The effect of engineered surface topography on the tribology of CFR-PEEK for novel hip implant materials

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Abstract

Carbon-fibre-reinforced polyether ether ketone (CFR PEEK) has the potential to improve the wear resistance of orthopaedic implants and its performance can further be enhanced by surface texturing. This scoping study investigates the effects of surface textures on the friction behaviour of CFR PEEK, using screening testing to identify textures suitable for development for acetabular cup applications.

Six surface textures were designed and applied to CFR PEEK discs using laser surface texturing, with the dimple diameter and area coverage being varied. These textures were tested using pin on disc testing, with a cobalt chrome pin representing the femoral head. Coefficient of friction and surface characterisation were used to assess the performance of each texture.

The results from the study demonstrated that all textures reduced the coefficient of friction compared to the plain material. The variation in the performance of the different textures highlighted a need for optimum texture characteristics to be found. 150 µm circular dimples, spaced 175-200 µm apart with an area coverage of 10-15% gave the best performance in saline lubrication at a contact pressure of 2 MPa and sliding speed of 50 mm/s. Tests should be repeated in a proteinaceous testing medium at various contact pressures and speeds.

Keywords; Artificial hip joint; surface topography; wear testing

1. Introduction

Over the course of the last decade the number of hip replacements being performed across England and Wales has increased dramatically, from 14,413 in 2003 to 76,274 in 2013, with around 93% of these surgeries being performed due to the patient suffering from osteoarthritis [1]. Throughout this period, the design of hip implants has continued to evolve due to an improvement in the understanding of material behaviour and joint tribology. For example, the adverse effects of metal – on – metal implants are well documented throughout literature and are the hip implant design most likely to result in revision surgery [1]. This is thought to be due to the wear particles causing aseptic loosening of the implant [1]. The most popular material choice for hip implants across England and Wales in 2013 was metal – on – polyethylene, accounting for 32.4% of all hip implants, with this material combination reducing the likelihood of subsequent revision surgery [1]. The improvements in this hip implant design are likely to be attributed to an improvement in wear performance, including a reduction in coefficient of friction and the production of fewer wear particles. Whilst this material combination has improved the performance of orthopaedic implant design there is still an interest in continued development of new implant technologies, in order to improve performance by further reducing the wear, increasing the lifetime of the implant and further reducing the need for revision surgery.

Many different material combinations have been investigated in an effort to improve implant performance, for example ultra-high-molecular-weight polyethylene (UHMWPE) or ceramic materials such as alumina can be used for the lining of the acetabular cup. A more recent material considered for use with orthopaedic implants is carbon fibre reinforced polyether ether ketone (CFR PEEK). This material consists of PEEK as a base material with the addition of short strands of carbon fibres in varying concentrations and orientations to improve the wear performance of the material. This material has been shown to perform as well or better than polyethylene for use within orthopaedic implants [2, 3, 4] although further investigation is required in order to understand fully the material behaviour and to optimise the application of such a material to implant design.

Further improvements in implant performance may be achieved by the use of different surface treatments. One such technique is the use of oxygen plasma treatment to help promote lubrication through protein absorption, controlling the hydrophilicity of the surface and reducing friction [5]. Other techniques to modify the surface of the material include surface texturing to improve the performance of implants. For example, textures may be used to control the size and shape of wear particles produced [6], control temperature within the implant [7], and reduce the coefficient of friction [5, 8-10]. A number of mechanisms have been suggested to explain the improvement in tribological performance achieved by textures surfaces, including: decreasing the contact area to reduce adhesion; trapping wear debris to prevent further abrasive wear; reserving lubricant to improve anti seizing ability; and boosting the hydrodynamic performance of the surfaces [11]. Additionally, by applying textures to the material surface, the surface energy also has the potential to be controlled and therefore it would be possible to create hydrophobic surfaces and promote boundary lubrication in a similar way to oxygen plasma treatment [5].

Surface texturing has been shown to improve the tribological performance of bearing surfaces but the optimal design for the surface texture is highly dependent on the operating conditions, bearing materials and lubricant. Whilst to fully assess the performance of textured surfaces for hip joint applications a more complex method is required, the initial testing in this paper has used a simple pin on disc tribometer. This allows the surfaces to be tested under conditions of load and speed which are representative of mean conditions within the hip, allowing rapid and low cost screening of candidate surface textures. In the literature related to textured surfaces for hip joints, circular dimples have been found most effective in reducing the coefficient of friction but the diameter, depth and spacing of these circular dimples can have a significant effect on the tribological performance [10]. The optimal dimple density reported varies significantly, with one study reporting an optimal density of 2 – 20% [12] and another reporting an optimal dimple density in excess of 40% [11]. This variation in optimal characteristics could be attributed to different testing conditions used within the different studies, as the effectiveness of the textures has been demonstrated to be dependent upon factors such as contact pressure and sliding speed [9].

This study aimed to investigate the use of CFR PEEK as a material for use in hip implant design, more specifically the lining of the acetabular cup, including investigating the behaviour of the material under different loading conditions. The primary focus of this study was to investigate the use of surface texturing to improve the tribological performance of CFR PEEK for use in hip implants with a metal counterface, through the use of pin – on – disc wear testing and surface profilometry. It was envisaged that the use of textures would lower the coefficient of friction between the two mating surfaces when compared to the non-textured surfaces. Furthermore, based on existing evidence within literature this work set out to investigate the hypothesis that certain of these textures will prove to be more effective at reducing the coefficient of friction than others.

