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Research paper

Improved fatigue life of acrylic bone cements reinforced with zirconia fibers

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ABSTRACT

Poly(methyl methacrylate) (PMMA) bone cements have a long and successful history of use for implant fixation, but suffer from a relatively low fracture and fatigue resistance which can result in failure of the cement and the implant. Fiber or particulate reinforcement has been used to improve mechanical properties, but typically at the expense of the pre-cured cement viscosity, which is critical for successful integration with peri-implant bone tissue. Therefore, the objective of this study was to investigate the effects of zirconia fiber reinforcement on the fatigue life of acrylic bone cements while maintaining a relatively low pre-cured cement viscosity. Sintered straight or variable diameter fibers (VDFs) were added to a PMMA cement and tested in fully reversed uniaxial fatigue until failure. The mean fatigue life of cements reinforced with 15 and 20 vol% straight zirconia fibers was significantly increased by ∼40-fold, on average, compared to a commercial benchmark (Osteobond™) and cements reinforced with 0–10 vol% straight zirconia fibers. The mean fatigue life of a cement reinforced with 10 vol% VDFs was an order of magnitude greater than the same cement reinforced with 10 vol% straight fibers. The time-dependent viscosity of cements reinforced with 10 and 15 vol% straight fibers was comparable to the commercial benchmark during curing. Therefore, the addition of relatively small amounts of straight and variable diameter zirconia fibers was able to substantially improve the fatigue resistance of acrylic bone cement while exhibiting similar handling characteristics compared to current commercial products.

1. Introduction

Poly(methyl methacrylate) (PMMA) cements have been the method of choice for affixing total joint replacements to peri-implant bone tissue ever since the pioneering efforts by Charnley and others in the 1960s (Charnley, 1960; Davies et al., 1987). Cement fixation of the femoral component is used in approximately one-half of all total hip arthroplasties and has proved to be an extremely effective technique with a 90% success rate after 15 years (Murray et al., 1995). However, increased life expectancy and the decreasing age of implant

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recipients suggest a clinical need for further improvements in the implant lifetime. Cemented implants can fail through a variety of mechanisms, including inflammation caused by wear particles, micro-motion at the bone–cement interface, and fracture of the cement mantle (Bauer and Schils, 1999). Thus, the fracture and fatigue resistance of PMMA bone cements is a significant factor affecting implant failure.

A wide variety of approaches have been used to improve the mechanical properties of PMMA bone cements (Lewis, 1997), including the addition of a reinforcing particle or fiber to increase cement strength, stiffness, and toughness (Lewis, 2003, 2008). Numerous reinforcements have been examined in fatigue, including carbon fibers (Martin et al., 1980; Pilliar et al., 1976; Robinson et al., 1981), hydroxyapatite particles (Harper et al., 1995, 2000) or fibers (Matsuda et al., 2004), PMMA fibers (Gilbert et al., 1995), stainless steel fibers (Kotha et al., 2004, 2006a), titanium fibers (Kotha et al., 2006b; Topoleski et al., 1995), and zirconia particles (Harper and Bonfield, 2000) or fibers (Kotha et al., 2009; Zhou et al., 2009), among others. Regardless of the reinforcement composition, short fibers or equiaxed particles are usually added to the cement at 1–20 vol%. Most studies have reported improved fatigue properties as a result of this reinforcement (Lewis, 2003). However, most reinforced cements also exhibit a significantly higher dough-stage viscosity, leading to difficulty in obtaining a reliable bone–cement interface (Lewis, 2008). Moreover, a high viscosity limits handling and the addition of higher reinforcement fractions.

Reinforced cements have also been limited by poor adhesion between the PMMA matrix and reinforcement fibers or particles. Therefore, recent studies have attempted to improve the interfacial strength or resistance to fiber pullout either chemically, using coupling agents (Harper et al., 2000; Kotha et al., 2006a,b; Lewis, 2008), or mechanically, using variable diameter fibers (VDFs) (Zhou et al., 2005, 2009). VDFs improve stress transfer by mechanical interlocking (Zhu and Beyerlein, 2002), analogous to fastening with a screw rather than a nail. In a preliminary study, cements reinforced with VDFs exhibited increased tensile strength and fatigue life compared to conventional straight fibers at low reinforcement fractions, up to 10 vol% (Zhou et al., 2009).

