Review

Orthopedic applications of silicon nitride ceramics

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Abstract

Silicon nitride (Si₃N₄) is a ceramic material developed for industrial applications that demand high strength and fracture resistance under extreme operating conditions. Recently, Si₃N₄ has been used as an orthopedic biomaterial, to promote bone fusion in spinal surgery and to develop bearings that can improve the wear and longevity of prosthetic hip and knee joints. Si₃N₄ has been implanted in human patients for over 3 years now, and clinical trials with Si₃N₄ femoral heads in prosthetic hip replacement are contemplated. This review will provide background information and data relating to Si₃N₄ ceramics that will be of interest to engineering and medical professionals.

1. Introduction

Silicon nitride (Si₃N₄) is a non-oxide ceramic that is rarely observed in nature, but may occur naturally, since it has been found in particles of meteorite rock [1]. Synthetic Si₃N₄ was first developed by Deville and Wöhler in 1859 [1]; but it remained little more than a curiosity for nearly a century. Commercial interest in the material increased in the 1950s, when it was developed for various refractory applications. However, it was not until the 1980s that its potential as a structural ceramic was clearly recognized. At that time, a worldwide effort was initiated to develop Si₃N₄ for use in internal combustion engines and high-temperature gas turbines. Significant improvements were made in its synthesis, processing and properties. As a result, it is now one of the most extensively studied ceramics in history. Its material properties are well understood, and its commercial use has expanded greatly.

Today, industrial uses of Si₃N₄ and its composites are well established and include high-performance bearings, turbine blades and glow plugs (i.e. applications that require a material with high fracture toughness, strength and low wear properties) [2]. Ceramic ball bearings made of Si₃N₄ are used in industrial applications where extreme strength and toughness are necessary [3]. The material properties of Si₃N₄ have led to speculation that it may have a role in biomedical fields also, since it is biocompatible [4,5] and is visible on plain radiographs as a partially radiolucent material. Because of a unique combination of material properties, Si₃N₄ has been used in spinal fusion implants, and has been developed for bearing components of prosthetic hip and knee joints.

As clinical data pertaining to the use of Si₃N₄ in orthopedic surgery become available in the future, it will be useful to have an overview of the rationale for the use of this material in biomedical applications. Cervical spacers and spinal fusion devices made of Si₃N₄ composites are presently in use, with successful short-term clinical results [6]. Surgical screws and plates made of Si₃N₄ as the source material, as well as bearings for spine disc surgery and prosthetic hip and knee joints have also been developed and tested [7–9]. This review will (1) examine the clinical rationale for using ceramic materials in orthopedic surgery, (2) summarize the limitations of existing ceramics that have been used in orthopedic surgery, and (3) review the scientific rationale for introducing Si₃N₄ ceramics in orthopedic implants.

2. Ceramic materials in orthopedic surgery

Modern biomaterials, such as titanium (Ti) alloys, polished cobalt–chromium (CoCr) and high-density polyethylene (PE) have revolutionized prosthetic replacement of diseased hip and knee joints since the 1970s, such that clinical outcomes are now predictable and durable [10,11]. However, a long-term concern related to prosthetic bearings in the human body is the adverse host biological response to accumulated, microscopic wear debris in the periprosthetic joint space, particularly PE wear particles. Less bearing wear is desirable because particulate wear in hip and knee replacements leads to localized inflammation, periprosthetic bone loss and premature implant loosening, necessitating revision surgery [12–15]. These considerations apply even more acutely...