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Research paper

Influence of femoral stem surface finish on the apparent static shear strength at the stem–cement interface

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ABSTRACT

The stem–cement interface has long been implicated in failure of cemented total hip replacement. Much research has been performed to study the factors affecting the bond strength between the femoral stem and the bone cement. The present study aims to further investigate the influence of femoral stem surface finish on the apparent static shear strength at the stem–cement interface through a series of pull out tests, where stainless steel rods are employed to represent the femoral stem. The results demonstrated that there was a general tendency for the apparent static shear strength to be increased with the rise of surface roughness. The polished and glass bead-blasted rods illustrated a slip-stick-slip failure whereas the shot-blasted and grit-blasted rods displayed gross interface failure. Following pull out test, cement transfer films were detected on the polished rods, and there was cement debris adhered to the surface of the grit-blasted rods. Micropores, typically 120 μm in diameter, were prevalent in the cement surface interfaced with the polished rods, and the cement surfaces in contact with the shot-blasted and grit-blasted rods were greatly damaged. There was also evidence of metal debris embedding within the cement mantle originating from the tests of the grit-blasted rods, indicating an extremely strong mechanical interlocking at the interface. In summary, this present research demonstrated that the grit-blasted rods with the highest surface roughness were the best in terms of apparent static shear strength. However, it seemed to be most applicable only to the stem designs in which mechanical interlocking of the stem in the initial fixed position was essential.

1. Introduction

Acrylic bone cement has been clinically employed in cemented total hip replacement (THR) for more than 40 years, and it will continue to be used in total joint replacement especially for those patients with poor bone stock (Charnley, 1960). It is generally accepted that long term durability of cemented THR requires meticulous attention to three elements and two interfaces, which are femoral stem, stem–cement interface, bone cement, cement–bone interface and bone. The stem–cement interface is a transitional zone which forms a mechanical bonding between the femoral stem and the bone cement, two materials with significantly different mechanical properties. Therefore, this interface has consistently been cited as a weak link in cemented THR. It has been demonstrated in the literature that failure of cemented THR was initiated by debonding at this interface (Jasty et al., 1991; Maloney et al., 2002; Verdonschot and Huiskes, 1997).

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Great effort has been made to investigate the factors influencing the bond strength at the stem–cement interface, such as increasing stem surface roughness (Chen et al., 1998; Lennon et al., 2003; Ohashi et al., 1998), pre-coating the stem (Fischer et al., 2001; Morita et al., 1997) and utilising "modern cementing techniques" (Geiger et al., 2001; Mulroy Jr. and Harris, 1990). The optimum surface finish of the femoral stem has been the focus of controversy for a long time, mainly concentrating on whether matt stems could accomplish permanent fixation during their in vivo service (Alfaro-Adrian et al., 2001; Shen, 1998). However, it seems that the controversy has intensified as reports have recently been published on failed prostheses that exhibit varying amounts of surface roughness. This present study therefore aims to gain a further insight into this issue by establishing the apparent static shear strength between bone cement and femoral stems with different surface finishes.

