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Quantification of Wear in Glass Reinforced Epoxy Resin Composites using Surface Profilometry and Assessing Effect of Surfacing Film Involvement

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Abstract

This paper investigates the performance of glass reinforced epoxy resin composites in plate-on-plate type sliding wear. Wherein the samples were subjected to wear on a specially designed wear test rig for 20000 cycles under an external load of 10N. Also, the effect of using carbide-based surfacing film on the intensity of resulting wear was studied. The quantification of the amount of wear, though in cubic micron volume, was uniquely done by the criteria of surface profilometry. Two methods of surface profilometry – (i) manual type using Mitutoyo SJ310 and (ii) automated setup using KLA P7 Tencor, were followed to quantify the wear. Of which the automated measurement data were further processed using a developed MATLAB code to uniquely quantify the wear volume instead of giving only the surface parameters unlike regular measurements. The designed code also allowed the visualization of the surface profile, for effective comparison of the before and after wear data. The results show that the involvement of carbide surfacing film dramatically reduces the wear, as the volumetric wear observed in such samples were almost 70% less as compared to the uncoated samples. Though, there were hardly any difference after wear between the samples having single and triple layers of surfacing film. Hence, it was concluded that single layer of surfacing film would suffice for getting the effectiveness for wear resistance over three layers for the tested 20000 number of wear cycles.

Keywords: Epoxy Resin; Glass Fiber; Wear; Surface Profilometer; Surfacing Film.

1. Introduction

The application of composites has dramatically increased into various industries, due to their high-strength and low-weight features. Making them increasingly popular for replacing conventional structural materials [1]. Composite materials can be defined as orthotropic materials (they react differently depending on the orientation that they are loaded). As such specific composite and polymer test procedures are needed to be followed to determine the composite material properties, which makes their analysis bit critical and time-consuming [2,3]. With the presence of multiple source materials, composites also tend to often show complicated failure modes like delamination, fiber pull, fiber breakage, fiber debonding, matrix cracking, shear-driven fracture, etc. or even combination of these. Though often not considered of much concern, but wear can also be a major criterion for applications involving contact between two composite materials.

Variable types of wear occur during practical operation, hence there are multiple literature discussing and classifying the various possible types of wear. A straightforward classification is been cited here based on the operating mechanism responsible for producing the wear damage (Table 1). The simplified descriptions in this Table

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1, have been referenced from the categorization document of the Elsevier materials selector [4], to which all readers can refer for a detailed explanation on fundamental mechanisms of wear.

Table 1. Categorization of types of wear in industry.

Type	Wear Challenges in Industry	Considerable Features	Examples
1	Surface wear by stream of fluid having hard particles.	Hard particles acting as erodent continuously introduced along with a fluid medium.	Oil and mud slurry flowing through a valve.
2	Surface wear by bed of hard materials.	Movement of hard abrasive materials in bed creating abrasion.	Powder mixing rotor blades.
3	Surface wear by mutual rubbing when in contact, under the presence of abrasive particles.	3-point wear, between metal-abrasive particle-metal contact under the continued introduction of abrasives.	Plaster mixing scrapper blades, pivot pins, shaft seals, etc.
4	Surface wear by mutual rubbing when in contact along with other solid parts.	Continued abrasion and adhesive wear, though one of the components is regularly renewed	Pressing and punching tools, cutter blades, sintering dies, etc.
5	Surface wear by mutual and repeated rubbing.	Abrasion and adhesive wear with variable wear rate.	cylinder liners, piston rings, gear teeth, etc.
6	Surface wear by mutual and repeated rubbing between dissimilar materials (like between nonmetal and metal).	Consistent components showing adhesive wear.	Artificial hip joints, clutches and brakes, etc.

The samples studied are subjected to reciprocating sliding wear similar to what will be the case for the actual use case scenario, hence they fall in the Type-5 wear. Under such wear (sliding wear – reciprocating motion) the quantification of wear can be done in various ways after the test completion. The quantification of wear, especially in epoxy composites is not very easy to measure. Ideally, the wear measurement techniques have been based on the change in mass or geometry. One widely used method for wear estimation is gravimetric analysis, involving the wear volume loss calculation [5-7]. Though being very easy and straightforward to perform, this method is not applicable when the test specimen mass loss/addition is lower than the accuracy range of the analytical scale, typically which is in the range of 0.01 mg [5]. Hence, many innovative methods have been tried involving optical or scanning electron microscopes wherein microscopic observations of the test specimen is made before and after the wear [8,9]. This helps to an extent in examining the surface morphologies after wear and categorizing them [10] into cracking, transfer layer, craters, plastic deformation, spallation, shear fracture, fatigue, etc.

