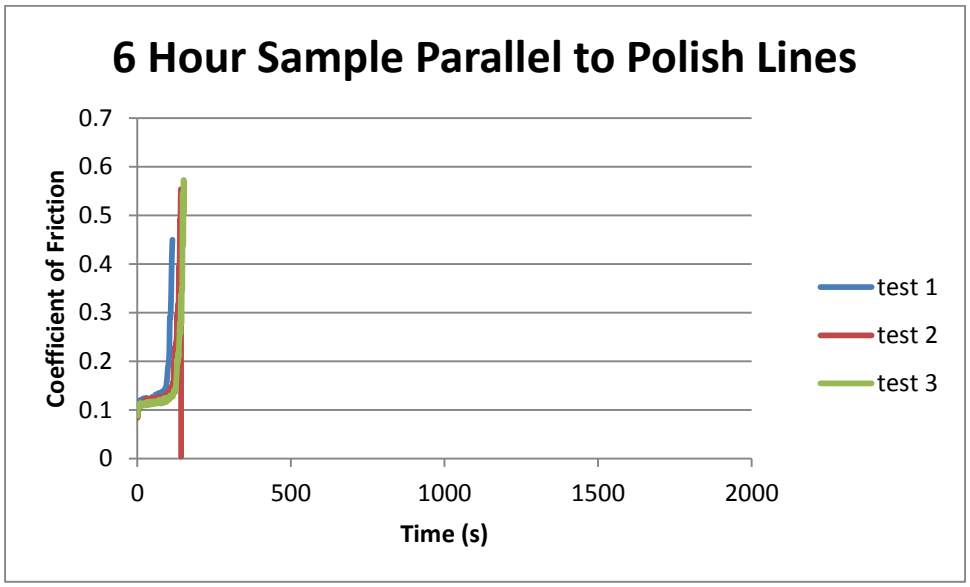


Figure 3.19. Sample extracted from solution after 6 hours, friction tested parallel to polish lines.

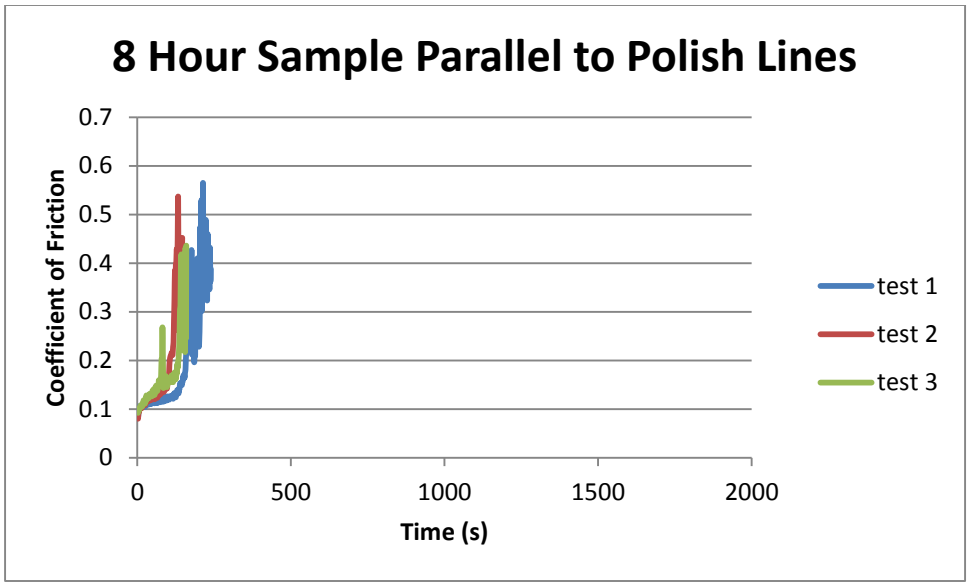


Figure 3.20. Sample extracted from solution after 8 hours, friction tested parallel to polish lines.

