Intermetallics 78 (2016) 17–20

Contents lists available at ScienceDirect

Intermetallics

journal homepage: www.elsevier.com/locate/intermet

Significantly enhanced drilling ability of the orthopedic drill made of Zr-based bulk metallic glass composite

T.H. Li [a], P.H. Tsai [a], K.T. Hsu [a], Y.C. Liu [b], J.S.C. Jang [a, b, *], J.C. Huang [c, **]

[a] Institute of Materials Science and Engineering, National Central University, Taoyuan 32001, Taiwan
[b] Department of Mechanical Engineering, National Central University, Zhongli, Taoyuan 32001, Taiwan
[c] Department of Materials and Optoelectronic Science, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan

ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form
26 July 2016
Accepted 1 August 2016

Keywords:
Functional alloys (magnetic, electrical, biomedical), metallic glasses (or amorphous metals)
Corrosion mechanical properties
Biomedical

ABSTRACT

Zr-based bulk metallic glass composite (BMGC) presents superior unique properties, including high hardness, high fracture strength, high toughness, large elastic limit, excellent corrosion resistance, and was believed as a promising material for medical-tool applications. In this study, the 4 mm diameter rods of ZrCuAlAgSi-based (Zr-based) BMGC containing ex-situ Ta particles were successfully fabricated by two-step arc melting and suction casting method. These Zr-based BMGC rods was ascertained their amorphous nature by X-ray diffraction and differential scanning calorimetry analyses, and then machined into the orthopedic drill bits with 2 mm in diameter. The drilling tests of the commercial and Zr-based BMGC orthopedic drill bits were conducted by a specially designed indentation-drilling rig. The data of thrust force as a function of drilling distance between drill and porcine bone was recorded and analyzed to evaluate the drilling ability of the Zr-based BMGC made and commercial orthopedic drills, respectively. As a result, the Zr-based BMGC made drill presents 73% reduced thrust force than the commercial one, this indicates that the Zr-based BMGC made drill has less friction force and performs much better drilling ability.

1. Introduction

Most operations of orthopedic surgery involve drilling and tapping before inserting the screws into bone. It has been reported that an excessive increase in temperature of over 50 °C around a drill hole will cause thermal necrosis of bone, and associated with irreversible changes in the structure and physical properties of bone [1–3]. The direct effect on the physical structure and the later effect on the cellular components both injury the hold of the screw. The presence of necrotic tissue may delay healing and predispose to infection. In addition, blunt drill bits will generate higher temperatures, while the increased thrust force for penetration causes poor control of drilling and uncontrolled bursting of drill. Moreover, the medical drills used in the orthopedic and dental fields are generally made of martensitic stainless steel with a crystalline structure and an elastic limit less than 0.5%. When the loading of drill diverges from the centerline often causes the breaking of drills, resulting in surgical inconvenience and even medical disputes [2]. Therefore, it is desirable to develop a novel material which has better mechanical properties with higher elastic limit and fracture toughness for orthopedic drill.

In the past two decades, Zr-based bulk metallic glasses (BMGs) have attracted lots of attention because of its unique engineering properties such as high glass forming ability (GFA), high yield strength and elastic limit, high hardness and wear resistance, high toughness, outstanding corrosion resistance and biocompatibility, and make them as potential candidates for biomedical applications [4–11]. In parallel, Zr-based BMGs possess a wide range of supercooled liquid phase about 100 K, which allows them to be processed into complex-shaped components by thermoplastic forming [12–16]. The combined quality in their mechanical and chemical properties gives great advantages for Zr-based BMGs to be an excellent choice for medical implants, surgical tools and other biomedical related components [7,17,18]. Furthermore, the Zr-based bulk metallic glass composites (BMGCs) with in-situ or ex-situ Ta

* Corresponding author. Institute of Materials Science and Engineering, National Central University, Taoyuan 32001, Taiwan.
** Corresponding author. Department of Materials and Optoelectronic Science, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan.
E-mail addresses: jscjang@ncu.edu.tw (J.S.C. Jang), jacobc@faculty.nsysu.edu.tw (J.C. Huang).

http://dx.doi.org/10.1016/j.intermet.2016.08.001
0966-9795/

particles have been invented recently and possess much better plasticity than the monolithic BMGs [19–23]. Accordingly, a ZrCuAlAg-based BMGC containing ex-situ Ta particles [22] with high GFA, high strength, and excellent plasticity was selected as the raw material for fabricating the orthopedic drill and evaluating its drilling ability in this study.

1.1. Experimental procedure

The alloy composition of $Zr_{48}Cu_{35.3}Al_8Ag_8Si_{0.7}$ (Zr-based) was selected as the base alloy for preparing the BMGC specimens. For a Ta-particle-reinforced BMGC, a two-step melting process was carried out. At first, the base alloy ingot was prepared by arc melting of the appropriate mixture of high purity Zr, Cu, Al, Ag, and Si under a Ti-gettered argon atmosphere. Then the alloy ingots were remelted with the 10 vol % Ta particles (with average particle size of 20 ± 8 μm) to obtain the target composite composition by arc melting. In order to separate the Ta particles in the amorphous matrix homogeneously, the master alloy composite ingots were remelted by turning over for four times. Finally, after complete melting, the liquid alloy was suction cast into the water-cooled Cu mold to form alloy rods with diameter of 4 mm. The amorphous nature of as-cast BMGC rods were examined by X-ray diffraction (XRD, Bruker D8 Discover Diffractometer with monochromatic Cu-Kα radiation) and differential scanning calorimetry (DSC, Mettler Toledo DSC1, with a heating rate of 40 K/min) analyses. Then these BMGC rods were firstly fluted into 2 mm diameter drill bit by lathe and then followed the fine surface polishing. All machining processes were water cooled to avoid the crystallization. Fig. 1(c) shows the appearance of drill bits used in this study.

