COMPOSITE BEARING DESIGN WITH IMPROVED TRIBOLOGY AND MACHINABILITY FOR AGGRESSIVE APPLICATIONS

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Introduction

Composites bearings are used in a wide range of industries for their strength, superior wear and friction characteristics, and their ability to operate without external lubrication. Filament wound composite bearings with the most effective tribological performance have historically been limited in their dimensional tolerance by the processing capabilities inherent to the winding process. The ability to machine composite bearings to a tight dimensional tolerance has been limited because they typically contain continuous PTFE fibers that fracture and fray in the machining process. Recent developments in self-lubricating fiber/resin composite bearing technology have included fiber construction to overcome machining limitations while providing superior tribological performance. This work offered insight into the nature of machining limitations, specific advancements in materials design to overcome those limitations.

1. Background

Composite bearings have been used in hydropower applications for greater than twenty years as a mechanism to replace grease with lubrication-free operation, and often to improve wear performance and life in comparison to the bronze bearings that have been replaced (1). The wicket gate location has been a particularly challenging bearing condition, including for composites. PTFE-containing composite bearings have been shown to provide superior tribological performance in hydropower (2), and an additional broad range of aggressive industrial applications.

Good dimensional tolerance and stability have been considered to be important to the success of composite bearings in hydropower applications such as the wicket gate location. It is typical to perform some method of secondary sizing on the bearing bore after the winding and curing process to achieve target dimensional tolerance. This has typically been performed on the bearing as part of the manufacturing process.

1.1 Dongfang Pumped Hydro Turbine

In 2016, Dongfang Electrical Company approached GGB for technical bearing solutions for their newly designed pump storage facility in JiXi, Anhui province. In-grid energy storage has been considered key to the growth of renewable energy because of the mismatch between renewable energy availability and peak demand and is a key hurdle to the continued growth of renewables. Pumped storage is by far the highest volume method of energy storage, and is a key tool to meeting the ever growing demands for electricity in China.

The bearing demands for this facility were unique in their requirements. While the need for tight tolerances has become more prevalent across the industry, this facility particularly required an allowance for eccentric machining of the bearings' bore after installation. It was essential for the facility design that the bearings be able to accommodate the possibility for a head cover offset. The final offset was not be known until the late stages of construction and after the bearings were installed, requiring the utmost flexibility of design and manufacture.

The machinable bearing product discussed here was particularly well suited to meet these demands. The wear resistant liner was designed especially for machinability by a customer after installation of the bearings. The design of discontinuous PTFE fibers contained within the thermoplastic fibers drove this favorable aspect. The machinable bearings were manufactured with a stable, oversized tribological layer to allow machining by the customer to accommodate their precise dimensional needs. To accommodate the need for such an offset, GGB's cross functional team of engineers calculated and designed bearings with an appropriately size tribological layer that could accommodate the full range of offset dimensions. This thicker layer was designed to be machined by the customer after the bearings were installed in their respective housings. The machinability of that liner is the primary subject of the work described below.

1.2 Composite Materials Design for Optimum Tribological Performance

One popular method of composite bearing construction has utilized continuous, twisted fibers of PTFE and another thermoplastic, such as polyester, to partially surround or encapsulate the PTFE fibers, which typically have unfavourable bonding characteristics requiring them to be supported within a resin matrix such as epoxy. Particulate fillers may also be added to a polymer composite resin matrix including graphite (1), PTFE (3) or a range of other particulate types (4). A previous investigation showed the benefits of bearing material design related to wear performance both of the bearing and the mating shaft material (5).

The typical wicket gate conditions have been defined in US Army Corps of Engineers test specification CERL TR 99/104 (2). That test entails a combination of moderate to high and variable loading (23-30 MPa), and a combination of dithering (low angle, high speed oscillation) and slower, large angle oscillating conditions. The potential tribological performance of self-lubricating bearings in a wicket gate application has been measured through the use of US Army Corps of Engineers (COE) Specification CERL TR 99/104 (2). This test utilizes two separate conditions within the same continuous test to evaluate bearing performance, described in Table 1.

