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

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A B S T R A C T

Carbon-fibre-reinforced polyether ether ketone (CFR PEEK) has the potential to improve the wear resistance of orthopaedic implants and its performance can be further 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.

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 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 with the addition of short strands of carbon fibre in varying concentrations and orientations to improve the wear performance of the material. This material has been shown to perform as well as 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

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performance achieved by textured 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 suggesting 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 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 Fig. 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.

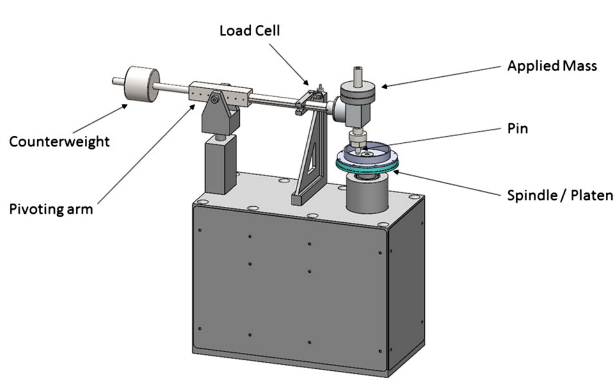

Fig. 1. Pin on disc tribometer used for wear testing.

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 of 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].

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

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