2. Materials and Methods

2.1 Pin on Disc Tribometer

A bespoke pin on disc tribometer was used for this work, and is shown in Figure 1. The rig consists of a 0.75 kW variable-speed motor driving a spindle and platen, to which the test disc is attached. The pin is mounted in a holder attached to a pivoting arm, which is mounted in supporting bearings such that it is free to move both vertically and horizontally. The arm is balanced by adjusting the position of a counterweight at the opposite end of the arm from the pin, to ensure that the contact force is only generated by the applied masses attached above the test pin. A load cell is used to prevent the arm from rotating in plan view, thus measuring the friction force generated at the contact. A tachometer is fitted to measure the rotational speed and count rotational cycles. Additionally two thermocouples are used to measure both pin and ambient temperature. Data is recorded on a PC through a LabVIEW program, using a National Instruments data acquisition device (USB-6211). For this work, data was captured every five rotations, with 500 samples being collected at a frequency of 10,000 Hz and averaged to reduce noise within the data.

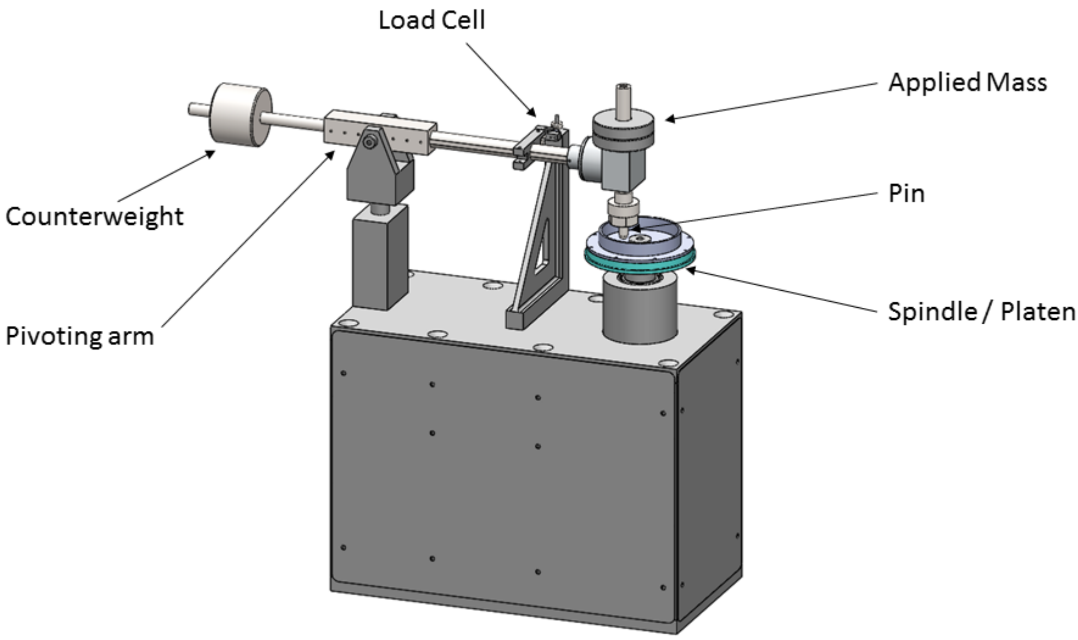

Figure 1: Pin on disc tribometer used for wear testing

Although using such a tribometer does not produce results which are mechanically equivalent to those produced using a hip joint simulator [5] and certainly does not replicate directly conditions within the human hip joint, it is argued that the use of this tribometer allows some efficient insights to be gained into the potential benefits of surface texturing for reduction in coefficient of friction in implants.

2.2 Loading Conditions

Due to the large range of contact pressures (0.12 – 3.60 MPa) and sliding speeds (10-109 mm/s) reported in literature [13-19], an initial study was conducted to investigate the effect of these test parameters on the behaviour of a polished CFR PEEK disc with a mean roughness (R_a) of around 0.15 µm. The test parameters are detailed in Table 1. Following the results from this initial study, each surface texture was assessed using the same loading and kinematic conditions as shown in Table 2, with the contact pressure and sliding speeds falling within the previously accepted ranges. Throughout the work, phosphate-buffered saline was used as a lubricant which has a viscosity of 0.931 mPa s [20]. This is comparable with the viscosity of bovine serum, commonly used in hip simulators, which has a typical value of 0.9 – 1.2 mPa s [20, 21]), and is of a similar order to periprosthetic human synovial fluid with a typical viscosity of 2.5 mPa s [21].

Table 1: Load conditions used for the various tests exploring the effect of load and speed on the performance of CFR – PEEK

Test Number	Test 1a	Test 1b	Test 2a	Test 2b	Test 3a	Test 3b
Sliding Speed (mm/s)	50.4	100.7	50.4	100.7	50.4	100.7
Disc Rpm	26	52	26	52	26	52
Wear track (mm)	ø37	ø37	ø37	ø37	ø37	ø37
Number of Revolutions	66,000	66,000	66,000	66,000	66,000	66,000
Applied load (N)	5	5	13	13	26	26
Contact Pressure (MPa)	2.02	2.02	2.78	2.78	3.50	3.50
Lubrication	PBS Saline	PBS Saline	PBS Saline	PBS Saline	PBS Saline	PBS Saline

Table 2: Standard test conditions for wear testing using the pin on disc rig

Test Conditions Summary	
Sliding Speed (mm/s)	49.8
Disc Rpm	27
Wear track (mm)	ø35.2
Number of Revolutions	66,000
Applied load (N)	5
Contact Pressure (MPa)	2.0
Lubrication	PBS Saline

2.3 Test Specimens

In order to determine an appropriate surface roughness for the discs prior to texturing, the surface of an existing polyethylene acetabular cup lining was characterised using a Taylor Hobson Form Talysurf 2 surface profilometer. Four areal measurements were conducted resulting in an average S_a value of 0.15 µm. A total of seven CFR PEEK discs were then prepared for testing. The CFR PEEK used within this study was 30% filled with pitch fibres, supplied by Invibio Limited, UK. Each disc was polished to a nominal surface roughness of 0.15 µm. Following polishing, six of the discs were subjected to laser surface texturing (LST), with the seventh disc being kept as a polished reference surface.