Load:	23 - 30 MPa	Dithering condition:	Once every 15 minutes:
Bearing size:	127 mm ID	+/- 1° 2 Hz	+/- 15° 0.1 Hz (10 seconds full sweep)
Shaft:	17 - 4		
Hardness:	HRC 40		
Roughness:	Rc: 0.4 µm max		

Table 1: Test Conditions: US Army COE Specification CERL TR 99/104

A previous investigation of the bearing type used within the current machining study was discussed previously regarding performance in the specified dithering condition (5). The tribological performance in that mode was evaluated in the presence of a range of shaft counterbody types in comparison to a baseline composite self-lubrication bearing (1). The shaft types investigated were thin dense chromium plating, hardened stainless steel (420 grade) and mild steel (1040 grade). It was shown that the baseline composite bearing caused tribo-oxidative wear in both of the steel grades, resulting in significant roughening of the shaft. This increased shaft roughness then resulted in accelerated bearing wear of the polymer-based self-lubricating wear surface. Figures 1a and b display these two accompanying phenomena, both shaft roughening and accompanying bearing wear.

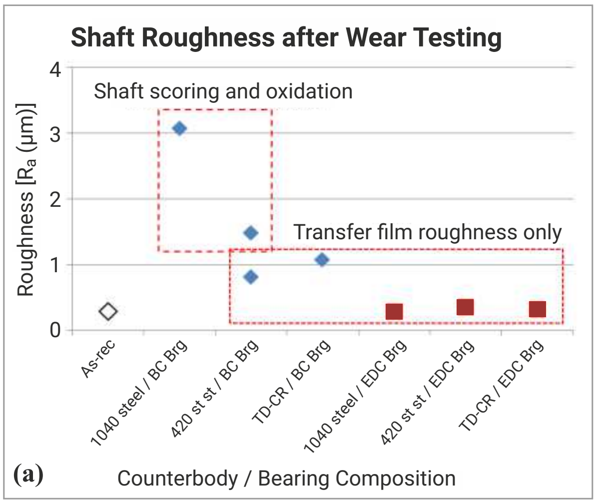
The PTFE fiber bearing studied in that work, by comparison, exhibited none of these deleterious responses (5). Figures 1a and b show this favorable performance, indicated in those charts as EDC, which referred to Enhanced Dithering Composite. Shaft roughness did not change notably for any of the three counterbody types, and bearing wear was correspondingly low. Favorable formation of a uniform, self-lubricating transfer film by the EDC bearing was proposed as the cause of the favorable tribological performance. It was shown that lubricious transfer film formation prevented tribo-oxidation and eliminated shaft damage resulting in low bearing wear and stable tribological system performance.

Enhanced fiber technologies have also allowed the use of standard machining procedures. Continuous PTFE fibers have demonstrated a tendency to fracture during the machining process, owing in part to poor bonding to the resin matrix in which they are embedded. Discontinuous PTFE fibers that are contained within thermoplastic fibers have been used to achieve favorable aspects of both tribology and machinability. The bearing described above as Enhanced Dithering Composite will be described herein as Discontinuous PTFE Fiber Composite.

1.3 Composite Materials Design for Machinability

Fiber / resin composite bearings designed for superior tribological performance typically are constructed using a combination of self-lubricating mechanisms. One method uses one of a combination of lubricating particulate fillers including graphite (1), polytetrafluoroethylene (PTFE) (3), or other types including multiple lubricating fillers in the same construction (4). The self-lubricating materials design often includes PTFE fibers to assist in reducing friction and wear, possibly including an additional thermoplastic fiber to provide structural integrity of the wear resistant layer of the bearing (1,3,4). The construction of these fibers may also impact the machining response of the wear resistant surface.

The experimental work described within was conducted to compare the machining response variation between composite bearings produced with two different fiber types, both manufactured using a filament winding process. One bearing type used separate but continuous fibers of both thermoplastic and PTFE compositions, blended and twisted together to provide a uniform fiber bundle. The second type used a composite fiber construction with discontinuous PTFE fibers contained within a thermoplastic fiber matrix. Figures 2 and 3 show cross-sectional images highlighting differences in the fiber structures. Figure 2b shows a highlighted long, continuous PTFE fiber. Figure 3b shows multiple short, discontinuous fibers contained within larger thermoplastic fibers.



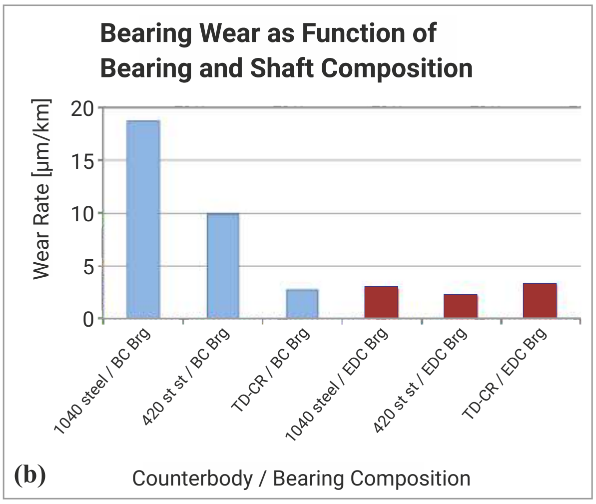


Figure 1: Tribological data showing (a) shaft roughness after wear testing exhibiting difference between baseline composite bearing and an advanced bearing designed for enhanced dithering performance. That bearing was the same on used in this work to investigate machining response. Accompanying bearing wear (b) also displayed.

