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Advances in metals and alloys for joint replacement

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ABSTRACT

Metals, ceramics, polymers, and composites have been employed in joint arthroplasty with ever increasing success since the 1960s. New materials to repair or replace human skeletal joints (e.g. hip, knee, shoulder, ankle, fingers) are being introduced as materials scientists and engineers develop better understanding of the limitations of current joint replacement technologies. Advances in the processing and properties of all classes of materials are providing superior solutions for human health. However, as the average age of patients for joint replacement surgery decreases and the average lifespans of men and women increases worldwide, the demands upon the joint materials are growing. This article focuses solely on advances in metals, highlighting the current and emerging technologies in metals processing, metal surface treatment, and integration of metals into hybrid materials systems. The needed improvements in key properties such as wear, corrosion, and fatigue resistance are discussed in terms of the enhanced microstructures that can be achieved through advanced surface and bulk metal treatments. Finally, far reaching horizons in metals science that may further increase the effectiveness of total joint replacement solutions are outlined.

Contents

Abbreviations: 3DP, 3D Printing; ALM, additive layer manufacturing; AM, additive manufacturing; ARB, accumulative roll bonding; ASTM, American Society of Testing Materials; AWJ, abrasive water jet; BCC, body centered cubic; CE, Conformité Européene; CP Ti, commercial purity titanium; CT, computed tomography; DLF, directed light fabrication; DMLS, direct metal laser sintering; EBFF, electron beam freeform fabrication; EBM, electron beam melting; EDM, electro discharge machining; EMAT, electromagnetic acoustic transducer; FCC, face centered cubic; FDA, Food and Drug Administration; FEA, finite element analysis; FEM, finite element method; FGM, functionally graded materials; HA, hydroxyapatite; HCP, hexagonal close packed; HPT, high pressure torsion; HR-pQCT, high resolution peripheral quantitative computed tomography; LBMD, laser based metal deposition; LENS™, laser engineered net shaping; LFIT, low friction ion treated; LEHT, low energy-high temperature ion implantation; LSEM, large strain extrusion machining; MAM, modulation assisted machining; PIII, plasma immersion ion implantation; PSII, plasma source ion implantation; PCL, poly (caprolactone); PE, poly (ethylene); PGA, poly (glycolic acid); PHB, poly (hydroxybutyrate); PIRAC, powder immersion reaction assisted coating; PMMA, poly (methyl methacrylate); PM, powder metallurgy; RP, rapid prototyping; RUS, resonant ultrasound spectroscopy; SFE, stacking fault energy; SFF, solid freeform fabrication; SLM, selective laser melting; SLS, selective laser sintering; SPD, severe plastic deformation; THA, total hip arthroplasty; TKA, total knee arthroplasty; TMZF, titanium molybdenum zirconium iron; TNTZ, titanium niobium tantalum zirconium; UNS, unified numbering system; UTS, ultimate tensile strength; UCS, ultimate compressive strength; UFG, ultrafine grain; UHMWPE, ultra-high molecular weight polyethylene; VAR, vacuum arc remelting; YS, yield strength.

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1. Introduction

High performance materials have been one of the central enablers of joint replacement technology. While ceramics, polymers, and metals have all been used in prosthetic joints, the focus of this work is on the longest enduring and most widely used joint replacement material class: metals and their alloys. This paper examines the status of metals and alloys in current joint replacement systems, as well as identifies the horizons of alloy technology that may appear in new orthopedic device offerings in the coming years. These systems include orthotic and prosthetic appliances most commonly used to augment or replace the function of the ankle, knee, hip, spine, shoulder, elbow, and fingers.

One of the most prominent demands that joint arthroplasty imposes on joint materials is the need for them to survive relative motion via sliding and highly localized loads. Thus, wear and surface properties of joint replacement alloys are of utmost importance. In Section 2, the history of joint replacement is reviewed, including the dependence of the evolution of joint design on advancements in metals technology. The mechanical, physical, and biological properties that are most important in joint replacement applications of metals and alloys are highlighted in Section 3. In Section 4, the major families of alloys and the key characteristics of their microstructures that make them useful in current joint replacement systems are systematically summarized. Section 5 focuses on current surface treatment and modification technologies, while Sections 6 and 7 then address emerging advances in alloy and manufacturing and finishing technologies that can enhance the performance and increase the longevity of joint replacements. Combining insights from Sections 6 and 7, Section 8 then identifies likely horizons for materials technology that may, in the long term, result in a completely new generation of joint replace-