Six different surface texture designs were applied to the discs, all utilising circular dimples as existing studies had found the circular shape to be the most effective in improving the tribological performance of various materials and surfaces [10]. The textures were designed to allow for various parameters, including dimple depth, diameter and texture density to be investigated (Figure 2, Table 3). The textures were applied to the disc using a 20 W single mode fibre laser operating at 1064 nm. Following the application of the textures, samples were cleaned using an ultrasonic cleaner, and then the textures were characterised by conducting areal measurements of the surface using surface profilometry subsequently analysed to characterise the dimple depth, diameter and density of the textures.

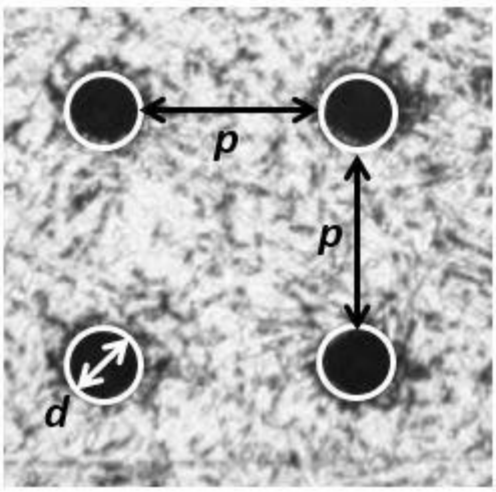

Figure 2: Circular dimple texture design parameters, demonstrated on microscope image, where *d* is the diameter of the dimple and *p* the dimple spacing

Table 3: Summary of texture parameters, with the target characteristics referring to the characteristics of the textures as designed, and the achieved characteristics referring to the values that were measured from the as-manufactured surfaces following the laser texturing process

Texture Number	Target Dimple Diameter, *d* / µm	Target Dimple Spacing, *p* / µm	Achieved Dimple Diameter, *d* / µm	Achieved Dimple Spacing, *p* / µm	Achieved Texture Density (% area coverage)	Achieved dimple depth *h* / µm
1	50	50	50.8	49.9	20.0	19.0
2	50	100	54.9	92.4	10.9	16.6
3	100	100	81.4	121	13.3	32.0
4	100	200	85.2	219	6.2	32.5
5	150	150	130.3	180.7	14.4	52.6
6	150	300	129.9	335	6.1	51.9

The pins were manufactured from cobalt – chrome, with the surface of the pins polished to a Ra better than 0.07 µm Ra, which is similar to that of a typical femoral head. Each pin was designed with a slight radius on the surface to allow for the required contact pressure to be generated when a reasonable load was applied to the test rig. All pins were manufactured by the industrial partner, with the material grade and surface finish meeting the specification of commercially available cobalt – chrome femoral heads. The surface of each pin was characterised using 3D surface profilometry before and after testing of the samples.

3. Results and Discussion

3.1 Influence of load and speed on coefficient of friction

Prior to testing the different surface textures, an investigation was carried out on the effects of load and speed on the coefficient of friction, using a polished disc. The test parameters and conditions investigated in this study were presented in Table 1, and were chosen to replicate the behaviour and environment within the human hip. Contact pressures occurring within the natural human hip are reported to range from 0.12 – 2.5 MPa, although these data were only based upon one patient study [13]. Instrumented hips have also been used to investigate contact pressure, with one study reporting a peak pressure of 3.69 MPa during a gait cycle [14], and a separate study reporting peak pressures of 5-6 MPa during gait [19]. Further studies using instrumented hips have found peak levels in excess of

7 MPa during stair climbing, up to 18 MPa when moving from a sitting to a standing position or walking downstairs, and also found an uneven pressure distribution within the hip, with these high peak pressures occurring at local points [19, 22]. Research also suggests that the highest peak forces occur during stumbling [23] although as this study presents the results in terms of contact forces it is difficult to convert these to contact pressure without reference to a particular geometry.

The contact pressures used within this study range from 2 – 3.5 MPa, which is below the peak contact pressures recorded within the instrumented hip studies (5 – 18 MPa) [19, 22]. When considering contact pressures used for *in vitro* simulation studies Baykal [15] stated that the critical contact pressure was 2 – 3.5 MPa, and that beyond this range articulating surfaces stopped displaying clinically relevant surface behaviour with different wear mechanisms occurring. Therefore all contact pressures used in this study were kept within the range reported by Baykal [15]. Similarly there is significant variation in the sliding speeds that occur within the hip joint and the values reported in the literature range from 10 to 109 mm/s [15-18].

The results for the varying of load and speed are shown in Table 4, with the mean coefficient of friction being considered. The experimental results demonstrate that at higher sliding speeds there is a lower mean coefficient of friction, which is as expected based on established hydrodynamic lubrication theory with a higher speed promoting more effective lubrication with a thicker lubricant film and less direct contact between the surfaces. These results clearly demonstrate the effect of speed, as consideration of the standard deviations given in Table 4 demonstrates that the difference in mean coefficients of friction as the speed is changed is much greater than the variability in the individual measurements. Additionally, the results show an increase in coefficient of friction with an increase in contact pressure, although this effect is less clear than the effects of speed.

Table 4: Mean coefficient of friction for the different tests under varying load and sliding speed, with all tests conducted on polished CFR PEEK

Mean coefficient of friction ± SD for full test duration (66,000 cycles)			
	2.0 MPa	**2.8 MPa**	**3.5 MPa**
50 mm/s	0.117 ± 0.056	0.120 ± 0.018	0.223 ± 0.024
100mm/s	0.031 ± 0.010	0.059 ± 0.038	0.096 ± 0.014

Sliding speed was found to be significantly more influential compared to the contact pressure, with the tests conducted at 50 mm/s resulting in a mean coefficient of friction approximately double that of the tests conducted at 100 mm/s for both the 2.8 MPa and 3.5 MPa contact pressures. Considering the tests conducted at 2.0 MPa, the mean coefficient of friction at 50 mm/s was over four times greater than the mean coefficient of friction at 100 mm/s.

