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ScienceDirect

Ceramics International 41 (2015) 681–690

CERAMICS INTERNATIONAL

www.elsevier.com/locate/ceramint

Improved friction and wear performance of micro dimpled ceramic-on-ceramic interface for hip joint arthroplasty

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Received 27 June 2014; received in revised form 27 August 2014; accepted 28 August 2014
Available online 6 September 2014

Abstract

The purpose of this study is to investigate the tribological effect of micro-dimpled surface textures for application in ceramic-on-ceramic hip prostheses. A rectangular array of circular dimples was selected as the texture pattern. A CNC micro drilling machine was used to fabricate these dimples on a flat ceramic substrate. Tribology tests were performed by using a pin-on-disk method with selected hertzian contact pressures and speeds based on normal gait of a hip joint, and results compared with non-dimpled surface. A dimpled surface with large dimple diameters and a high dimple density (Ø400 μm and density 15%) showed significant tribological performance gains, including a nearly 22% friction and 53% wear reduction.

Keywords: ceramic-on-ceramic hip joints; Micro-dimple; Wear

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1. Introduction

Hip joint replacement is one of the most successful orthopaedic surgery procedures, and is a widely practised method for restoring mobility to hip joints. It is estimated that more than 0.6 million hip replacements are performed per year worldwide, and the number will increase 170% by the year 2030 [1]. Despite the excellent success of hip arthroplasty, it is still affected by a need for revision surgery. Therefore, there is scope to improve it, either from an engineering or patient point-of-view. In general, the durability of artificial hip joints (either metal-on-polyethylene or ceramic-on-polyethylene) is 15 years with active lifestyles, which may not be acceptable to patients under 60 years. These younger people make up 44% of overall osteoarthritis patients, and longer lasting hip prostheses would be much more suitable for them [2–5]. A ceramic-on-ceramic (CoC) hip prosthesis is a potential candidate to fulfil the demands of young patients; however, aseptic loosening and fracture rates have still concerns with their use [6–9]. Otherwise, ceramic hip joints have better mechanical properties, such as hardness, and a superb polishing capability, and better biocompatibility. Aseptic loosening is a complex mechanism which is mostly associated with an excessive wear rate and morphology of wear debris. The wear of the articulating surfaces and adverse tissue reactions to wear debris causes loosening and implant failure [10]. CoC hip joints have lower wear rates, compared to metal-on-metal and metal-on-polyethylene hip joints. Removal of micro or nano sized wear debris from the contact interface reduces further abrasive wear of contact interface and possible reaction with surrounding tissue [3,11].

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http://dx.doi.org/10.1016/j.ceramint.2014.08.123
0272-8842/

The application of a surface texture, such as micro-dimples or grooves, is already established as a way to improve the tribological performance of sliding surfaces. For example, dimpled golf balls have a much higher aerodynamic lift force [12]; textured engine cylinders have lower friction thus are more effective in engine performance [13–16]; and sliding bearings have a longer life with a well-defined micro dimple. Yu et al. [17] showed that micro-textured surface geometry is capable of producing a higher hydrodynamic pressure and thus increasing the load carrying capacity. Dimpled surfaces decrease the surface contact area, and thus the coefficient of friction deceases. Further, such dimples can trap wear debris, preventing wear of contacting surfaces from third body hard particles. Previous studies [4,18–22] mentioned a thicker tribological film due to the micro dimples.

The application of a micro dimpled surface texture to artificial hip joints has been investigated recently. A numerical model, established by Gao et al. [23], indicates that dimpled surfaces have potentially beneficial effects on the lubrication performance of metal-on-metal hip replacements, particularly under predominant boundary lubrication conditions. The experimental investigation conducted by Sawano et al. [24] with metal-on-polyethylene demonstrated that a 1 μm deep micro dimple was successful at reducing the amount of wear by up to 61% compared to a polished surface. Ito et al. [11] conducted tribological tests to identify the effect of a dimple surface on metal (Co–Cr)-on-polyethylene (UHMWPE) hip joints on the hip simulator that represented the load and motion of hip joints. A significant percentage of friction (30%) and wear rate (68%) was reduced after 10×10^5 cycles with a well-designed dimpled surface (diameter of 0.5 mm, pitch of 1.2 mm, and depth of 0.1 mm). Choudhury et al. [25,26] conducted both theoretical and experimental investigation of simulated metal-on-metal hip joints, and came to the conclusion that a well-defined honed surface has high potential for use as a hip joint interface, since it was found to increase hydrodynamic pressure, captured wear debris, and lower the friction coefficient.

Our previous study [27] also revealed that the friction coefficient can be significantly reduced by using a micro-dimpled ceramic surface in simulated CoC hip joints. Two sets of dimple parameters (diameter and dimple density) were utilised and it focused mainly on the precision of micro tool induced dimples and their effects on the mechanical properties of the surfaces. The aim of the present study is to conduct a detailed tribological investigation (friction, wear and wear debris) on 3 different types of dimple array, and compare their performance to non-dimpled ceramic surface with selected loads and speed based simulated hip joints.

2. Material and methods

2.1. Sample preparation

A pin on disk experiment was conducted using a tribometer to measure the frictional coefficient, as it enables to measure frictional force. Modern hip simulators enable the replication of many operating parameters, including dynamic loading, multidirectional sliding direction, controlled temperature, and both multi-station and long-run programmes. However, none of them provides in-situ friction coefficients. Thus, most research into friction relies on the more conventional pin-on-disk tribometer method to understand the fundamental mechanisms of biotribology, such as friction coefficient and film thickness variation over time. For the present study, we have used a pin-on-disk tribometer to partially replicate a hip joint, in terms of contact pressure, speed and lubrication [27,28]. The rectangular disk (dimension $15 \times 15 \times 6$ mm^3, 99.6% Al_2O_3) and the cylindrical pin (dimension Ø6.35 mm × L6 mm, 99.6% Al_2O_3) were prepared based on the specification of the tribometer. All the samples were polished in a grinder with different grades of diamond polycrystalline suspension to achieve a mirror surface finish.

2.2. Dimple fabrication

The key parameters for this experiment are the dimple array patterns and the dimple profile, because it was previously reported that these parameters affect the tribology of a system [29–34]. Three types of dimple array patterns were chosen for this study. The fixed variables in this study are the diameter of the dimple, the dimple depth, and the dimple pitch (centre distance between two dimples). Table 1 summarises the dimple parameters. CATIA V5 design software was used to draw the dimple array patterns. According to these designs, a CNC micro drilling machine (Mikrotools DT110, Singapore) was programmed. For this study, diamond drill bits (UKAM Industrial Superhard Tools, U.S.) were used to produce the micro dimples via a drilling machine. The polished disk samples were placed inside the CNC micro drilling machine.

Table 1
Dimple parameters.

Samples	Diameter, Ø (μm)	Depth, h (μm)	Aspect ratio (λ=h/Ø)	Pitch, (μm)	Dimple density, A (%)	Total no. of dimples
Non-dimple	0	0	–	0	–	0
1: D300-P5	300	30	0.1	1000	5	121
2: D300-P10	300	30	0.1	550	10	225
3: D300-P15	300	30	0.1	400	15	324
4: D400-P5	400	30	0.075	1800	5	49
5: D400-P10	400	30	0.075	1200	10	100
6: D400-P15	400	30	0.075	900	15	144