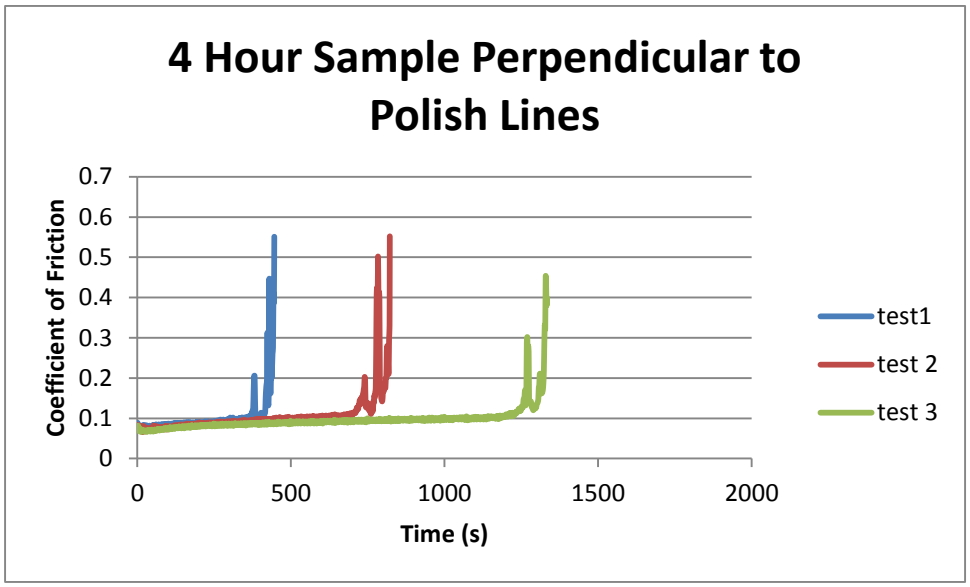


Figure 3.21. Sample extracted from solution after 4 hours, friction tested perpendicular to polish lines.

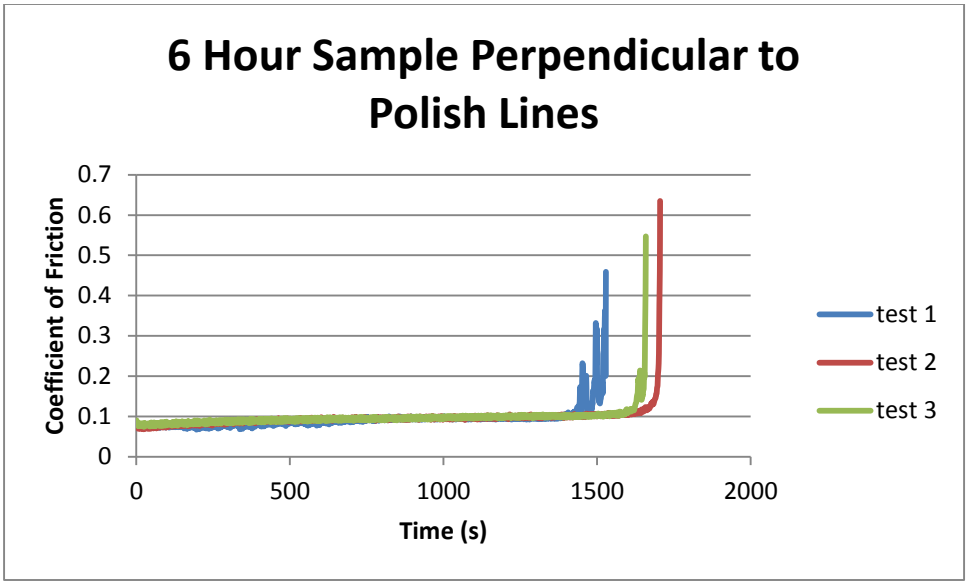


Figure 3.22. Sample extracted from solution after 6 hours, friction tested perpendicular to polish lines.