In addition to evaluating the mean coefficient of friction for each of the different loading conditions, the wear occurring on the surface of each disc and pin was also considered. Optical microscopy showed varying levels of wear on the test discs with most discs showing only negligible levels of wear. For example, at 2.0 MPa contact pressure, the test conducted at 100 mm/s shows negligible surface modification whereas the test at 50 mm/s sliding speed shows clear indication of wear, as shown in Figure 3. At this condition there was measureable difference in the pre and post-test average roughness of the CFR PEEK disc with an increase in Ra from 0.10 µm pre-test to 0.14 µm post-test demonstrating a roughening of the specimen surface. This could potentially be due to the exposure of carbon fibres within the PEEK matrix, with Wang [4] demonstrating that such a mechanism occurs when investigating the wear performance of CFR PEEK against ceramic. As such this set of test conditions was chosen for the analysis of the tribological performance of the various textures, as this was likely to demonstrate the greatest differences between texture performance and the test conditions were known to fall within the physiological range of the hip.

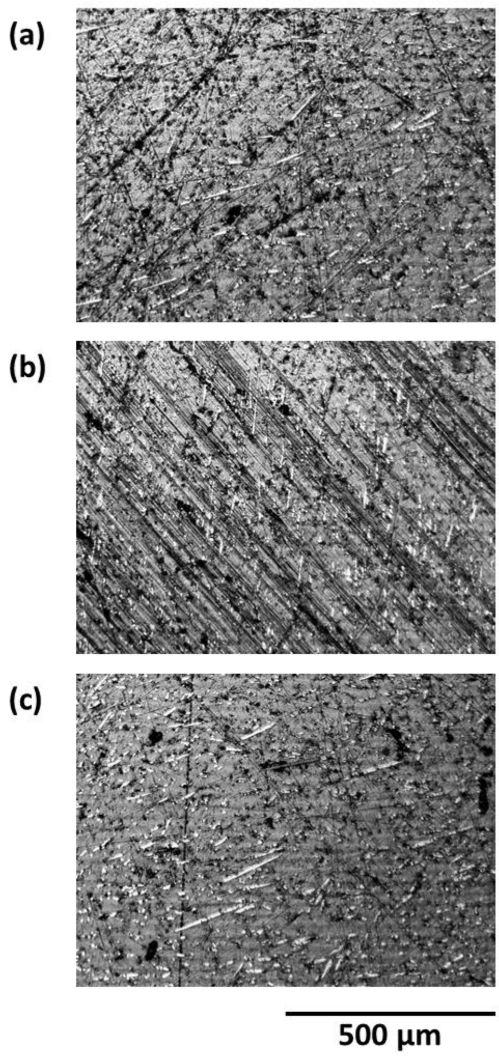

Figure 3: Optical micrographs of (a) pre-test disc surface (b) post-test wear track (2 MPa, 50 mm/s) (c) post-test wear track (2 MPa, 100 mm/s)

In order to assess repeatability of the experimental results, four repetitions were performed of the test undertaken at a contact pressure of 2 MPa and a sliding speed of 50 mm/s. These four tests resulted in a mean coefficient of friction of 0.12 with a standard deviation of 0.016, and an intraclass correlation coefficient of 0.884, demonstrating the repeatability of the results and thus validating the testing procedure used throughout this study.

3.2 Performance of textured surfaces

Following the investigation into the effects of load and speed, the performance of the different textures was assessed. The test conditions used for this study were presented previously in Table 2. The coefficient of friction for the different textures throughout the full test duration (approximately 7300 m of sliding distance) is displayed in Figure 4. Figure 4(a)-(c) clearly demonstrates a spike in the coefficient of friction for the tests using the polished disc, texture 1, and texture 2, with this sudden increase in coefficient of friction occurring at a similar point for each of these tests, between 40,000 and 50,000 disc rotations. This sudden increase in the coefficient of friction is important when considering the performance of the textures as a consistent performance of the textures is necessary for the application to hip joints. This sudden spike in coefficient of friction highlights the importance of the test duration when assessing the performance of these textures. In previous studies, tests have been run until the coefficient of friction stabilised, but from the results shown in Figure 4, this stable period does not necessarily last and the subsequent spike and unstable coefficient of friction has a significant effect when determining the optimal texture characteristics.