2. Materials and methods

In the present study, the apparent static shear strength at the stem–cement interface was investigated through a series of pull out tests, employing Simplex P bone cement and stainless steel rods (type: 316L; composition: C—0.02%, Cr—17.9%, Ni—12.9%, Mo—2.55%, Si—0.8%, Mn—0.1%, Fe—balance; mechanical properties: hardness—HB140, Young's modulus—197 GPa, 0.2% yield strength—310 MPa, ultimate tensile strength—635 MPa) with four kinds of surface finish—polished (with the use of 45 μm, 15 μm, 6 μm and 1 μm diamond pastes respectively), —glass bead-blasted (with the use of glass beads, size range: 0.15 mm–0.25 mm), —shot-blasted (with the use of carbon steel balls, nominal size: 0.5 mm) and —grit-blasted (with the use of non-spherical carbon steel, size range: 0.3–0.7 mm). For each surface finish, totally four cylindrical rods were manufactured with a diameter (D) about 8 mm. The polished rods were measured using a Talysurf CCI interferometer with an area of 0.34×0.34 mm^2, and the other rods were measured by utilising a Form Talysurf PGI with an area of 2×2 mm^2. The measurements obtained are shown in Fig. 1. Three measurements were carried out on each rod surface. The mean values of some selected 3D surface parameters—Sq, Sz, Sdq and Sdr were calculated by Surfstand software V3.3. These parameters were further expatiated in Table 1, and they were considered to give a full description of the surface in height deviation, which correlated with the apparent static shear strength. A cylindrical holder made of mild steel was fabricated for the bone cement to be poured into, with an internal diameter of 18 mm, an external diameter of 28 mm and a length of 40 mm. This geometry gave a nominal cement mantle thickness of 5 mm. Simplex P bone cement was hand mixed at room temperature, according to the manufacturer's instructions. Before cementing, the stainless steel rod was cleaned with alcohol and then fixated using a milling machine chuck, which ensured accurate axial alignment of the rod within the cement mantle. Following cementing, the stainless steel rod was embedded in the cement mantle, with an internal length (L) about 35 mm, i.e. the stainless steel rod was embedded in a blind hole. The specimen was laid aside for 24 h to fully cure before being tested on a Hounsfield Test Machine H20-W, Fig. 2. All the tests were performed at a constant speed of 2 mm/min by displacement control. A load–displacement plot was finally recorded for each pull out test.

After the test, the stainless steel rod was investigated using an optical stereomicroscope (MZ6, Leica Microsystems Ltd.) to detect any cement debris remaining on the surface. The exact value of the diameter of the stainless steel rod and its internal length within the cement mantle were further measured utilising a vernier caliper. The apparent static shear strength (σ) was calculated using the initial debonding force (F, defined as the peak force during the pull out process) divided by the apparent contact area, Eq. (1).

$$\sigma = \frac{F}{\pi D L}. \tag{1}$$

Additionally, the bone cement was cautiously extracted from the metallic holder and cut longitudinally into two equal parts. The inner surface of the cement was cleaned with alcohol and measured using the Form Talysurf PGI. Likewise, three measurements were performed on the cement surface, with each area 2×2 mm^2. The mean values of Sq, Sz, Sdq and Sdr were also calculated using Surfstand software V3.3. Furthermore, the bone cement which contacted with the polished rod was cut into smaller pieces, enabling the observation of porosity by utilising a scanning electron microscope (SEM, JEOL JSM-6060, Oxford Instruments).

The same tests were repeated four times for each surface finish rod. The final apparent static shear strength was calculated as the mean value of the four tests performed. Statistically significant difference was investigated to establish the influence of surface roughness on the results, employing a one-way analysis of variance (ANOVA). Furthermore, a Tukey–Kramer Post Hoc Test was carried out to determine significant differences among the means.

3. Results

The selected 3D surface parameters of the four kinds of surface finish rods are listed in Table 2. It is demonstrated clearly from these parameters that the grit-blasted rods generate the roughest surface, followed by shot-blasted, glass bead-blasted and polished rods. The mean values of the apparent static shear strength for these rods are shown in Fig. 3, from which it is evident that the strength in general increases with the rise of surface roughness. It was further revealed from the one-way ANOVA that the apparent static shear strength was significantly influenced by surface roughness ($P < 0.01$), although there was no great increase from the polished rods to the glass bead-blasted rods, and from the glass bead-blasted rods to the shot-blasted rods. In addition, the Tukey–Kramer Post Hoc Test indicated that the apparent static shear strength using the grit-blasted rods was significantly different from that using the other surface finish rods ($P < 0.01$), i.e. the grit-blasted rods were markedly better in terms of apparent static shear strength.

Fig. 4 displays the typical load–displacement plots for these four kinds of surface finish rods, from which two kinds