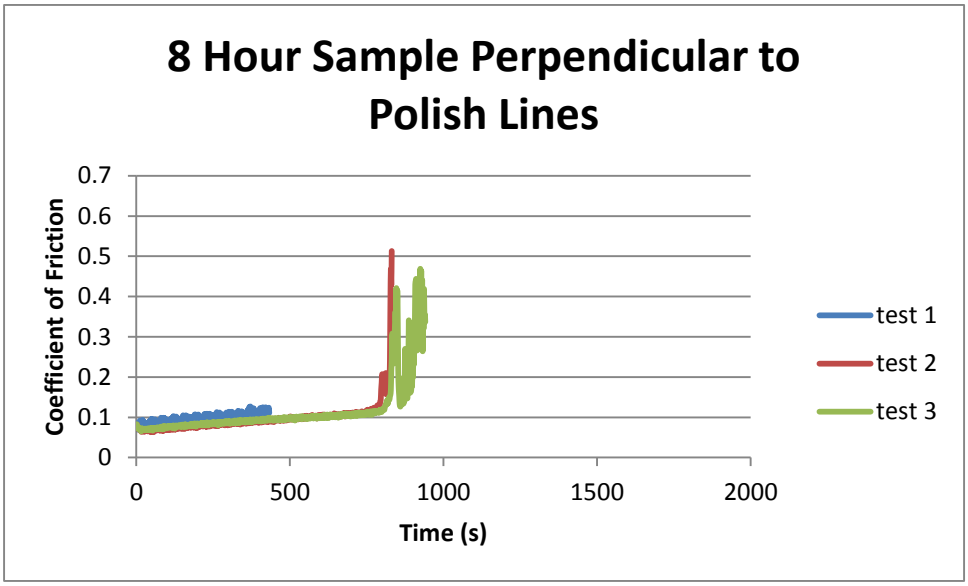


Figure 3.23. Sample extracted from solution after 8 hours, friction tested perpendicular to polish lines.

The summarized data from each test can be found below in tables 3.1 – 3.4. The data in these tables filter out coefficients of friction that were statistically irrelevant as well as convert the test time into a cycle count. The number of cycles represents the durability of the PDA/PTFE coating; an increased cycle count is a result of the PDA/PTFE coating adhering to the steel substrate longer and not wearing off.

Time (hours)	Test 1 COF	Test 2 COF	Test 3 COF	Average COF	Standard Deviation COF
4	0.1268	0.1321	0.1272	0.1287	0.00296
6	0.1277	0.1260	0.1216	0.1251	0.00316
8	0.1218	0.1268	0.1268	0.1251	0.00290

Table 3.1. Coefficient of friction for PDA/PTFE coating friction tests parallel to polish lines.

Time (hours)	Test 1 cycles	Test 2 cycles	Test 3 cycles	Average cycles	Standard Deviation cycles
4	48	31	55	44.7	12.34
6	31	38	41	36.7	5.13
8	46	33	23	34.0	11.53

Table 3.2. Durability of PDA/PTFE coating friction tests parallel to polish lines.

Time (hours)	Test 1 COF	Test 2 COF	Test 3 COF	Average COF	Standard Deviation COF
4	0.0928	0.0995	0.0967	0.0963	0.00335
6	0.0911	0.0968	0.0973	0.0950	0.00346
8	0.1013	0.0935	0.0934	0.0961	0.00449

Table 3.3. Coefficient of friction for PDA/PTFE coating friction tests perpendicular to polish lines.

Time (hours)	Test 1 cycles	Test 2 cycles	Test 3 cycles	Average cycles	Standard Deviation cycles
4	122	236	406	255	142.9
6	463	546	526	512	43.3
8	140	257	258	218	67.8

Table 3.4. Durability of PDA/PTFE coating friction tests perpendicular to polish lines.

All coatings fail easily when the friction test is parallel to the polish lines (figure 3.14 and table 3.2). The sample that had the highest durability and lowest coefficient of kinetic friction is the sample that was extracted from solution after 6 hours and friction tested perpendicular to the polish lines (figure 3.16c and tables 3.3 – 3.4). The coefficient of kinetic friction is higher when testing parallel to polish lines compared to testing perpendicular to polish lines.

4. Comparison to Previous Work

4.1 PDA Deposition

The PDA coating time of 30 minutes claimed by Zhou [1] was not achieved. Zhou's work used solution heated to 60°C and rotating steel substrates at 300 revolutions per minute. The work presented in this report used solutions up to 90°C mixing the solution while holding the steel substrates stationary.