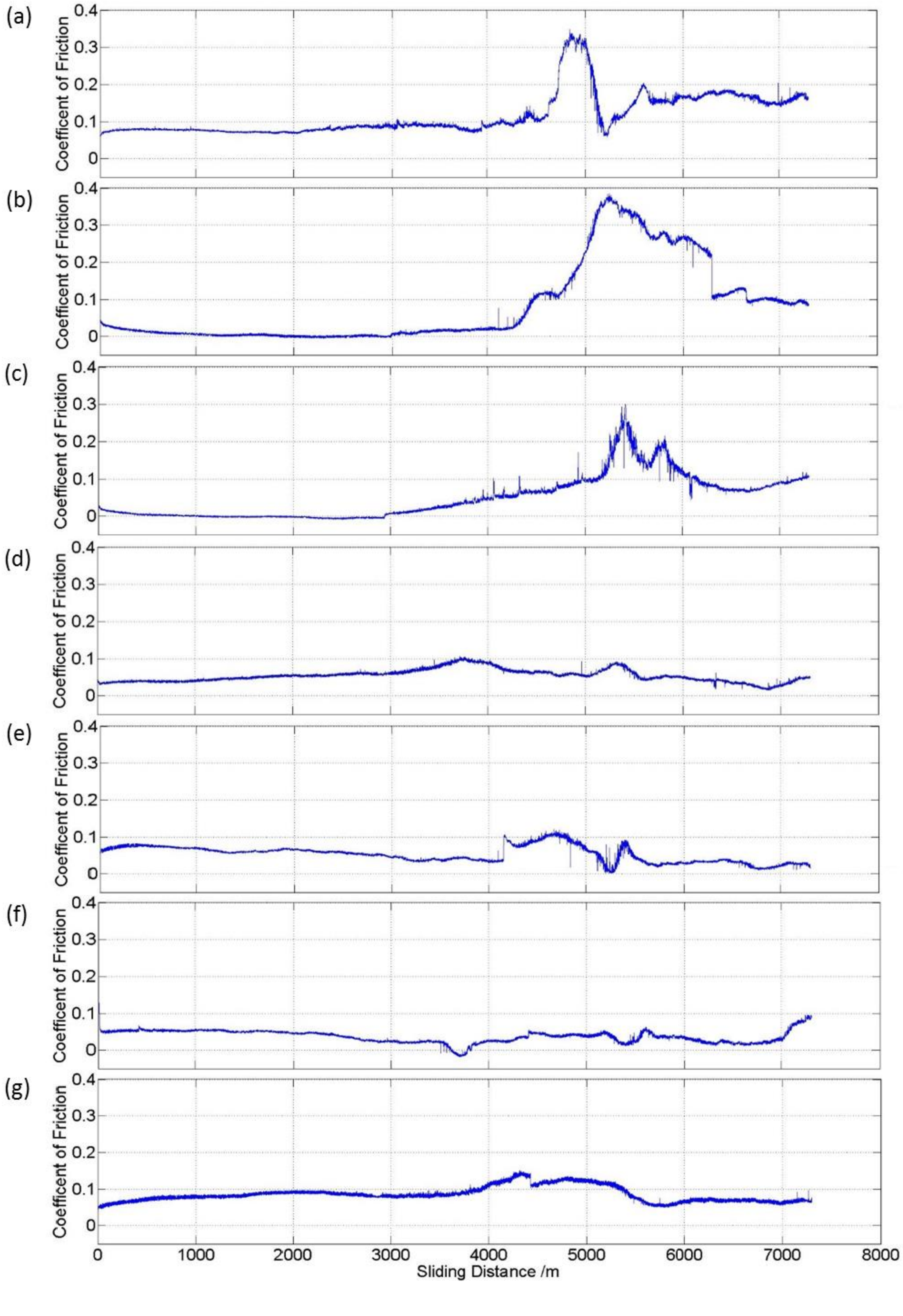

Figure 4: Coefficient of friction throughout the tests: (a) Polished Disc, (b) Texture 1, (c) Texture 2, (d) Texture 3, (e) Texture 4, (f) Texture 5, (g) Texture 6

As a result of this spike in coefficient of friction the results were analysed in two stages, the relatively stable pre-spike stage up to 40,000 cycles, and then for the entire test duration including the friction spike. Figure 5 shows the mean coefficient of friction for each of the different textures for both the pre spike period and the full test duration. As these data demonstrate, textures 3 – 6 show a more consistent performance over the full duration of the test and are therefore more suitable for use within artificial hip implants, with texture 5 showing the lowest coefficient of friction indicating that, of those textures tested, this shows the most suitable performance for hip-joint applications. When considering the mean and standard deviation of the different textures (Figure 5), textures 2-6 can be considered to perform differently to a non-textured surface. However with texture 1, the error within this data over the full test duration overlapped with the mean and error of the non-textured surface and therefore the frictional performance cannot be considered to be significantly different. Additionally the results demonstrate how the performance of each of the textures varies under the same loading conditions, further highlighting the importance of texture design optimisation to ensure the most effective design would be implemented in future hip implants.

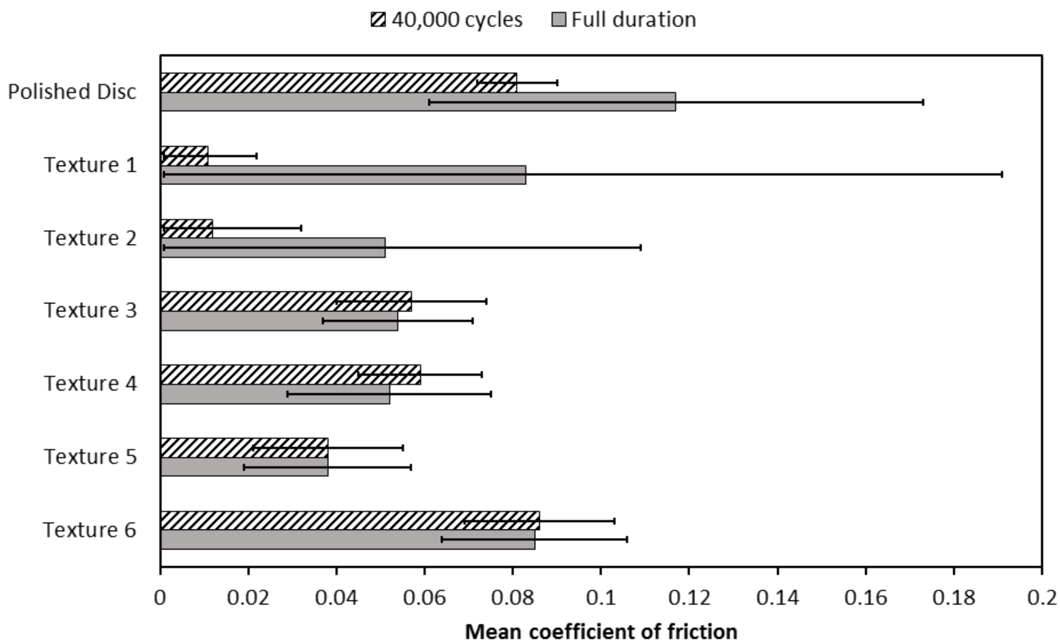

Figure 5: Mean coefficient of friction for the different textures with all tests conducted under the same loading conditions. Error bars represent ± 1 Standard Deviation.

