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Review

A review of biocompatible metal injection moulding process parameters for biomedical applications

M.F.F.A. Hamidi [a], W.S.W. Harun [b,*], M. Samykano [c], S.A.C. Ghani [b], Z. Ghazalli [b], F. Ahmad [d], A.B. Sulong [e]

[a] Institute of Postgraduate Studies, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
[b] Green Research for Advanced Materials Laboratory, Human Engineering Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[c] Structural and Material Degradation Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[d] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Malaysia
[e] Department of Mechanical & Materials Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Malaysia

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ABSTRACT

Biocompatible metals have been revolutionizing the biomedical field, predominantly in human implant applications, where these metals widely used as a substitute to or as function restoration of degenerated tissues or organs. Powder metallurgy techniques, in specific the metal injection moulding (MIM) process, have been employed for the fabrication of controlled porous structures used for dental and orthopaedic surgical implants. The porous metal implant allows bony tissue ingrowth on the implant surface, thereby enhancing fixation and recovery. This paper elaborates a systematic classification of various biocompatible metals from the aspect of MIM process as used in medical industries. In this study, three biocompatible metals are reviewed-stainless steels, cobalt alloys, and titanium alloys. The applications of MIM technology in biomedicine focusing primarily on the MIM process setting parameters discussed thoroughly. This paper should be of value to investigators who are interested in state of the art of metal powder metallurgy, particularly the MIM technology for biocompatible metal implant design and development.

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* Corresponding author.
E-mail address: sharuzi@ump.edu.my (W.S.W. Harun).

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1. Introduction

The use of biomaterial can be dated from thousands of years ago. Archaeologists have discovered and evidenced the use of biomaterial as dental implants from as early as 200 CE However, the use of this implants came to glory after World War II [1]. Biomaterials were initially known as nonviable materials that widely used in biomedical applications. Predominantly in medical devices which aimed to interact with biological systems [2]. Biomaterials in the form of implants classically employed to ligaments, vascular grafts, intraocular lenses, heart valves, dental implants, and in medical devices like pacemakers, artificial hearts, and biosensors, which are widely used to replace and restore the function of traumatized or degenerated tissues and organs in the human body. The primary aim of these implants is to contribute to a better quality of life for the patients [3,4]. The medical community started to accept metals as implant materials upon Lane's success of using metal plate for bone fracture fixation in 1895 (Lane, 1895) and later came to be known as biocompatible metal [5].

To date, biocompatible metals had become the most favored materials for the commercial production of medical implants due to their outstanding mechanical, physical and chemical properties [6–11]. From the vast choice of metals and alloys available in the industry, only a handful are biologically compatible and have the aptitude to become long-term implant materials [12]. These metals are principally used to replace and support parts of the damaged bones. Routinely also used as artificial joints, plates, screws, intramedullary nails, spinal and spacer fixations, external fixators, pacemaker casings, artificial heart valves, stents, and as dental implants. In comparison to ceramic and polymeric materials, biocompatible metals are ideal as implant since they exhibit greater fracture toughness, tensile strength, and fatigue strength [13–19].

Implants developed from stainless steel, titanium and its alloys, and cobalt based alloys are the most extensively used in the present-day biomedical applications [20–27]. They fit biomaterial prospects due to their outstanding mechanical, chemical properties and corrosion resistance. During the initial period of medical implant evolution, the key consideration criteria for implant material selection were the satisfactory physical properties and their non-toxicity nature [4]. At present date, the criteria have been broadened even to include the ability of the implant material to assist in the growth of human body tissues and its physical properties [28–33].

Powder metallurgy (PM) technology, in specific the MIM technique, has been recognized as one of the prominent methods to produce exceptional components or parts for numerous fields and industries in the past several years. Additionally, this technique had also been exploited in medicine field as an optional method for fabricating implants used in surgery and dentistry [12,34–39] befitting for economical mass production. Also, MIM are known for its near net shaping technique that is particularly advantageous for the development of complex shapes of high density, and with excellent dimensional accuracy [40–48]. The MIM technique invented from the idea of plastic injection moulding, of which metal powder particles mixed with a binder and the mixture (usually in slurry form) injected into the cavity of the mould of desired shape [49–51]. The four major stages in MIM technique to produce a part are; (1) Mixing of powder and binders to produce feedstock; (2) Injection moulding process to get a green compact; (3) A de-binding process to extract away the binders; and (4) Produce a brown compact and sintering process to produce a sintered compact.