The goal of this research is to examine the wear performance of glass fiber reinforced epoxy composite samples with and without a surfacing/coating film made of impregnated SiC microspheres. The wear estimation for plate-on-plate type wear for such samples are very difficult, due to the nature of micron level wear. Wear-rig was fabricated for the samples to carry on the Type-5 wear with the controlled number of wear cycles. A method and novel criteria based on the 3D profilometric measurement is developed and tested to quantify the micron size wear. This gave the basis for justifying the wear and to support the selection amongst the uncoated and coated samples.

2. Experimental Section

2.1. Wear Test-Rig

The setup for testing the plate-on-plate type wear arrangement is prepared as shown in Fig. 1. The samples are tested in dry-wear condition, wherein two samples of similar type are worn against each other in an open atmosphere at room temperature. The samples are subjected to cyclic wear of 20,000 cycles applied with a stroke speed of 0.4 m/s – 0.6 m/s, further the worn surface samples will be studied under the surface profilometer for calculating the z-direction variations and to estimate the volumetric wear for all the samples.

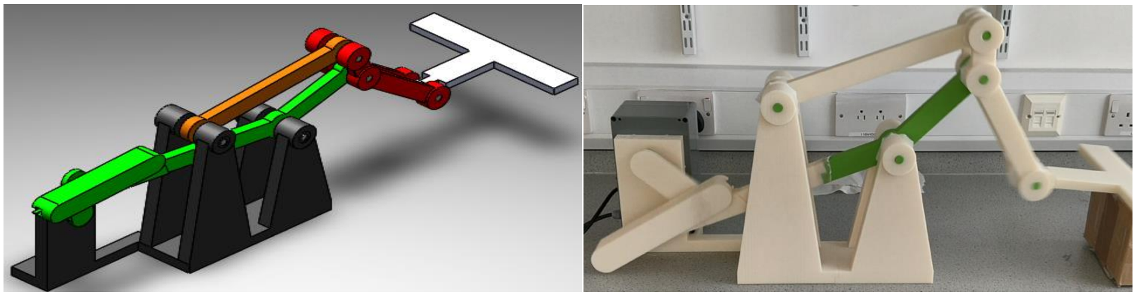

Fig. 1. The experimental setup for the plate-on-plate type reciprocating wear setup. (a) Simulated CAD model and (b) 3D printed assembly of the test-rig.

2.2. Surface profilometry

The setup used is Mitutoyo SJ310 contact type Surface Profilometer, contact configuration involves a diamond tip stylus having reciprocated sinusoidal movement with 10 Hz frequency and 4 mm amplitude. The test duration for each measurement usually took 25 s relating to a reciprocating travel of 8.80 mm each way. The positioning of the stylus in the marked region over the samples is done manually and hence is prone to be affected by uncertainty in the range of 0.5 mm. To check the effect of this uncertainty, each measurement is repeated by repositioning the stylus at least twice each time. The sample is prepared as following Fig. 2, for the surface profilometer study.

