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Functionally graded Co–Cr–Mo coating on Ti–6Al–4V alloy structures

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Abstract

Functionally graded, hard and wear-resistant Co–Cr–Mo alloy was coated on Ti–6Al–4V alloy with a metallurgically sound interface using Laser Engineering Net Shaping (LENS™). The addition of the Co–Cr–Mo alloy onto the surface of Ti–6Al–4V alloy significantly increased the surface hardness without any intermetallic phases in the transition region. A 100% Co–Cr–Mo transition from Ti–6Al–4V was difficult to produce due to cracking. However, using optimized LENS™ processing parameters, crack-free coatings containing up to 86% Co–Cr–Mo were deposited on Ti–6Al–4V alloy with excellent reproducibility. Human osteoblast cells were cultured to test in vitro biocompatibility of the coatings. Based on in vitro biocompatibility, increasing the Co–Cr–Mo concentration in the coating reduced the live cell numbers after 14 days of culture on the coating compared with base Ti–6Al–4V alloy. However, coated samples always showed better bone cell proliferation than 100% Co–Cr–Mo alloy. Producing near net shape components with graded compositions using LENS™ could potentially be a viable route for manufacturing unitized structures for metal-on-metal prosthetic devices to minimize the wear-induced osteolysis and aseptic loosening that are significant problems in current implant design.

Keywords: Functionally graded materials; Laser processing; Laser engineered net shaping (LENS); Biocompatibility; Osteoblast

1. Introduction

Over 200,000 total hip replacements (THRs) are performed in the USA each year. Although the average life time of an implant is 7–12 years, around 10% of the implanted prosthesis requires revision within 10 years. A short implant life is a significant problem, especially for the growing number of younger patients, because of their active lifestyle. The worldwide population of people younger than 40 years of age who receive hip implants is expected to be 40 million by 2010 [1]. Similarly, by 2030 the population of this age group is expected to be 80 million [1], which is likely to create a need for implants which can last longer in vivo. Such a trend is common in other load-bearing devices as well.

Although ultrahigh-molecular-weight polyethylene (UHMWPE) liner used in traditional hip replacements is durable, the rate of wear is still significant and is a cause of serious concern due to osteolysis. Osteolysis and aseptic loosening have been identified as major factors limiting the life of prostheses, with indications that fine UHMWPE wear debris [2–6], generated primarily at the interface between the femoral head and the acetabular cup, promotes this degradation. Thus, wear-particle-induced bone loss is one of the main limiting factors affecting the long-term stability of UHMWPE liner-based THR and other load-bearing implants in which UHMWPE is used [7–9]. The hypothesis is that implant-derived wear particles, and other wear products, induce a foreign body inflammatory response in the joint capsule and along implant–bone interfaces, which results in bone loss and therefore aseptic loosening. Due to this concern, there is considerable interest in alternative wear-resistant systems. Such alternatives include ceramic-on-ceramic (CC) and metal-on-metal (MM) configurations.

Hip simulator testing has shown that an MM bearing has considerably less linear and volumetric wear than a

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metal-on-UHMWPE couple [10]. More importantly, this improved wear, seen on hip simulators, has been borne out in clinical retrievals [11–14], where a 40 times lower linear wear rate and 200 times lower volumetric wear rate than conventional UHMWPE bearings were observed [11–14]. Typically, these long-surviving MM implants had highly polished surfaces with minimal scratches, had the expected low wear and caused minimal osteolysis [15,16]. These results confirm that MM implants are viable alternatives to metal-on-UHMWPE implants [17]. Among various metallic implant alloys, Co–Cr–Mo alloys are the only materials used for MM hip implants because of their remarkable wear and corrosion resistance [18–20]. These alloys are known to possess a certain self-healing capacity – the ability to polish out visible surface scratches with continued wear cycles rather than to experience a progressive deterioration of the surface topography, leading to accelerated wear [21]. This is a valuable property in light of the possibility of entrapment of third-body wear particles between the articulating surfaces during in vivo service.

