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Review

Corrosion fatigue fracture of magnesium alloys in bioimplant applications: A review

R.K. Singh Raman [a,b,*], Sajjad Jafari [a], Shervin Eslami Harandi [a]

[a] *Department of Mechanical & Aerospace Engineering, Monash University (Melbourne), VIC 3800, Australia*
[b] *Department of Chemical Engineering, Monash University (Melbourne), VIC 3800, Australia*

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ABSTRACT

Magnesium (Mg) alloys have recently attracted great attention for potential biodegradable implant applications. Cracking/fracture of metallic implants under the simultaneous action of corrosion and mechanical stresses, viz., corrosion fatigue (CF) or/and stress corrosion cracking (SCC) is an obviously critical criterion before any new material could be deployed as implants. This article presents a review of the available literature on CF of Mg alloys in corrosive environments including simulated-body-fluid (SBF) and the associated fracture mechanism, and identifies the knowledge gap. A brief overview of the mitigation strategies to combat the possible CF failures of Mg alloys is also presented.

Contents

* Corresponding author. Address: Department of Mechanical & Aerospace Engineering, Department of Chemical Engineering, Bldg 31, Monash University – Clayton Campus (Melbourne), VIC 3800, Australia. Tel.: +61 399053671.
E-mail address: raman.singh@moansh.edu (R.K. Singh Raman).

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Nomenclature

Symbols

da/dN	crack growth rate
K_{max}	stress intensity factor
K_{Iscc}	stress intensity threshold for stress corrosion cracking
$K_{max,th}$	stress intensity threshold for fatigue
ΔK	stress intensity factor range
N	Newton
Hz	Hertz
ρ	Density
E	elastic modulus

Abbreviations

CF	corrosion fatigue
Ca-P	Calcium phosphate
c-SBF	Conventional simulated-body-fluid
DCPD	Dicalcium phosphate dehydrate
DMEM	Dulbecco's modified Eagle's medium
ECAP	Equal channel angular pressing
HA	Hydroxyapatite
HBF	Human-body-fluid
HCF	High cycle fatigue
m-SBF	Modified simulated-body-fluid
SBF	Simulated-body-fluid
SCC	Stress corrosion cracking
SMAT	Surface mechanical attrition treatment
PBS	Phosphate buffered saline
PEO	Plasma electrolytic oxidation

1. Introduction

Addressing health issues of an ageing population is among the greatest challenges of current times. In this regard, using magnesium (Mg) alloys for temporary implant devices (such as pins, wires, screws, plates, stents etc.) is emerging as an innovative and extremely attractive approach, since use of such alloys may completely avoid the cumbersome procedure of second surgery. Such a surgery is commonly undertaken to remove the temporary implants when they are constructed out of commonly used traditional materials such as stainless steel, Ti-alloys, Co-alloys, etc. This second surgery amounts to added duress to patients and added costs, besides possible complications of patient morbidity and infection.

Among all metallic engineering materials, Mg possesses one of the best bio-compatibilities with human physiology. Mg alloys also possess the best mechanical compatibility with human bones, as well as the required mechanical strength. Thus, the use of Mg alloys as human implants has attracted forefront research attention [1,2]. However, in such use, the alloys must possess adequate resistance to cracking/fracture under the simultaneous action of the corrosive human-body-fluid and the cyclic and/or tensile mechanical loading characteristics of human-body. Thus, corrosion fatigue (CF, under cyclic loading) and stress corrosion cracking (SCC, under tensile loading) of Mg alloys due to loading in human-body and corrosive body fluid is a critical research topic, as emphasized below:

- Human-body-fluid-assisted fracture is always among major concerns [3] in use of implants of traditional materials. Such fracture of Mg alloys as bio-implants [4,5] is a vastly underexplored research area.
- Recent studies have confirmed simulated-body-fluid-assisted SCC of Mg alloy [6–9].
- *In-vivo* tests of a few Mg alloys specifically developed for body implant applications [1,10–12] have shown their specific attributes of harmlessly dissolving away while a fractured bone joins (Fig. 1). But, the resistance of these alloys to human-body-fluid-assisted fracture is still a critical concern, and a grossly unexplored research topic.
- This article specifically presents a review of CF and the associated fracture mechanisms of Mg alloys in corrosive environments including simulated-body-fluid (SBF).

2. Mg alloys as bio-degradable orthopedic implants

Mg alloys have attracted rapidly increasing research attention for their potential use as orthopaedic implants [13–15] because the fundamental properties of Mg are quite suitable for this application, viz., low density (ρ = 1.74–2.0 g cm^{-3}), and elastic modulus (E = 41–45 GPa), both of which are similar to these properties of human bones (ρ = 1.8–2.1 g cm^{-3}