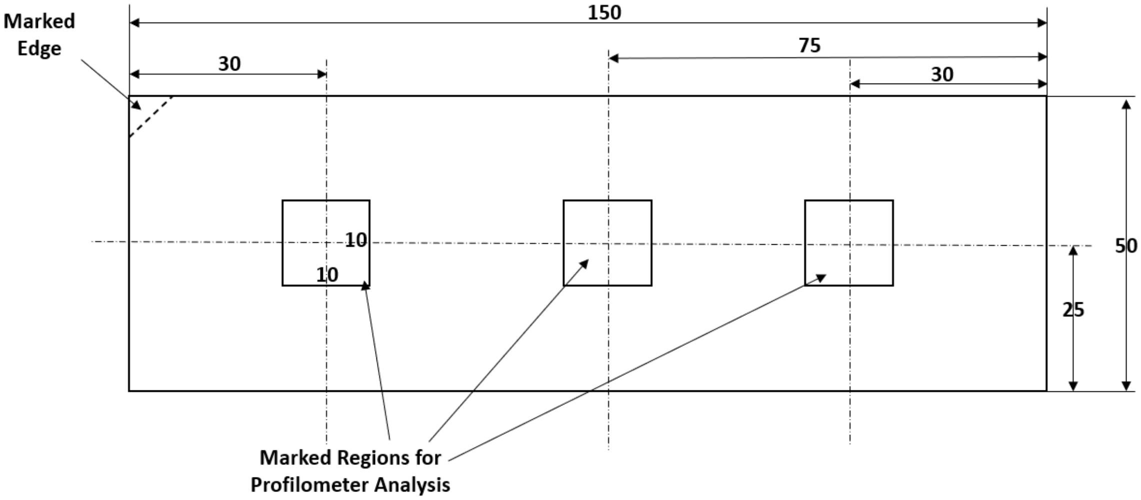

Fig. 2. Sample prepared as such for the surface profilometer study on Mitutoyo SJ310 contact type Surface Profilometer.

Automated surface profile measurement is also done on samples, using KLA Tencor P7 having diamond tip stylus with 250 µm spacing between measured tracks and 400 µm/s stylus tracing speed. The observed regions are marked as shown in Fig. 3.

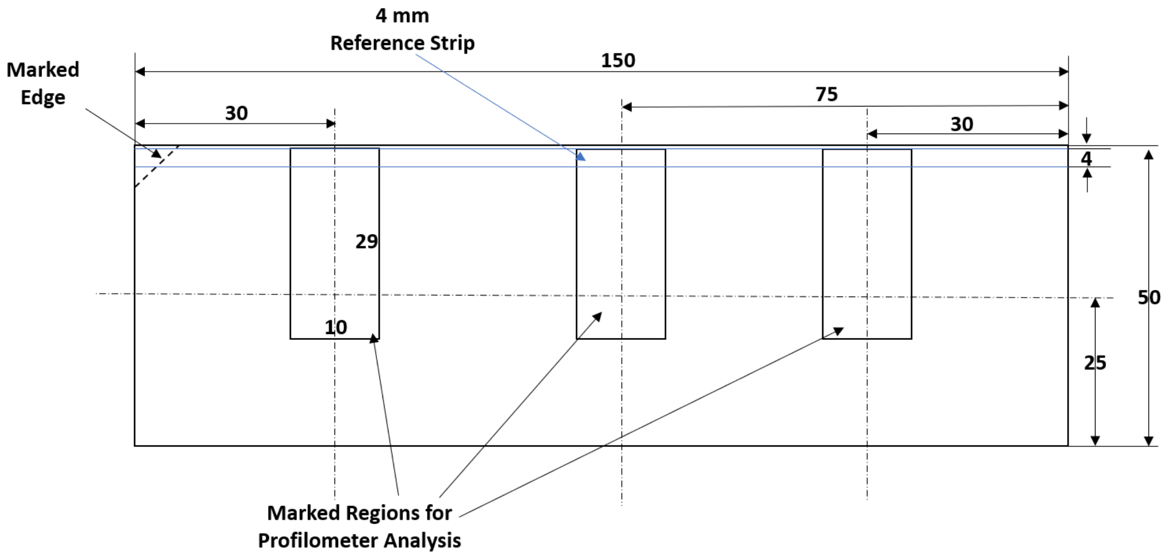

Fig. 3. Sample prepared as such for the surface profilometer study on KLA Tencor P7 contact type Surface Profilometer.

The wear volume is calculated from the length and wear track cross-sectional area. This gives a direct comparison for the measured unworn and worn samples from the reconstructed 3D profiles.

2.3. Flexural (3-Point Bending) Test

The ASTM D790 testing method was used to determine the flexural (bending) response of unreinforced and reinforced composite materials. Herein, the flexural response of the composite material is estimated under bending strain or deflection. The test is conducted on universal testing machine (UTM) using a 3-point attachment, with deflection rate decided based on the sample thickness. The testing was done on Instron 1195 tensile testing machine. The strain rate was set at 0.01 mm/mm/min with load versus displacement and stress versus strain plot data captured using the automated (Blue Hill) system. The test was carried on until sample breakage or if the strain rate increased by 50%.

3. Results & Discussion

The standard method of surface profilometry using probe-profilometer gave the surface parameters with averaged measurements. The measurements were noted as arithmetical average roughness value (R_a) which is the arithmetical mean of the measured profile absolute values deviations over the average level of the profile roughness; root mean square roughness (R_q) is the RMS average of the profile heights over the measurement length; and average roughness depth (R_z) for the average value of the five greatest height of the sample profile estimates over the five measured lengths inside the estimation length. The measurement values for a single sample are shown graphically in the bar-chart plotted in Fig. 4 for easier comparison of the before and after wear surface parameter values.