Both the continuous and discontinuous PTFE fiber types are capable of providing favourable self-lubricating characteristics (1, 4). Significant differences in machining response between the two types have provided different application conditions. Machining via "standard" machining techniques is considered desirable to achieve optimum dimensional characteristics while maintaining maximum flexibility in the final manufacturing process, with those "standard" techniques considered to be machining via a conventional lathe and single point tooling. The continuous PTFE fibers have shown a tendency to break and fray when machined via these standard methods. That structure has been demonstrated to be machinable for tight dimensional tolerance via an ID grinding process employed by the original bearing manufacturer. This process was determined not to be transferable to the end user, requiring the innovation of an alternate material structure to provide favourable machining response able to be used by the end-user by standard machining techniques at the final assembly location.

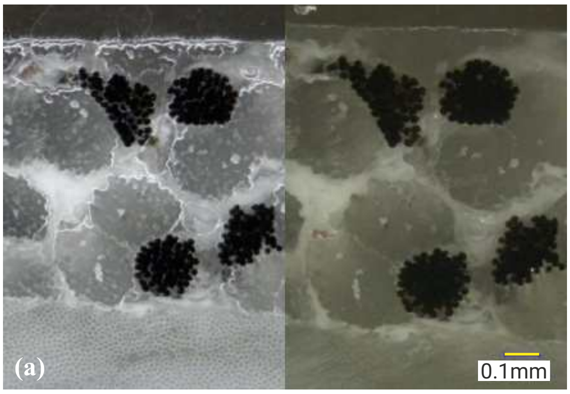


Figure 2: Cross-sectional images showing the continuous PTFE fiber construction. Image (a) shows the fiber structure in transverse view while (b) shows a fiber longitudinally, highlighted by the red oval.

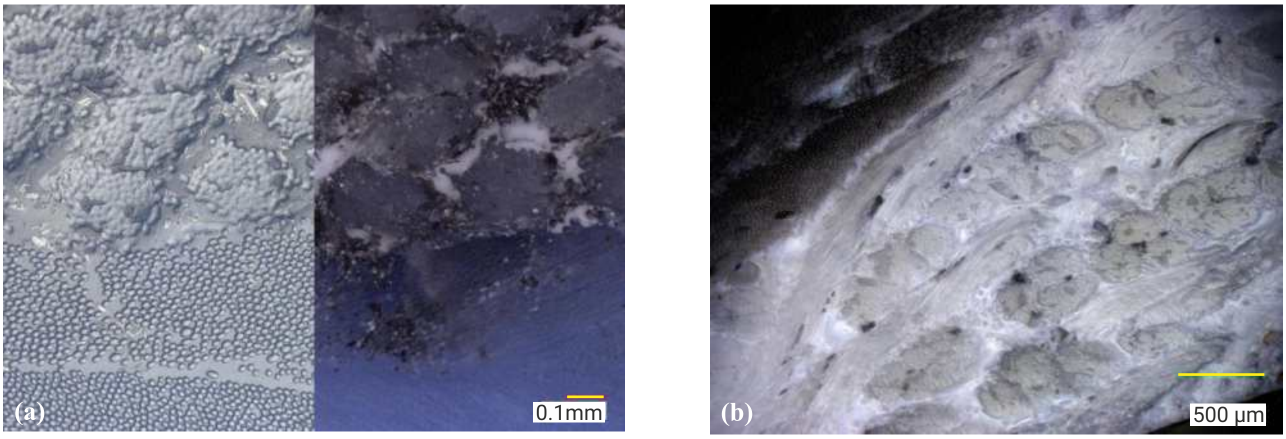


Figure 3: Cross-sectional images showing the discontinuous PTFE fiber construction. Image (a) shows the fiber structure in transverse view while (b) shows fibers longitudinally, highlighted by the red ovals.