When considering the coefficient of friction data for the initial 40,000 cycles of each texture, the results suggest that a small dimple size of 50 μm provides a lower coefficient of friction than the other larger dimples and would thus offer the greatest improvement in performance. However due to the spike in coefficient of friction that was seen within both data sets for these specimens they were found to be unsuitable for use in future implant design. The reason for this sudden spike in coefficient of friction seen within a number of the samples is potentially due to wear particle build up, with the smaller dimples providing insufficient volume to remove these wear particles from the lubricant, leaving them to remain an active component of the wear mechanism. The size and shape of the wear particles can be influenced by the lubrication used with Fang *et al.* [6] reporting that smaller wear particles were generated when using serum compared to those generated in using water as a lubricant. Furthermore Widmer *et al.* [5] found the choice of lubricant to affect polymer transfer between the mating materials when considering the behaviour of UHMWPE and Al_2O_3. They found that a transfer layer of polymer built up on the surface of the ceramic when testing with pure water, but not when testing with lubricants containing proteins. When using lubricants containing proteins, a boundary layer of proteins built up on the polyethylene surface, preventing polymer transfer. These results suggest that the spike in coefficient of friction seen within this study could be partially dependent on the lubricant used affecting the build-up of tribofilms on the surfaces and therefore requires further investigation.

The results from this study demonstrate that laser surface texturing can be effective in reducing the coefficient of friction, with the need to optimise the texture design for the desired application. This was expected based on existing literature, with a number of studies finding reduced friction and improved wear resistance. Qin *et al.* [10] found surface texturing reduced the coefficient of friction and displayed excellent wear resistance, attributing this performance improvement to a change in wettability or surface energy. Chyr *et al.* [9] suggests that microstructures increase the load-carrying capacity and the thickness of the joint lubricant film, reducing contact between the articulating surfaces. Furthermore surface texturing has been shown to influence the size and shape of the wear particles produced [6], this could be one of the reasons for the difference in performance of the different textures within this study, although the effects of using a non-proteinaceous lubricant must be borne in mind. Whilst the benefits of surface textures have been demonstrated, the effectiveness of surface texturing appears to be dependent on the lubrication regime, and under full fluid film lubrication conditions, surface dimples may in fact have a negative effect, resulting in a reduction in film thickness and increased asperity contacts [24]. This suggests the need to be wary when applying surface textures, and further emphasises the need to optimise textures for a desired application. However, in the hip joint where the lubrication regimes vary over the gait cycle, the benefits of surface texturing may be significant.

In order to consider the influence of each of the texture properties (coverage and dimple size) on frictional performance, Figure 6 (a) shows the mean coefficient of friction compared to the dimple spacing (p), and Figure 6 (b) shows the mean coefficient of friction compared to the percentage area coverage of the texture. This analysis of texture design suggests that the optimal dimple spacing for future textures lies within the 175 – 200 µm range, and percentage area coverage of the texture would be 10-15%. The optimal texture characteristics reported in literature vary, although this is likely to be due to a variation in the materials or testing conditions used within the study. Hunag *et al.* found that textures with a diameter of 50 µm were most effective at reducing friction when used to create a high percentage area coverage [11]. When considering the first 40,000 cycles conducted within this study the most effective texture had a dimple diameter of around 50 µm, although this texture was found to be unsuitable when used for long durations. However, Wakuda *et al.* suggests an optimal dimple size of 100 µm at a density of between 5-20% [12]. Whilst the optimal texture density or percentage area coverage is in line with the findings of this study (10-15%), the dimple size is smaller. This variation can be attributed to different loading conditions, and highlights the need to explore the textures under a range of conditions to fully optimise the texture design.

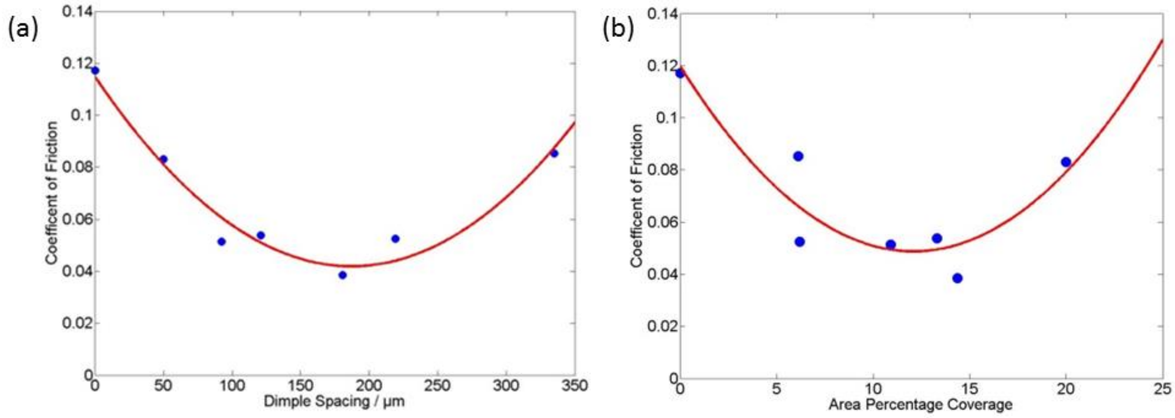

Figure 6: Comparison of surface characteristics to coefficient of friction, with a showing the effect of dimple spacing (curve is polynomial order 2, R^2 = 0.9578, p=0.002) and b showing the effect of area percentage coverage (curve is polynomial order 2, R^2 = 0.833, p=0.028).

In addition to considering the coefficient of friction of each of the different textures, the wear on the surfaces of the pin and disc specimens was also investigated through the use of surface profilometry and optical microscopy. Figure 7 shows the pre and post-test images of each of the different textures, with the post-test images showing a qualitative variation in the appearance of the wear scars occurring on the surface of the discs. Textures 1, 2 and 6 appear to show the most severe wear scars on the surface of the discs. Textures 3, 4 and 5 show negligible visible wear scars. However, it must be noted that this assessment is purely based on visual observations of the wear scars, and that to fully investigate the wear performance of these surfaces more quantitative approaches would be necessary.