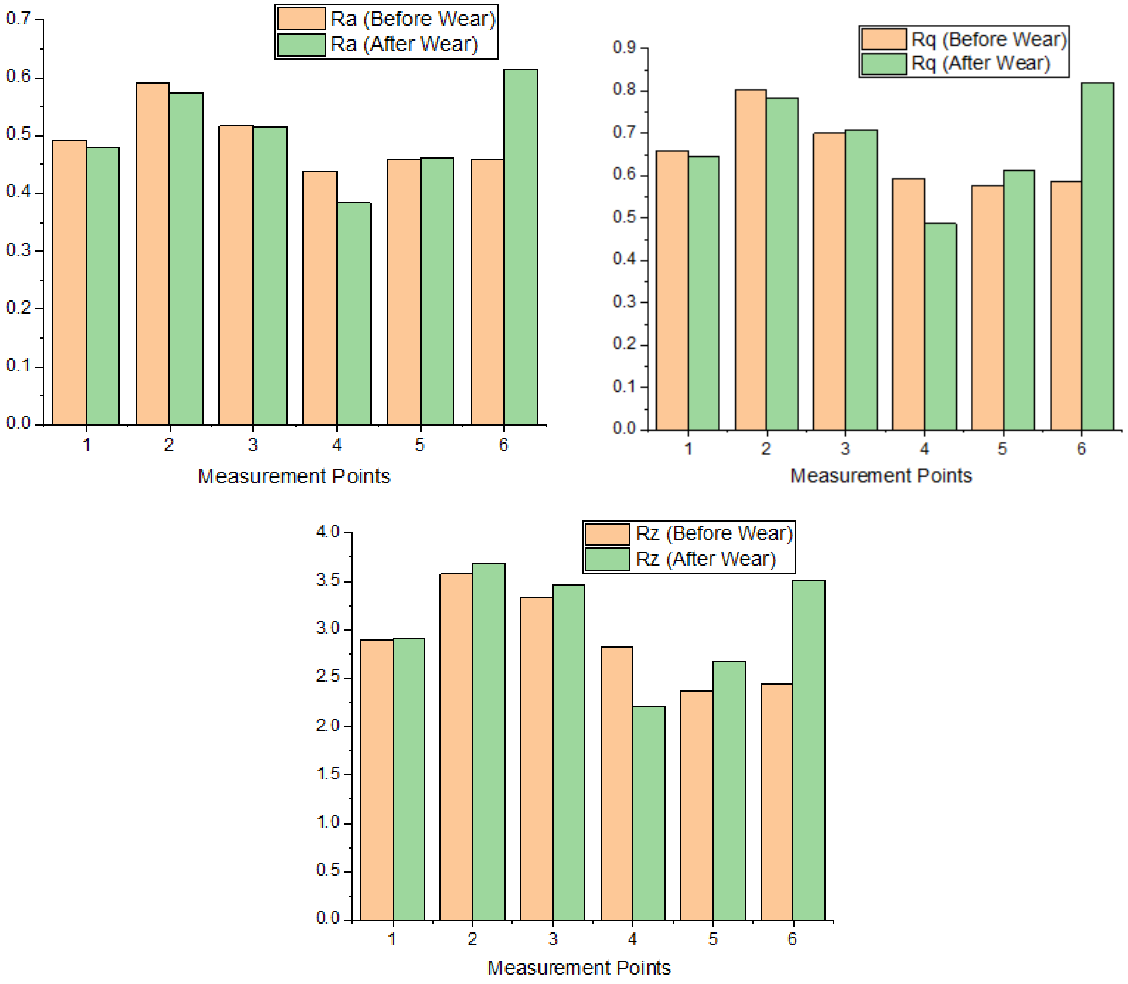

Fig. 4. Surface parameter comparison before and after wear (for No Coating Sample).

The summary results for all the sample measurements are included in the following Table 2. The summary table gives a clear comparison for all the samples (i.e., without and with coating surface) with the measured parameter values before and after wear. Though the data is quantitative, but still the comparison cannot be justified as many of the regions or instances of wear in the marked regions weren't accounted in the probe measurement, as they didn't fall within the probe track. Hence, these measurement data can be considered highly subjective, as considering higher number of probe measurements within the marked region could even give a different scenario. To address such issues, the automated 3D profilometer measurement taken for the entire marked region was hence used.

