Available online at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/jmbbm

Research Paper

Experimental investigation of the effect of surface roughness on bone-cement-implant shear bond strength

Alexander Franciscus van Tol[a], John E. Tibballs[b], Nils Roar Gjerdet[c], Peter Ellison[a,*]

[a]Biomaterials, Department of Clinical Medicine, University of Bergen, Bergen, Norway
[b]NIOM, Nordic Institute of Dental Materials, Oslo, Norway
[c]Biomaterials, Department of Clinical Dentistry, University of Bergen, Bergen, Norway

ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form
12 July 2013
Accepted 4 August 2013
Available online 19 August 2013

Keywords:
Shear strength
Surface roughness
Bone-cement
Femoral stem
Total hip replacement

ABSTRACT

Debonding of cemented bone implants is regarded as a major contributor to complications. The relationship between shear bond strength and surface roughness has been investigated, however there are inconsistencies in the trends reported in different studies. The shear strength between poly(methyl methacrylate) bone-cement and sand blasted cobalt–chromium and titanium alloy surfaces was measured to investigate the relationship between interfacial shear strength and surface topology. Surface roughness was quantified by a power law relationship fitted to Fourier spectra as well as three traditional parameters (arithmetical average roughness (*Ra*), volume of interdigitation (*Rr*), and RMS slope (*Rdq*)). We found that the interfacial shear strength is directly proportional to the exponent of the surfaces power spectra (P2) and *Rdq*, but not to *Ra* and *Rr*. However, *Rdq* is shown to be critically dependent on sampling frequency, making it sensitive to measurement settings. P2 was found to be a robust measure of the surface roughness being independent of sampling frequency.

1. Introduction

Total joint replacement has revolutionised the treatment of patients crippled with arthritis (Learmonth et al., 2007). As with other endoprosthetic devices one of the keys to successful outcome is the creation and maintenance of a stable bond between the device and the host tissue (Aebli et al., 2005). Degradation of the bond, as a result of the harsh biological conditions and repeated high loading contributes to implant instability, and can ultimately lead to clinical complications such as peri-prosthetic fracture, aseptic loosening, pain and loss of bone, making subsequent revision surgery challenging (Amstutz et al., 2007; Hallan et al., 2012; Hendrix et al., 1983).

Since its introduction in the 1960s acrylic bone-cement has become one of the most successful methods to fix total joint replacements into patients, and whilst much research focuses on cementless technologies, it is still widely used (Troelsen et al., 2013). Furthermore, national registries continue to report that cemented fixation has a lower risk of revision than uncemented fixation in knee implants, and hip

*Corresponding author. Tel.: +47 55978495.
E-mail address: Peter.Ellison@outlook.com (P. Ellison).

1751-6161/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmbbm.2013.08.005

implants in patients older than 75 years (Gandhi et al., 2009; Morshed et al., 2007; Troelsen et al., 2013).

Implants are commonly manufactured from titanium or cobalt–chromium alloy, and unless the metallic surface is chemically modified the cement–alloy bond is mechanical, being dependent on the surface topology. In general, an increase in roughness is proportional to an increase in both shear bond strength and tensile bond strength (Akiyama et al., 2012). The traditional method of quantifying surface finish is through the profile roughness parameter *Ra*, which characterises the surface by the average vertical deviation from the mean line (i.e. arithmetical average roughness). The descriptive capability of this parameter is limited because it does not take into account the frequency and shape of the roughness profile, both of which influence shear strength (Chen et al., 1999; Dong et al., 1994a; Arola et al., 2001; Zhang et al., 2008). Nevertheless, arithmetic average roughness is still used to characterise the surface of implants (Iesaka et al., 2008; Wennerberg and Albrektsson, 2009) and the majority of existing data investigating the relationship between surface roughness and the shear strength created with acrylic bone-cement is based upon *Ra,* with the conclusion that shear strength increases monotonically with *Ra* provided that the surfaces are made using the same finishing methods (Chen et al., 1999).