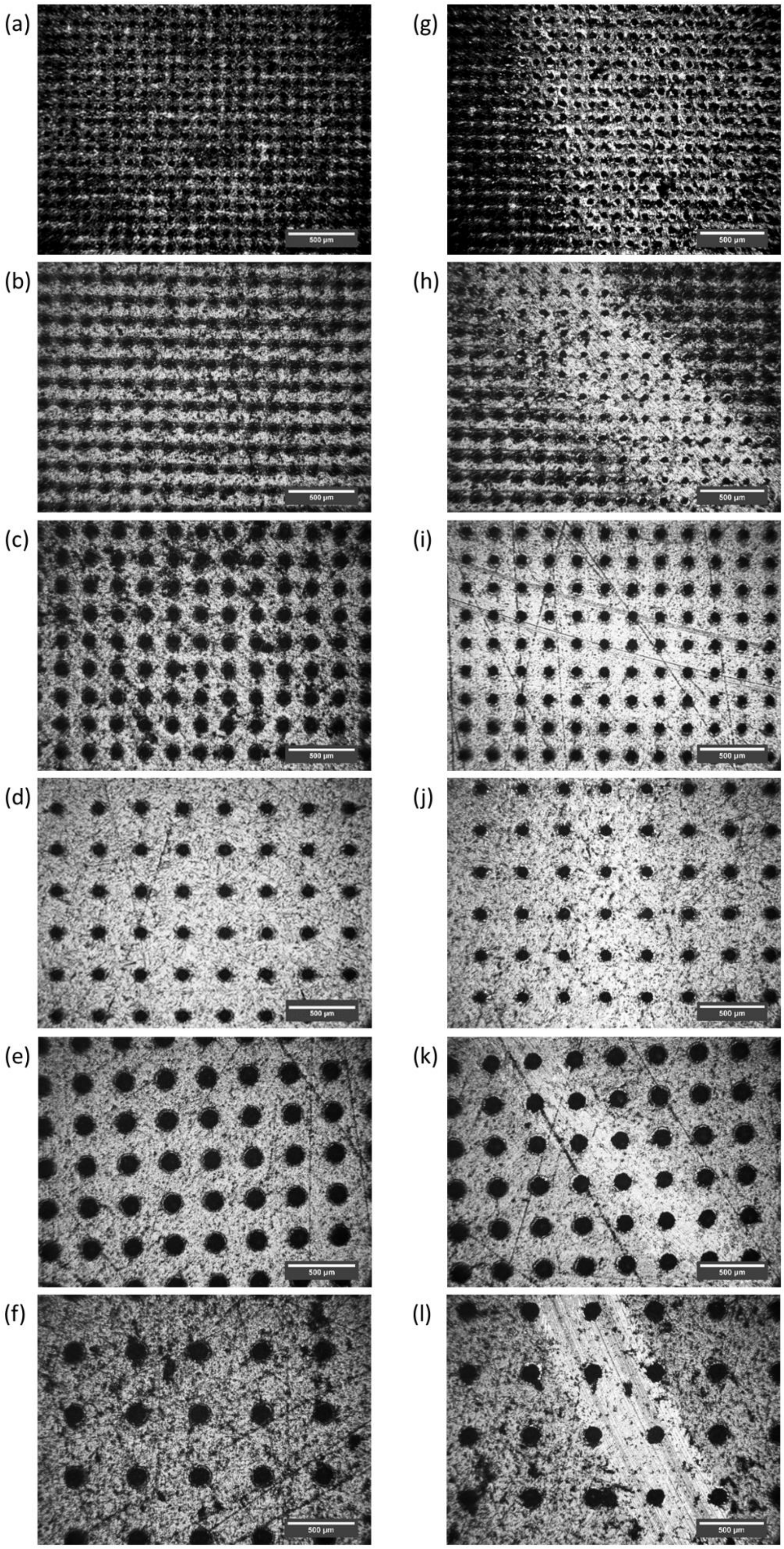

Figure 7: Microscope images of the textures pre-testing, (g-l) microscope images of the wear scars. Each scale bar represents 500 µm.

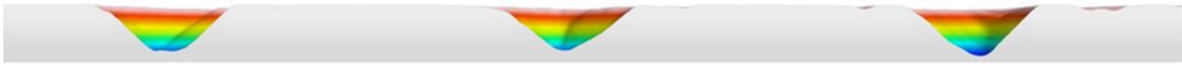

Figure 8: Profile of the dimples created using laser surface texturing. Example shown is an section of Texture 2

Whilst each of the textures produced as part of this study had similar geometries due to being produced using lasers, it is important to note that the shape of the dimple profile can affect the results. An example of the dimple profile created using laser surface texturing for this study can be seen in Figure 8, which shows the conical shape of the dimples. Existing studies have investigated the effect of the shape of the texture using numerical and computational methods. Results demonstrated that textures with a flat or wedge shaped bottom lead to the greatest increase in fluid film thickness [25, 26], suggesting that these shapes would offer a greater reduction in friction when compared to the conical shapes created within this study.

When considering the surface of the pins used for each of the textures there was again a noticeable variation in the wear scars seen using optical microscopy. An example of this can be seen in Figure 9(a) showing the post-test pin of texture 5, and Figure 9(b) showing the post-test pin of texture 6. Both texture 5 and 6 had dimples of the same diameter (150 µm) but had different dimple spacings of 150 µm and 300 µm, respectively. These images clearly demonstrate the important links between texture design and the resulting wear on the surface of the specimens. Again, more quantitative wear measurements are required to investigate this fully, but optical inspection suggests that the more severe wear scar was seen on the pin used for texture 6 which was found to have the higher mean coefficient of friction of the two samples. The difference between the two textures relates solely to texture density, with texture 5 having a percentage area coverage of 14.4% compared to 6.1% for texture 6. This further demonstrates optimal texture characteristics, with the optimal percentage area coverage within this study found to 10-15%, based on coefficient of friction measurements. When comparing this with the results from Wakuda *et al.*, the optimal texture density was found in their work to be 5 – 20% [12], with texture 6 being at the lower end of the values suggested by Wakuda.