Table 2. The observed surface parameter results for all the samples are summarized herein.

Sample	R_a (µm)		R_q (µm)		R_z (µm)	
	Value	Std. Dev.	Value	Std. Dev.	Value	Std. Dev.
No Coating - Before Wear – Vertical (Across)	0.560917	0.093647	0.695146	0.129329	2.860229	0.708328
No Coating - Before Wear - 45°	0.427917	0.111988	0.538813	0.160737	2.365208	0.913126
No Coating - After Wear – Vertical (Across)	0.567542	0.094825	0.709375	0.115614	3.107792	0.569325

No Coating - After Wear - 45°	0.730292	0.191430	0.866958	0.222099	3.350333	0.824027
Single Coating - Before Wear – Vertical (Across)	0.556396	0.162533	0.700083	0.211059	2.997813	0.88626
Single Coating - Before Wear - 45°	0.496979	0.092160	0.655625	0.143135	3.075708	0.776492
Single Coating - After Wear – Vertical (Across)	0.604542	0.106888	0.752875	0.135378	3.273708	0.648487
Single Coating - After Wear - 45°	0.603917	0.149303	0.795333	0.170314	4.221333	0.703457
Triple Coating - Before Wear – Vertical (Across)	0.543875	0.125522	0.689938	0.170803	2.977729	0.765537
Triple Coating - Before Wear - 45°	0.501792	0.110058	0.657729	0.166398	3.046604	0.910016
Triple Coating - After Wear – Vertical (Across)	0.643458	0.133062	0.798625	0.160092	3.344250	0.698472
Triple Coating - After Wear - 45°	0.787125	0.167888	0.947042	0.201408	3.796667	0.868539

The automated measurement data were further processed using a developed MATLAB code to uniquely quantify the wear volume instead of giving only the surface parameters unlike regular measurements. The designed code also allowed the visualization of the surface profile, for effective comparison of the before and after wear data. The change in volume referring to the volumetric wear for the no coating, single-coating, and triple-coating samples were calculated by the developed code as 0.0652, 0.0208 and 0.0216 cubic micron respectively. The summary results from the automated profiles are included in the Table 3 below. The results show that the involvement of carbide surfacing film dramatically reduces the wear, as the volumetric wear observed in such samples were almost 70% less as compared to the uncoated samples.

Table 3. The summary results from the Matlab processing for the volumetric wear before and after wear.

Sample	Before Wear Profile Volume (cu. micron)	After Wear Profile Volume (cu. micron)	Volumetric Difference (cu. micron)
NC-EBX950	$6.4939 \times 10^9 \pm 0.25 \times 10^9$	$6.4287 \times 10^9 \pm 0.20 \times 10^9$	0.0652×10^9
1C-EBX950	$5.0109 \times 10^9 \pm 0.30 \times 10^9$	$4.9793 \times 10^9 \pm 0.25 \times 10^9$	0.0208×10^9
3C-EBX950	$5.1903 \times 10^9 \pm 0.20 \times 10^9$	$5.1687 \times 10^9 \pm 0.25 \times 10^9$	0.0216×10^9

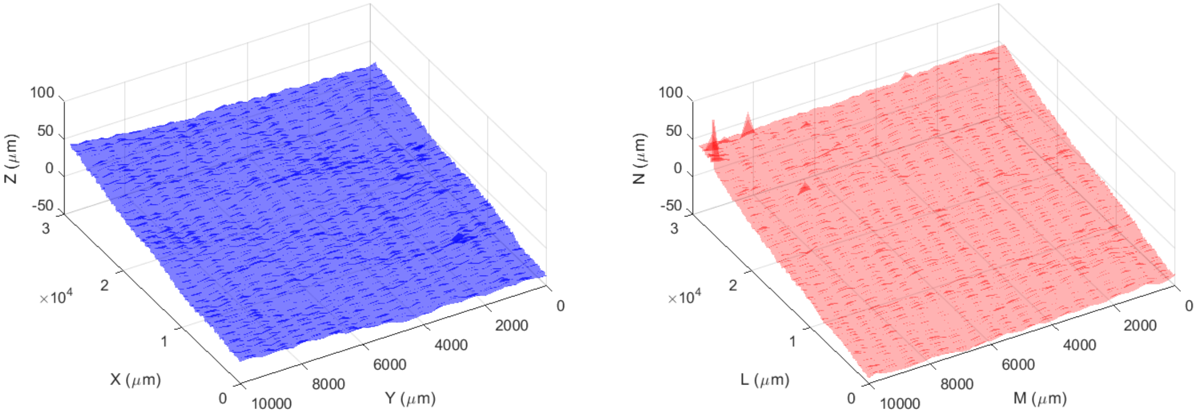

Fig. 5. Comparison of Surface Profile before (Left) and after (Right) wear with the same axis setting (for No Coating Sample).