1. Experimental Procedure

Machining Studies

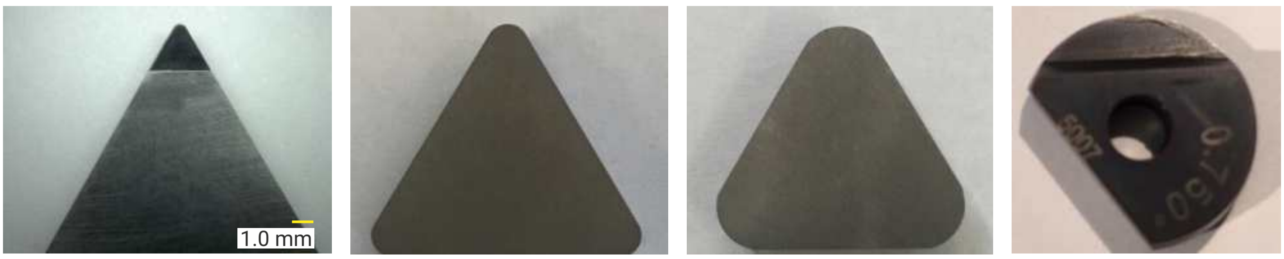
A machining study was conducted to investigate the machining response of composite bearings as a function of fiber matrix construction. This compared bearing liners manufactured with continuous PTFE fibers twisted with a secondary thermoplastic fiber to bearings produced with fibers of a composite nature with discontinuous PTFE fibers contained within a spun thermoplastic. A test matrix was designed to test a range of conditions including:

- Tool type (varied cutting tip radii)
- Surface speed
- Cut depth

The bearings used for this study for this study were of 127 mm internal diameter (ID). Tool types were all of carbide construction, of tip radii: 0.4 mm, 1.6 mm, 3.1 mm, 9.5 mm. Cutting surface speed of the part was varied from 1.2 to 3.3 m/s (180 to 500 rpm on 127 mm ID). Depth of cut was varied from 0.635 mm (on diameter) to 1.27 mm.. Travel speed was constant at 0.127 mm / revolution. Cutting tools used in this study are shown in Figure 4, a through d, showing the variation of cutting radius between the different tools in the study. This figure shows the range from a sharp tool point at 0.4 mm radius to a fully circular tool for the 9.5 mm radius.

The machining configuration is shown in Figure 5a. This shows a machining test part held in a lathe, being single-point machined using a toll held by a boring bar. The test part was rotated while the boring bar and cutting tool were translated longitudinally along the surface of the part.

Two measures of machinability were utilized. General machining response was evaluated by the measurement of surface roughness. Surface roughness was measured quantitatively using a Zeiss Surfcom 130A profilometer. Surface condition was also evaluated visually through imaging using a Keyence VHX-1000 microscope, capable of high depth-of-field resolution to exhibit the condition of curved and rough surfaces. Dimensional response to the machining process was evaluated separately on certain bearings. Parts to be used for the dimensional study were inserted into a fixed steel master die as shown in Figure 5b to ensure full roundness of the part and consistent outer diameter. The master die and enclosed part were then held in a lathe and the test part machined using a method similar to that shown in Figure 5a (next page).



a. 0.4 mm radius b. 1.6 mm radius c. 3.1 mm radius d. 9.5 mm radius

Figure 4: Tool types used in the machining study. Tools were carbide with cutting radii from 0.4 to 9.5

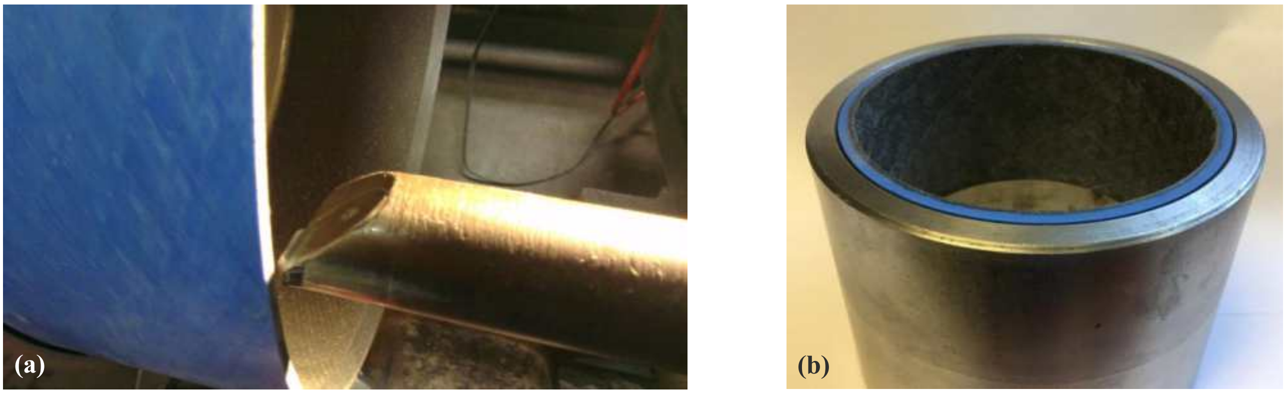


Figure 5: Image showing the methods used in the machining study. Image (a) shows a part being machined in the free state, used to analyse surface roughness following machining. Image (b) shows a machined part in a master die, used to evaluate dimensional response.