The surface morphologies of drill head before and after drilling test were examined by scanning electron microscopy (SEM, Hitachi S4700 FESEM) with bird view function. The friction coefficient of drill bits was measured by the J&L Tech Scratch Tester with a 200 μm-sized diamond probe. The initial load is set to 0.2N and the maximum load is 100N under indent speed of 0.08 mm/s. According to Lee's report [24], a specially designed rig with a handy power drill and a specimen fix stage was applied to evaluate its drilling ability, as shown in Fig. 1(d). The rig was connected to a 50 kN Hung-Da universal testing machine with operation condition of 5000 rpm and 6 mm/min feeding rate. The sample for drilling test is the pre-treated (no ligament and tendon) tight bone of pig. To distinguish the chisel-edge forces from the cutting-lip forces, a pilot hole (see Fig. 1(a)) with a diameter equal to the chisel-edge length was first drilled to a depth of three times the drill-head height. During the drilling test, the forces slowly increase as the drill head enters into the bone (Zone I) (see Fig. 1(b)). When the drill head is completely inside the bone (Zone II), the forces arise only from the cutting lips. After the depth exceeds that of the pilot hole (Zone III), the forces from both the cutting lips and the chisel edge are measured. Each experiment was repeated at least four times to ensure repeatability. During the drilling, the whole set was spray by saline to avoid the drill bit from overheating and the bone from burning. The data of thrust force as a function of drilling distance between drill and porcine bone was recorded and analyzed to clarify the difference between the Zr-based BMGC made and commercial medical drill bits.

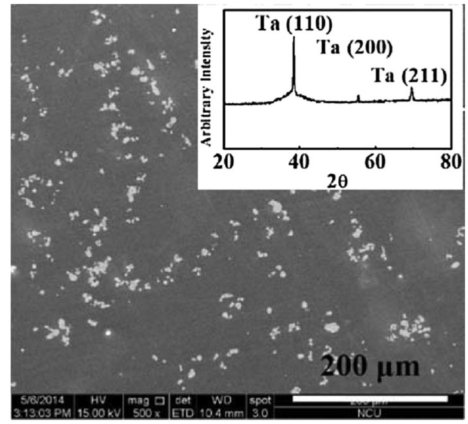

Fig. 2. Cross-sectional SEM image of Zr-based BMGC rod and inserted is the XRD pattern of the Zr-based BMGC rod.

2. Results and discussion

The result of EDS analysis reveals that the matrix composition of as-cast Zr-based BMGC rod is very close to the pre-set composition with about 0.3 at% difference. In parallel, the XRD pattern of the Zr-based BMGC drill show the amorphous matrix phase with a broadened hump in the 2θ range of 30–50° accompanied with three clear crystalline peaks from the BCC-structured Ta particles, as shown in Fig. 2. In addition, the metallographic examination by SEM also revealed that many Ta-rich particles with size around 20 μm can be observed in the amorphous matrix, as shown in Fig. 2. The final volume fraction of the Ta particles in the composite estimated by image analysis was found very close to the initial addition. The mean inter-particle free spacing of Ta particles in the current Zr-based BMGC is estimated to be 21 ± 8 μm.

The result of each drilling test can be draw as a thrust force – displacement curve. However, each drilling test will not show the same curve because each piece of bone is unique, but it will show a similar performance structure. The main criterion chose in this

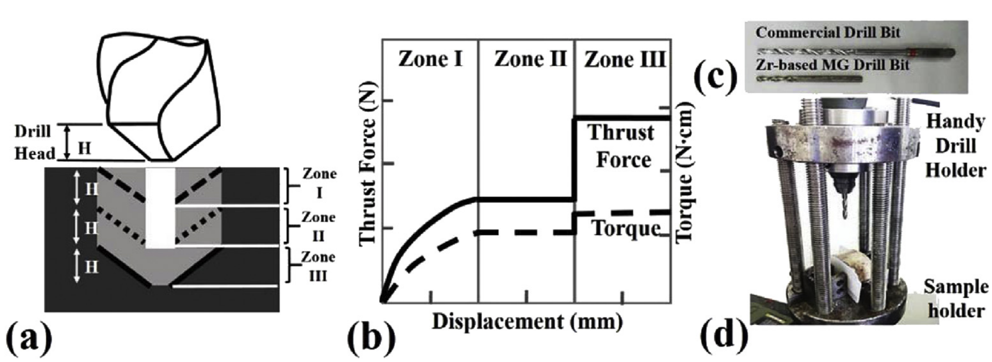

Fig. 1. (a) Schematic drawing of three step of drill process ("H" represent the length of drill head), (b) Thrust force and torque performance during drilling process though each drilling step, (c) Appearance of 3 mm diameter commercial (upper) and Zr-based BMGC-made (bottom) drills, and (d) the setup of drilling test.