4.2 PDA Uniformity

The PDA uniformity has been shown to improve on steel substrates on the macro scale compared to the previous work by Beckford and Zou. The PDA application method of Beckford and Zou was repeated and is shown in figure 3.4.

4.3 PDA/PTFE Durability

A direct comparison cannot be made between the durability of the previous work of Beckford and Zou and the work presented in this paper. The work presented by Beckford and Zou [2] shows up to 5000 cycles but the normal load is far less than the load used in the friction tests in the results presented in this paper. The detachment of PDA/PTFE coating in the outer wear track was not seen in previous research because of the light load used in previous research compared to the heavy load tests presented in this paper.

5. Conclusions and Future Research

The work presented in this paper studied the changes in procedure to PDA application in order to increase uniformity and decrease application time. By heating the PDA solution and changing the mixing method from a magnet stir rod to a particle disperser, the PDA application time was reduced from 25 hours to 6 hours and the uniformity was increased across the entire substrate.

Future research includes further heating the PDA solution, adding nanoparticles to the PDA solution, and work with the polish lines on the steel substrates. Further heating the PDA solution would

require an environment in which the PDA solution could not evaporate during PDA deposition. The addition of nanoparticles would increase the roughness of the PDA coating, allowing it to bond to the PTFE better. This would improve the durability of the low friction coating and allow it to endure more cycles. Adjusting the polish lines would make the PDA/PTFE coating wear uniformly in all directions of friction testing.

REFERENCES

1. Zhou, P., Deng, Y., Lyu, B., Zhang, R., Zhang, H., Ma, H., Lyu, Y., and Wei, S., Rapidly-Deposited Polydopamine Coating via High Temperature and Vigorous Stirring: Formation, Characterization and Biofunctional Evaluation, PLoS ONE, 2014.

2. Beckford, S., Zou, M., Wear Resistant PTFE Thin Film Enabled by a Polydopamine Adhesive Layer, Elsevier, 2013.

3. Beckford, S., Cai, J., Chen, J., Zou, M., Use of Au Nanoparticle-Filled PTFE Films to Produce Low-Friction and Low-Wear Surface Coatings, Springer, 2014.

4. Beckford, S., Mathurin, L., Chen, J., Zou, M., The Influence of Cu Nanoparticles of the Tribological Properties of Polydopamine/PTFE + Cu Films, CrossMark, 2015.

APPENDIX

Equipment list

- Beaker. 50 mL. Pyrex. No 1000.
- RO water.
- Liquinox. Alconox. 1 quart.
- Hot plate/stirrer. VWR 4x4 CER HOT/STIR. 120V. 121018005.
- Magnet stir rod.
- Steel substrates.
- Plastic tray and stem.
- Fume hood.
- Sonicator. Branson 1510.
- Safety glasses.
- Lab coat.
- Acetone. EMD. AX0115-1. 4L. HPLC Grade. Made in USA.
- Acetone disposal container.
- Sink.
- Isopropyl alcohol. EMD. PX1838-1. 4L. HPLC Grade. Made in Canada.
- IPA disposal container.
- DI water.
- Nitrogen gas.
- Weighing paper. VWR. 12578-201. 6x6 in^2.
- Dopamine hydrochloride.
- Ball bearings
- Trizma base. Sigma. 1001320796. T1503-25G. Made in USA.
- Graduated cylinder. 50 mL. Made in USA.
- Particle Disperser. IKA T18 digital ULTRA TURRAX. T 18 D S1.
- Tweezers. VWR. Stainless. Made in Pakistan.
- Universal Tribometer Module UMT-3MT. Bruker. T1523. University of Arkansas s/n: 268345. Made in USA.
- Dipcoater. KSV instruments LTD. KSVDC. University of Arkansas s/n: 263630. Made in Finland.
- KSV Nima software. Version 2.1.1. Copyright Biolin Scientific Oy (1997 – 2010).
- Data Viewer software. Version 2.20. Copyright 1997 – 2012.
- CETR UMT software. Version 1.138.264. Build 1383. Copyright 1997 – 2012.