3. Results

Two measurement methods were used to quantify machining response in the study. One was surface roughness, reported as average roughness, Ra. The other method measured internal diameter measured by coordinate measuring machine (CMM).

3.1. Roughness Measurements

Figures 6 and 7 exhibit roughness data as functions of machining parameters and fiber type. Figures 6a and b compare discontinuous fibers to continuous ones as functions of tool radius and cutting speed. Tool radius varied from 0.4 mm to 9.5 mm. The roughness data showed that the discontinuous construction provided notably reduced roughness in comparison to the continuous type, through the entire range of tool radii.

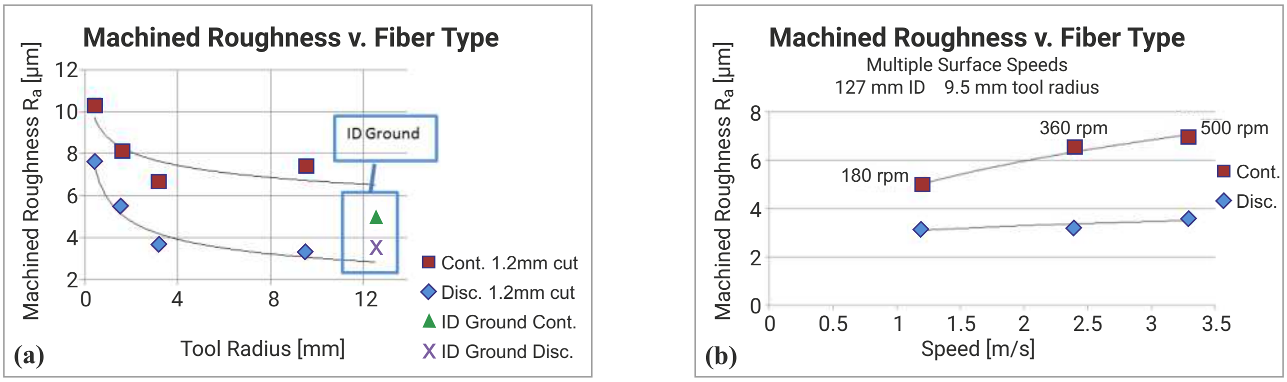


Figure 6: Roughness data comparing machining response for continuous PTFE fiber structures and discontinuous. Data are shown as functions of tool radii and cutting speed.

Machined roughness was also measured for ID ground samples, the incumbent method prior to the development of the single point tool machining method. Those roughness data showed roughness improvement for the continuous fiber composite, but still rougher than discontinuous fiber machined surfaces. The grinding method did not show roughness improvement for the discontinuous fiber structure in comparison to either 3 mm or 9.5 mm radii tools. The cutting speed was shown to have little or no impact on roughness of the discontinuous fiber composite within the range tested. The continuous fiber structure was impacted notably by cutting speed, with increased speed resulting in increased roughness.

Roughness was also measured as a function of cut depth. Figure 7 shows the impact of cut depth on roughness of the resulting composites. Both composite types showed no impact of cut depth at larger tool radii, which produced finer finishes in both composite types. The effect of tool radius was more dramatic at the lower cut depths and smallest tool radius for both fiber types.