The objective of this study was to investigate the fatigue life of PMMA bone cements reinforced with straight or variable diameter zirconia fibers compared to a commercial benchmark. Moreover, the PMMA cement composition was tailored such that the pre-cured viscosity of reinforced cements exhibited similar handling characteristics compared to the commercial benchmark.

2. Materials and methods

2.1. *Cement preparation*

Zirconia fibers were prepared by Advanced Cerametrics Inc. (Lambertville, NJ), using the viscous suspension spinning process (VSSP) and sintering, as described elsewhere (Cass et al., 1998, 2003). Straight fibers were approximately 100 μm in length and 20 μm in diameter, on average (Fig. 1(a)). VDFs were approximately 750 μm in length, with a maximum diameter of 200 μm and minimum diameter of 100 μm (cf. Zhou et al., 2009). The larger size of VDFs was dictated by processing constraints, but the approximate aspect ratio (ratio of the length and mean width) was similar to the straight fibers. Both types of fibers were polycrystalline with a submicron grain size and surface roughness (Fig. 1(b)).

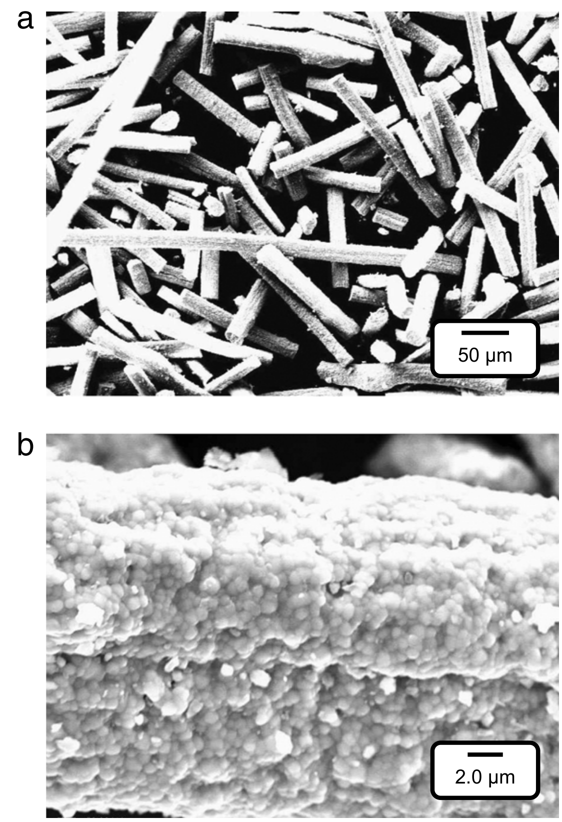

Fig. 1 – Scanning electron micrographs showing the (a) fiber morphology, and (b) submicron grain size and surface roughness of as-prepared polycrystalline, straight zirconia fibers.

Acrylic powder beads comprised a poly(methyl methacrylate-*co*-styrene) copolymer with 0.85 wt% residual benzoyl peroxide (BPO) as a polymerization initiator. The mean bead size was 37 μm with a maximum bead size of 150 μm. Cements reinforced with 15 vol% straight fibers were also prepared using acrylic beads with a mean size of 26 and 48 μm for comparison. The powder component was provided without a radiopacifier (e.g., barium sulfate) due to reinforcement by zirconia fibers which also provided radiopacity. Zirconia reinforcements have been used as a radiopacifier in a number of commercial cements (Harper and Bonfield, 2000; Lewis, 1997, 2003). The liquid component was composed of methyl methacrylate (MMA) monomer, with 0.725 vol% *N*, *N*-dimethyl-*p*-toluidine (DMPT) as a polymerization accelerator and 60 ± 10 ppm hydroquinone as a stabilizer.

The acrylic cement was formulated for decreased viscosity prior to the addition of 5, 10, 15, and 20 vol% straight fibers or 10 vol% VDFs. The powder and liquid components were vacuum mixed (∼70 kPa) at a powder-to-liquid ratio of 0.9 g/ml following standard clinical methods, except that zirconia fibers were added at the same time as the