This paper summarizes the MIM process parameters for three groups of biocompatible metals which are stainless steel, titanium and its alloys, and cobalt based alloys, focusing primarily towards biomedical applications. This review covers pertaining research works that published between years of 2001 to 2016. Strengths and weaknesses respect to mechanical properties and corrosion resistance of these biocompatible metals systematically discussed. In MIM technique, it assumed that biocompatible metal feedstocks consist of multicomponent binders, and high powder loading will lead to successful injection process eventually deliver enhanced properties for green compacts. Where else, for the de-binding process, the binders expected to be fully removed when the de-binding temperature increased to the melting and decomposition temperatures. Finally, to attain higher relative density and full-dense compact, the brown compact is sintered at a higher temperature, close to the melting temperature of these alloys.

2. Biocompatible metals for biomedical applications

The use of metallic materials for medical applications, especially implant devices can be traced back from the 19th century (metal industry revolt era, also known as Industrial Revolution Era). The progression of the metallic implants was instigated by the demands for better means to bone repair, especially for long bone internal fracture fixation [12]. Numerous types of metals have been tried and used in biomedicine according to the required specification of an implant. However, the most popular and accepted biocompatible metals at present for implants are from stainless steel, titanium and its alloys, and cobalt based alloys. Table 1 summarizes the types of metals used for different implant devices [5,52].

2.1. Stainless steels

Stainless steel originally discovered in 1904 by Leon Guillet. However, it was Strauss who began applying stainless steel for surgery in 1926. He discovered stainless steel type 316 (which contain 18 wt% Cr and ~8 wt% Ni stainless steel that contained 2–4% molybdenum) with very low carbon, were profoundly suitable as an implant and surgical devices due to their excellent corrosion resistance and relatively stronger than steel. The corrosion resistance of stainless steel alloys is highly dependent on the formation of thin Cr, Mo-containing passive surface oxide layer, whereby the Mo imparts stability in a Cl^- containing environment. It forms a designed single phase (FCC austenite phase) from its forging temperature (~1050 °C) to room temperature and attain acceptable fatigue resistance and improved strength as a result of strain hardening and solid solution strengthening mechanisms and a fine grain size [5,60,75]. The chemical structure of 316L SS was developed uniquely to achieve stable austenitic structure. Therefore, this structure obligates several advantages, namely; 1) Austenitic stainless steel has a face-centered cubic structure and characterised by very low yield strength, tensile strength ratio, and high formability ability; 2) Successive strain aging and cold working can be used to increase its strength; 3) Austenitic stainless steel exhibits excellent corrosion resistance than ferritic stainless steel due to the crystallographic atomic density of the former is greater than that of the latter; and 4) Austenitic stainless steel is basically nonmagnetic [5,13].

Furthermore, biomedical devices that are made from stainless steels expose a right combination of fabrication response of mechanical strength, cost effectiveness, ductility, and mechanical strength [60]. Compared to cobalt- and titanium-based alloys, 316L SS is widely used as implant devices because they are less expensive by a factor of one-tenth to one-fifth [76–78]. Even though this material is rather cheap, biocompatible, and vigorous, but it does subject to slow corrosion in the body. The grain size and inclusion of metal impurities should also be administered with caution as it is found to affect corrosion resistance and the strength of the material. Another concern for 316L SS is its high modulus of elasticity (of nearly 200 GPa) compared to human bone. These values are about ten times greater than the modulus of elasticity of human bone. Therefore, to alleviate the stress shielding effects caused by high modulus material, the stainless steel prostheses have been employed with a lower modulus polymer like polymethylmethacrylate for both fixation and implant in bones [79].