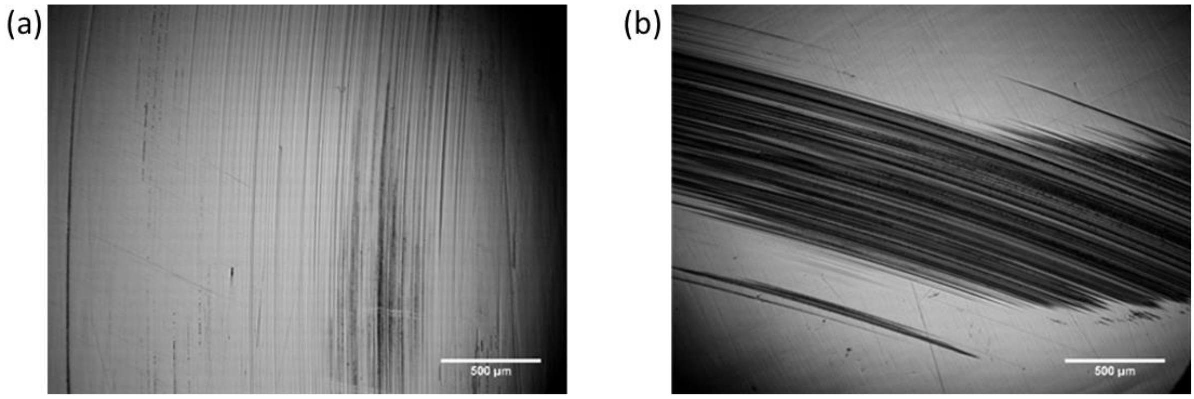

Figure 9: Microscope images post wear test of the surface of the pins, with (a) showing the surface of the pin for texture 5, and (b) showing the surface of the pin for texture 6

3.3 Limitations and further work

The results presented within this study provide an initial understanding of the effect of surface texturing on the tribological performance of CFR PEEK as a material for use in hip implants. The results demonstrate the potential benefits of using such technology to reduce the coefficient of friction within the joint, and highlights the importance (and difficulty) of determining the optimal texture design characteristics. To expand upon this body of work, further additional textures should be assessed to help identify optimal texture characteristics and improve confidence in the results presented. More complex textures could also be investigated, such as a combination of large and small dimples. Textures 1 and 2, which featured small dimples (50 µm) had a very low average coefficient of friction up to 40,000 cycles, but failed to provide a consistent performance over a longer test duration. However textures with the larger dimples provided a consistent performance but failed to lower the coefficient of friction up to 40,000 cycles when compared to Textures 1 and 2. Therefore a combination of different sized dimples may produce a more effective texture, utilising the best characteristics of both the small and large dimples. Testing of these combined textures could be used to determine if the area percentage coverage and dimple spacing relationships are unique to dimples of the same size or if the same trends occur with dimples of various sizes.

Pin on disc testing was used to assess the tribological performance of the different textures. This test uses simplified geometry and kinematics compared to the natural hip, and is a limitation within the current study. This testing method was chosen due to simplicity and low cost for this initial study into surface texturing, as it allowed the efficient and rapid screening of various textures, but for any further work more advanced testing techniques would be beneficial, that more accurately replicate hip kinematics [4, 27, 28]. Whilst this would be the aim for future testing and texture development, further study could be conducted exploring different kinematics under the same loading conditions, such as reciprocating wear, to understand the potential limitations and benefits of the individual textures, further aiding the development of optimal textures. Pin on disc testing does however provide valuable knowledge, allowing some texture designs to be immediately eliminated from future studies.

Additionally, bovine serum lubrication should be used in place of PBS saline (chosen for simplicity of handling in the current study), as testing with protein-free lubricants such as saline will not necessarily produce wear-surface appearances and wear debris morphology characteristic of that observed following clinical retrieval [26]. Additionally a boundary layer of proteins can build up on the surface, leading to a reduction in friction [5] and test results becoming more representative of *in vivo* conditions. The lubricant used also has the potential to influence the size and shape of the wear particles produced [6]. These effects could in turn influence the spike in friction data seen within this study in Figure 4 (a-c). A further limitation of this study was that no quantitative wear measurements were conducted. Any future studies would be improved by incorporating quantitative wear measurements, for example measuring mass loss or calculating volume loss based on surface profilometry measurements, as used in other studies [4, 27]. In order to do this an additional soak study would be required in order to correct for the absorption of lubricant [4]. Furthermore to fully understand the effect textures can have on the tribological performance of CFR PEEK, the change to the microstructure due to the application of laser surface texturing needs to be considered. Further work would incorporate more advanced microscopy techniques to begin to study and understand these changes.

4. Conclusions

All textures investigated as part of this study reduced the coefficient of friction and would therefore be expected to improve the performance of future hip implants. Although all texture designs reduced the coefficient of friction of the mating materials, each texture performed very differently, demonstrating a need to determine the optimal texture design. The most effective texture tested within this study was found to be circular dimples of 150 μm diameter spaced at 150 μm, with this texture resulting in the lowest mean coefficient of friction and low levels of wear on the surfaces of both mating materials. Additionally textures with a small dimple diameter were found to be unstable over the full test duration, suggesting they would not be suitable for long term use within implants. It was also noted that the typical test duration reported in previous studies could give anomalous results when compared to the longer tests in this work.

When considering the optimal design characteristics of the different textures, the results from the study suggest a dimple spacing within the range of 175 – 200 μm and a percentage area coverage of 10-15% would be the most effective in reducing the coefficient of friction. These results require additional textures to be designed and evaluated to improve the confidence within these design parameters.

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6. Disclosure

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7. References

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