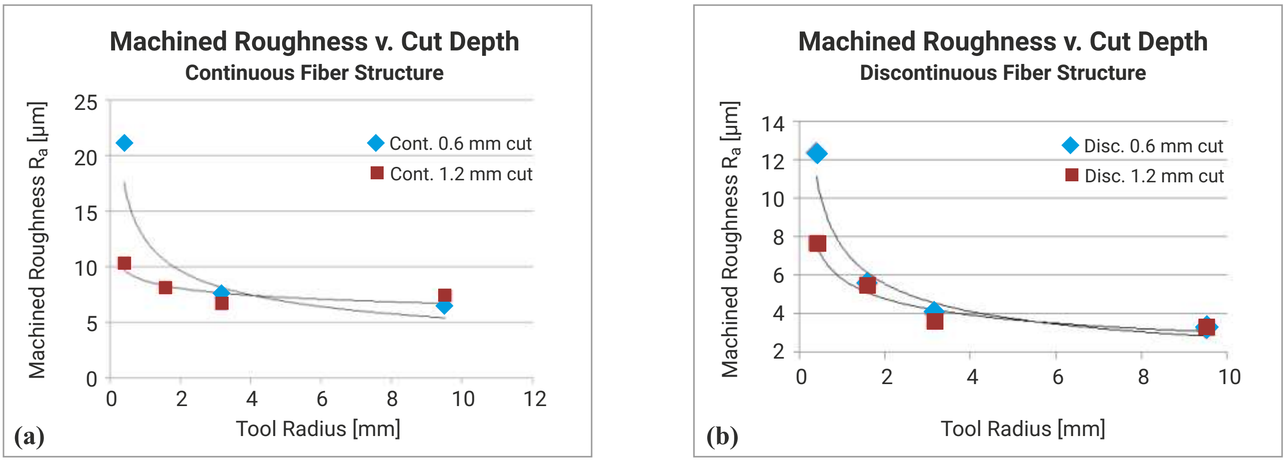


Figure 7: Machined roughness data showing impact of depth of cut. Graph (a) shows data for continuous PTFE fiber structure; graph (b) for discontinuous PTFE fibers.

3.2. Imaging of Machined Surfaces

Visual evaluation of the machined surfaces was conducted to support numerical analysis of the machining responses. Figure 8 shows the surfaces of both composite types following ID grinding, the process developed for machining of the continuous fiber product. The continuous fiber surface showed a minor degree of fiber fraying, considered normal and acceptable for the finished product. The discontinuous fiber surface shown in 8b exhibited a smooth surface with no loose or frayed fibers. It should be noted that the roughness measurement of the discontinuous fiber composite surface was lower than that of the continuous fiber composite, 3.5 v. 5.1 µm R_a.

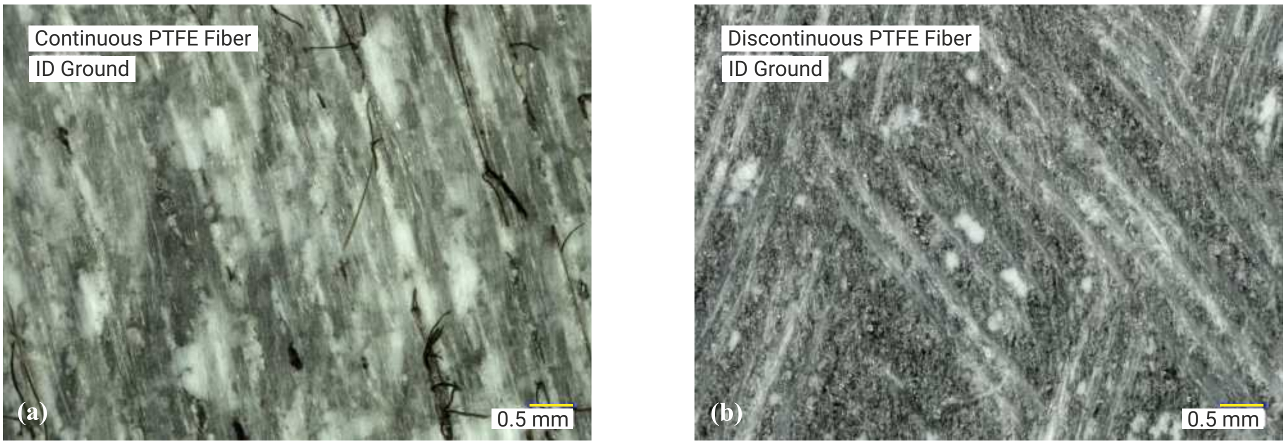


Figure 8: Surface image of the continuous PTFE fiber bearing using the baseline (ID grinding) process method for secondary machining (left, (a)). Image on the right (b) shows the discontinuous PTFE fiber bearing surface machined by the same ID grinding process.

The surfaces machined with the smallest radius, 0.4 mm, are shown in Figure 9. These had the roughest measured surface of any of the tool radii within their respective data sets at 7.6 µm Rafor discontinuous and 10.3 µm for continuous. The continuous PTFE fibers were shown to exhibit a significant fractured and frayed appearance. The surrounding fiber/resin matrix was also observed to be altered in an unfavorable manner with apparent machining chips of the matrix material apparent in the final machined surface. The discontinous fiber surface shown a notably improved condition in comparison to the continuous fiber version, but still with some degree of fiber fraying not observed with larger radii tools.