The most widely used materials for THR components are shown in Table 1. Wear debris essentially originates from the femoral head–acetabular liner and acetabular liner–shell interfaces. Titanium alloys are preferred for stems and shells because of their bone-friendly nature and low elastic modulus. Similarly, the femoral heads and acetabular liners are made using Co–Cr–Mo alloy due to their excellent wear resistance. However, when Ti alloy acetabular shells are used in combination with Co–Cr–Mo alloy liners, the wear of the shell dominates over the wear of the liner. In such cases the methodologies used to improve the wear resistance of the Ti alloy shell are very important. Ceramic coatings have been proposed, in the past, as being wear-resistant and a metal ion release barrier for THR. These coatings were obtained using different vapor deposition techniques, such as physical vapor deposition, ion implantation, sputtering and the coatings consisted of diamond-like carbon [22,23] or nitrides [24,25]. These coatings have found little application in the field of THR due to their inherent brittleness and catastrophic fracture possibilities. While a wear-resistant alloy coating on metal substrates seems plausible [26,27], there is only one metallic alloy combination, i.e. Co–Cr–Mo and Ti–6Al–4V, suitable for surgical implant, which shows metallurgical incompatibility. Interaction between cobalt and titanium at high temperature can lead to the formation of various intermetallic compounds, such as Ti_2Co, $TiCo_2$ and $TiCo_3$ [28]. Moreover, the mismatch in elastic moduli, thermal expansion coefficient and hardness between the two materials could lead to excessive residual stresses in the coatings and consequent delamination or cracking of the coating. One way to overcome these problems is the use of functionally graded coatings (FGCs). In a functionally graded coating, an intermediate layer with a gradual compositional variation is applied between the top wear-resistant coating and the substrate. This layer consists of several sections composing of two alloys in various ratios, i.e. with gradual changes in composition and microstructure, and, therefore, its properties. Compared with regular multi-component coatings, FGCs can effectively reduce the discontinuity of thermal expansion coefficient between the materials, and also minimize the residual stresses in the coatings.

In this work, we have demonstrated the fabrication of functionally graded Co–Cr–Mo-coated Ti–6Al–4V alloy implants using Laser Engineering Net Shaping (LENS™), which ensures a metallurgically sound interface between the two alloys and increases the surface hardness. Such gradient structures provide useful mechanical support for the wear-resistant exterior layers and minimize the likelihood of localized Hertzian failure during implant service. Our work focuses on processing, coating characterization and in vitro biocompatibility of these LENS™-processed functionally graded structures.

Table 1
Total hip implant materials

Component	Material
Femoral stems	Co–Cr–Mo alloy or titanium alloy
Femoral heads	Co–Cr–Mo alloy
Acetabular shells	Titanium alloy or Co–Cr–Mo
Acetabular liners	Polyethylene (UHMWPE) or cast Co–Cr–Mo alloy

2. Materials and methods

Ti–6Al–4V alloy powder (Advanced Specialty Metals, Inc., Nashua, NH) with particle size between 50 and 150 μm and Co–Cr–Mo alloy powder (Stellite Coatings, Goshen, IN) with 50–100 μm particle size was used in this study. The nominal composition (wt.%) of the Ti alloy was 6.37 Al, 3.86 V, 0.17 Fe, 0.18 O, 0.026 C, balance Ti, and that of the Co–Cr–Mo alloy was 27 Cr, 5.2 Mo, 0.3 C, 1.2 Fe, 0.7 Mn, 2.8 Ni, 1.6 Si, balance Co. Gradient samples of 10 mm diameter were fabricated on a substrate of 3 mm thick rolled, commercially pure Ti plates using LENS™-750 (Optomec Inc. Albuquerque, NM) equipped with a 500W Nd:YAG laser and a double powder feeder system. The first hopper contained Ti–6Al–4V alloy powder and the second hopper contained Co–Cr–Mo alloy powder. Samples were fabricated in a glovebox containing argon atmosphere with O_2 content less than 10 ppm to limit oxidation of alloys during processing. The LENS™ process uses a Nd:YAG laser, up to 2 kW power, focused onto a metal substrate to create a molten metal pool on the substrate. Metal powder is then injected into the metal pool, which melts and solidifies. The substrate is then scanned relative to the deposition head to write a metal line with a finite width and thickness. Rastering of the part back and forth to create a pattern and fill material in the desired area allows a layer of material to be deposited. Finally, this procedure is repeated many times along the *Z*-direction, i.e. height, until the entire object represented