The results of the samples with surface coating (one coating or triple coating) showed almost similar response. Since, the surfacing film was made of the similar material (SiC coating) hence the similar response was expected. Also, since the wear extent was not that severe the surfacing films were hardly worn/damaged, hence the similar response recorded by the single coated or triple coated samples. Though, in terms of non-coated samples, the samples with variable reinforcements of glass fibers showed better surface parameters after wear, with lower Ra, Rq and Rz parameters recorded. Although, the standard deviation observed for the gathered data of no coating reinforced samples were bit lower. The all cases tested and summarized above in Table 1 suggest that the single-coated and triple-coated samples fared well amongst the coated sample variants.

For further justification on the selection of one of them, the 3-point bending test was carried on for justifying the choice between 1C and 3C samples. And it also made the basis for judging the boding between the base matrix and the coating layer.

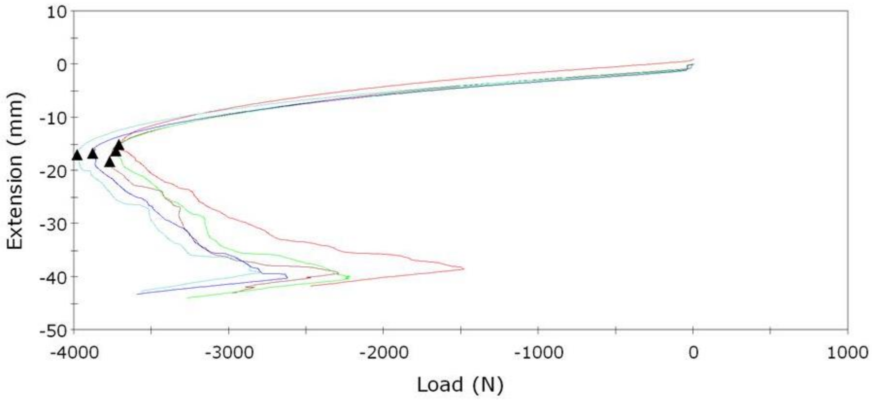

Fig. 6. 3-Point flexural testing trend plots for set of single-coated samples.

The results from the 3-Point flexural testing for the single-coated and triple-coated samples are summarized in the Table 4 for quicker comparison amongst the coated sample variants.

Table 4. Summary of the 3-point flexural test for all the tested samples.

Sample	Flexure Stress at Breakage – Mean (MPa)	Flexure Stress at Breakage – Std. D. (MPa)	Maximum Flexure Stress (MPa)	Maximum Flexure Stress Std. D. (MPa)
Single Coating Sample	421.68	38.97	565.78	28.79
Triple Coating Sample	448.14	46.83	577.86	5.37

Though, during the testing itself there were no cases of wherein the coating layer (either 1C or 3C) peeled off from the base material. This suggests that the bonding between the epoxy base and the coating material are structurally sound. The overall results clarify that the samples with 1C and 3C coating behaved in almost similar manner.

4. Conclusion

The study discussed the effect of wear in epoxy composite samples and an effective way of assessing it. The developed and tested method of 3D surface profilometer based wear quantification is very unique in its approach and gives the wear estimation in terms of the volumetric changes even in the range of cubic microns. Of the tested samples with no coating, single-coating, and triple-coating, the coated samples had similar wear behavior but showed ca. 70% less wear as compared to the uncoated sample. And to make a clear justification on the interface strength between the base epoxy and the coating material, 3-point flexural testing was also executed. Considering the overall scenario in terms of the surface profilometer data (wear performance) and the mechanical testing (3-point bending) the sample having single coating can be considered as the suitable choice in terms of cost-effectiveness, in order to be able to deliver the required wear duty for 20,000 cycles. Though, if the performance cycle increases beyond 20,000 cycles it would be interesting to observe whether the single coated sample would still be the suitable choice or instead the triple coated sample would have to be then selected for extensive wear performance. This would be part of the future investigation.

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