Surfaces machined with the largest, 9.5 mm radius tool are shown in Figure 10. The continuous PTFE fibers in 10a exhibited a degree of fracture, but less than with the 0.4 mm tool. The surrounding matrix did not exhibit damage from the larger radius tool as was seen with the 0.4 mm radius. The surface of the discontionuous fiber composite machined with 9.5 mm radius exhibited no fiber fraying or other surface damage as seen with the 0.4 mm radius. The surfaces of discontinuous PTFE fiber parts are also shown in Figure 11 in macro-scale images. The surface was shown to be smooth without visual evidence of damage or other visible roughness.

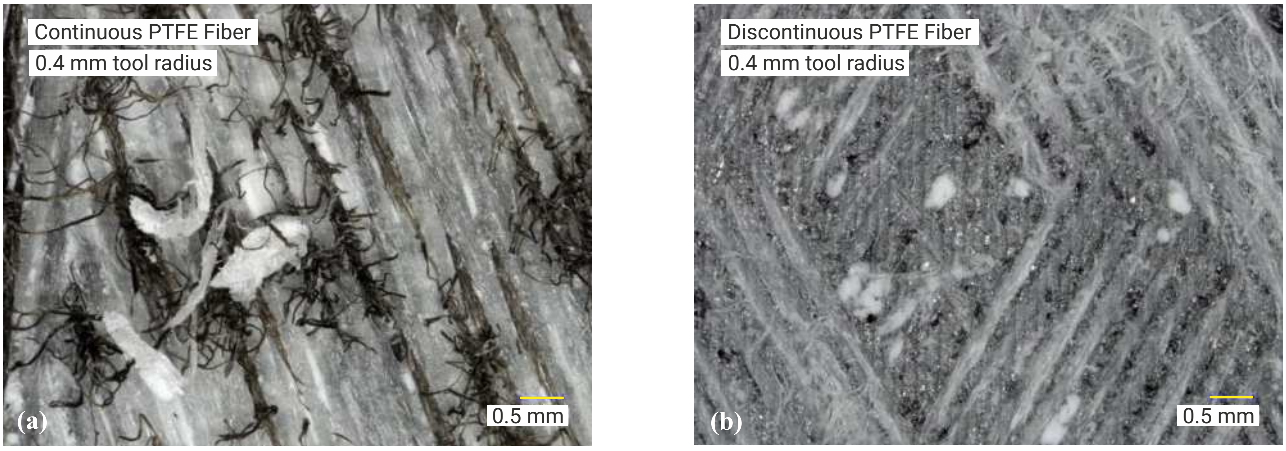


Figure 9: Surface conditions of the two materials following single point machining using a 0.4 mm radius tool. Image (a) shows the continuous PTFE fiber bearing and (b) the discreet PTFE fiber bearing material.

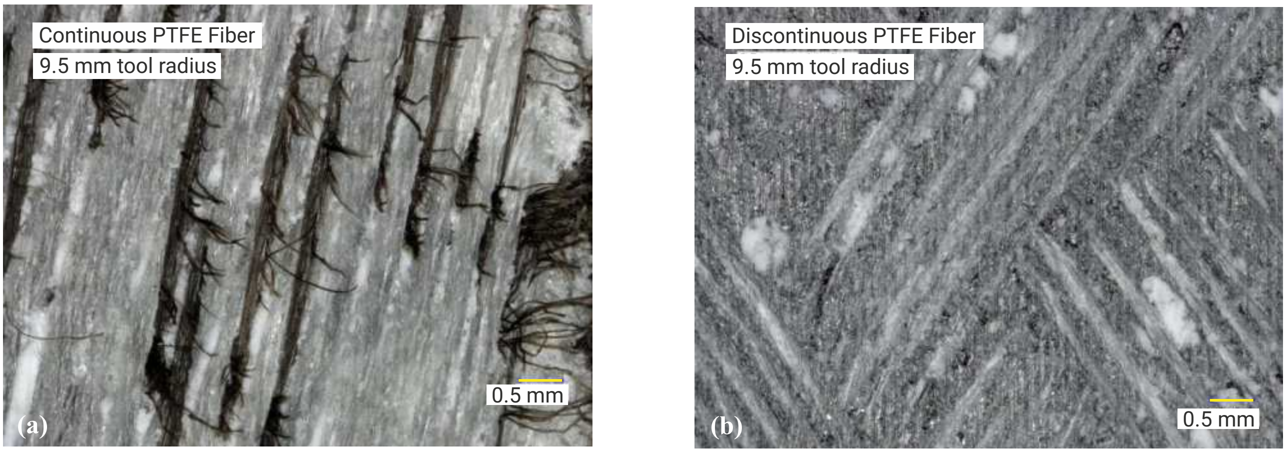


Figure 10: Surface conditions of the two materials following single point machining using a 9.5 mm radius tool. Image (a) shows the continuous PTFE fiber bearing and (b) the discreet PTFE fiber bearing material.