Several alternatives to *Ra* have been proposed although there is little work to systematically determine which of these are best suited in characterising the surface in implant adhesion studies. Volume of interdigitation has been proposed as it is a direct measure for the volume of bone-cement embedded in the metal surface (Arola et al., 2001) which has been proposed to be a governing factor in implant fixation (Verdonschot et al., 1998). Chen et al., (1999) proposed the use of the surface root mean square (RMS) slope as an alternative measure of surface roughness, showing that it was directly proportional to shear strength and is independent of the method of manufacture used. However this parameter also has limitations since it is a function of the sampling interval and profile trace length, and therefore comparison of data across studies requires knowledge of the equipment settings. Furthermore, data acquired with different classifications of measurement equipment (e.g. profilometers, atomic force microscopes, scanning electron microscopes), which may be needed to investigate different scales of magnitude, cannot be compared. Hence, there remains a need to find a robust measure of roughness to characterise the relationship between an implants surface topology and shear strength.

Fast Fourier transformation (FFT) is a method which can be used to transfer spatial surface topology into the frequency domain. It is shown that roughness calculations based on FFT are scale invariant, robust to linear translations (Wang et al., 2011). Fast Fourier spectra, and thus surface topology, relate to both material properties and manufacturing process (Majumdar and Tien, 1990). Four major advantages of the use of Fourier spectra are that: (1) often the surface topology of random isotropic surfaces can be characterised by a simple numeric function, (2) the spectra can be calculated from both profilometer measurements and grey scale images, (3) the variance in spectra is independent of number of points in the profile (Elson and Bennett, 1995), and (4) three dimensional surfaces and two dimensional profiles can be analysed (Zwiggelaar and Bull, 1995; Xin and Georganas, 2009; Dong et al., 1994b). Therefore it is surprising that spectra obtained from FFT have not to date been used in investigations of bond strength between orthopaedic devices and bone-cement.

The purpose of this study was to investigate the effect of surface roughness on the shear strength of the cement–alloy interface with the aim of identifying a robust roughness parameter able to explain the relationship between shear strength and surface topology. To achieve this shear strength was determined for cobalt–chromium and titanium alloy surfaces prepared with a range of different roughnesses. Roughness was characterised using *Ra*, volume of interdigitation (*Rr*, often called surface fluid retention), RMS slope ($R\Delta q$) and fast Fourier transformation (FFT), allowing the hypotheses that for a given adherend the shear strength to acrylic bone-cement is proportional to surface roughness parameter to be tested.

2. Methods

Specimens of surgical alloys with different surface roughness were made to study the effect of surface topology on the shear strength between bone-cement and metal surfaces.

2.1. *Preparation of specimens*

Specimens were turned (Fig. 1) from bar stock of Co–28Cr–6Mo (alloy 2 ASTM F1537) and Ti–6Al–4V (grade 5 ASTM SB348). Test surfaces were ground with a sequence of progressively finer (grit 320, 500, 1200, 2400 and finally 4000) silicon grinding paper and by polishing with diamond lubricant followed by Active Oxide Polishing (OPS). Cobalt–chromium alloy test surfaces were ground to a mirror-like surface with grinding paper only. Titanium grade 5 test surfaces were polished after grinding. The specimens were then sand-blasted with Al_2O_3 or SiO_2 grit ranging from 50 to 250 μm to create six replicate surfaces of seven different isotropic roughness conditions (Table 1). Specimens were cleaned for 5 min in methanol and then acetone using an ultrasonic bath prior to drying in air.

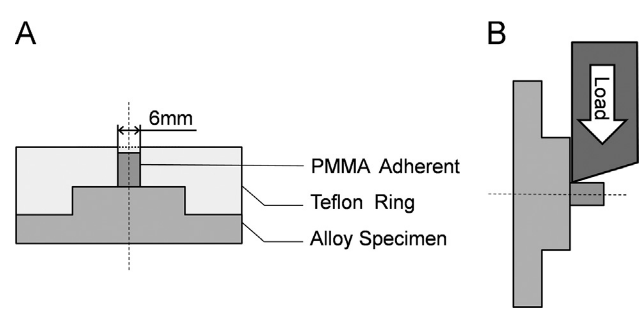

Fig. 1 – Cross section of the moulding and shear testing. A Teflon ring is used to mold the bone-cement onto the alloy surface of the specimen (A). A guillotine is used to perform a shear test (B).