3.3 Dimensional Analysis

Discontinuous fiber composites were machined in a master die (Figure 5b) to evaluate dimensional response. Parts were removed from the die and measured in the free state via CMM to identify the final diameter. Diameter was measured at 3 points along the 75 mm bearing length and resultant diameters were compared to ISO tolerance ranges H4 to H7 as shown in Figure 12. The diameter data showed that the discontinuous fiber structure demonstrated the capability to meet H4 tolerance range. It should be noted that the tolerance capability in ongoing production would be highly dependent on the capability of the equipment used to perforrm the machining process.

4. Conclusions

- Effect of cutting tool radius used a single point machining process had a significant impact on surface roughness of the final composite.
- Discontinuous PTFE fibers bound in a thermoplastic fiber matrix were shown to be favourably responsive to single point machining in comparison to continuous PTFE fiber composites.
- Cutting speed was shown not to impact machining response on the discontinuous PTFE fiber composite in the range from 1.2 to 3.3 m/s, but did impact the response of the continuous PTFE composites with higher speed resulting in greater roughness.
- Dimensional capability of the discontinuous fiber bearing structure was measured to be with H4 tolerance in this study, but was noted to be highly dependent on equipment used to machine.

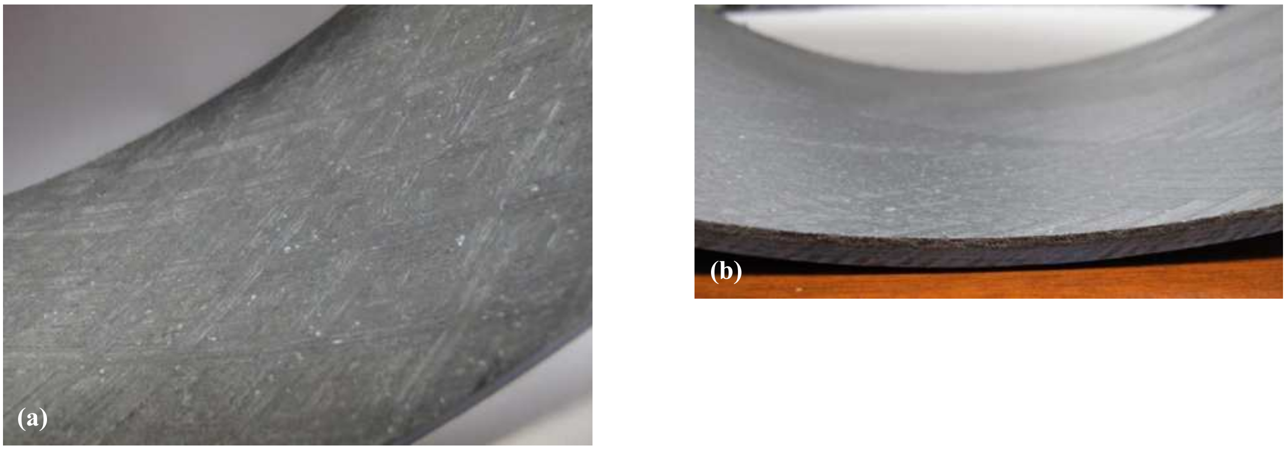


Figure 11: Macro images of the machined surface of the discontinuous PTFE fiber bearing liner, produced with a 3 mm radius tool. Images (a) and (b) were processed similarly, photographed at different angles.

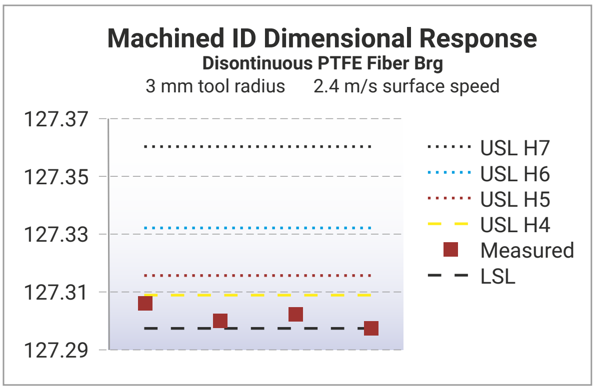


Figure 12: Dimensional results from discontinuous fiber bearing machined with a 3 mm radius tool. Dimensional ranges are shown for a range of tolerance limits as reference.

4. References

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