Journal of the Mechanical Behavior of Biomedical Materials 79 (2018) 246–253

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

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

Effects of alumina nanoparticles on the microstructure, strength and wear resistance of poly(methyl methacrylate)-based nanocomposites prepared by friction stir processing

Hamed Aghajani Derazkola[a,*], Abdolreza Simchi[b,c,**]

[a] Young Researchers and Elites Club, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Department of Materials Science and Engineering, Sharif University of Technology, P.O. Box 11365-9466, Azadi Avenue, 14588 Tehran, Iran
[c] Institute for Nanoscience and Nanotechnology, Sharif University of Technology, P.O. Box 11365-9466, Azadi Avenue, 14588 Tehran, Iran

A R T I C L E I N F O

Keywords:
Friction stir processing
Polymer-matrix nanocomposite
PMMA
Al_2O_3
Mechanical property
Sliding wear

A B S T R A C T

In this study, alumina-reinforced poly(methyl methacrylate) nanocomposites (PMMA/Al_2O_3) containing up to 20 vol% nanoparticles with an average diameter of 50 nm were prepared by friction stir processing. The effects of nanoparticle volume fraction on the microstructural features and mechanical properties of PMMA were studied. It is shown that by using a frustum pin tool and employing an appropriate processing condition, i.e. a rotational speed of 1600 rpm/min and transverse velocity of 120 mm/min, defect free nanocomposites at microscale with fine distribution of the nanoparticles can successfully been prepared. Mechanical evaluations including tensile, flexural, hardness and impact tests indicate that the strength and toughness of the material gradually increases with the nanoparticle concentration and reach to a flexural strength of 129 MPa, hardness of 101 Shore D, and impact energy 2 kJ/m^2 for the nanocomposite containing 20 vol% alumina. These values are about 10% and 20% better than untreated and FSP-treated PMMA (without alumina addition). Fractographic studies indicate typical brittle features with crack deflection around the nanoparticles. More interestingly, the sliding wear rate in a pin-on-disk configuration and the friction coefficient are reduced up to 50% by addition of alumina nanoparticles. The worn surfaces exhibit typical sliding and ploughing features.

1. Introduction

During the last decade, polymer-based nanocomposites have received tremendous amount of interest for many applications for load-bearing structures, electronics, optics, sensors, packaging, environment, energy, biology and medicine (Singhal et al., 2013; Palanivel et al., 2016; Maxwell Rejil et al., 2012). The high strength, wear resistance and physicochemical properties of inorganic reinforcements along with the lightweight, flexibility, corrosion resistance and ease of processing of polymers yield composites with superior mechanical, physical and anti-aging properties at reasonably low cost (Lee et al., 2006; Doddapaneni et al., 2017; Qu et al., 2017). Among various polymers and ceramic fillers, poly(methyl methacrylate) (PMMA) reinforced with alumina has received increased attention for protection of oxidation and corrosion of metals (Siegel et al., 2001a), high energy density capacitors (Siegel et al., 2001a), acoustic emission sensors (Ash et al., 2004), optical devices (Cinausero et al., 2008), electronic packaging (Ritzhaupt-Kleissl et al., 2006), and dentures (Siegel et al., 2001a). PMMA is a transparent polymer with moderate mechanical and physical properties but non-toxic and compatible with ceramics (Mark, 1985; Vallésa et al., 2013; Zeng et al., 2013). Due to the good mechanical properties of PMMA, it used for many biocomponents like joints, interim fixed restorations, dental material, bone cement and many parts for bio medical use (Yu et al., 2014; Arun and Kanagaraj, 2015; Topouzi et al., 2017; Kawaguchi et al., 2014; Ayre et al., 2014; Aghyarian et al., 2015; Letchmanan et al., 2017). Alumina is an insulator but has good thermal conductivity and high mechanical strength and wear resistance (Zhang and Lei, 2008). Therefore, PMMA/Al_2O_3 composites have been investigated in details (Zhang and Lei, 2008). Nevertheless, nanometric alumina particles are prone to agglomeration which along with their chemical incompatibility with the organic matrix restricts its efficient use (Aliofkhazraei, 2015; Kasprzyk-Hordern, 2004; Abdelkader and Abdecharif). For fine and uniform distribution of alumina nanoparticles through the PMMA matrix, chemical approaches such as solution blending technique (Shi et al., 2018), sol-gel (Drah et al., 2017), in situ polymerization (Mallakpour and

* Corresponding author.
** Corresponding author at: Department of Materials Science and Engineering, Sharif University of Technology, P.O. Box 11365-9466, Azadi Avenue, 14588 Tehran, Iran.
E-mail addresses: hamed.aghajani@srbiau.ac.ir (H. Aghajani Derazkola), simchi@sharif.edu (A. Simchi).

https://doi.org/10.1016/j.jmbbm.2018.01.007
Received 23 November 2017; Received in revised form 4 January 2018; Accepted 9 January 2018
Available online 10 January 2018

Table 1
Mechanical properties of PMMA.

Property	Measured values	Reported values
Density (g/cm^3)	2.57	2.58
Tensile strength (MPa)	69.8	70
Young modulus (GPa)	72	72.3
Elongation (%)	4.73	4.8
Poison's ratio	0.2	0.2

Khadem, 2015), and surface treatment of the ceramic phase (Reyes-Acosta et al., 2015) have been examined. Severe plastic deformation techniques including friction sir processing (FSP) are relatively new routes to prepare microstructurally homogeneous nanocomposites either through ex-situ or in-situ methods (Khodabakhshi and Simchi, 2017). Particularly, FSP is an attractive solid-state technique for the preparation of polymer matrix nanocomposites. In this process, a non-consumable rotating tool with a pin is plunged into the surface, and due to interaction between tool and surrounding materials, frictional and deformation heat are generated (Aghajani Derazkola et al., 2015; Elyasi et al., 2016; Liu et al., 2016). As a result, materials flow from the front to the back of the pin by the acting force of stirring finely distribute the nanoparticles into the matrix (Aghajani Derazkola et al., 2018; Aghajani Derazkola and Simchi, 2017; Aghajani Derazkola et al., 2017). This process is frequently utilized for lightweight metals including Al and Mg to be reinforced with different nanoparticles, but mostly SiC (Zhu et al., 2016; Devaraju et al., 2013a, 2013b; Khodabakhshi et al., 2017a), TiO_2 (Khodabakhshi et al., 2017b; Khodabakhshi et al., 2014; Khodabakhshi et al., 2015; Zhang et al., 2009) and Al_2O_3 (Shafiei et al., 2009). As similar to metal matrix nanocomposites, enhanced physico-mechanical properties of polymers through reinforcing with ceramic nanoparticles and carbon materials have been reported (Azdast et al., 2018).

Examples include polycarbonate (PC)/Al_2O_3 (Doniavi et al., 2016), polypropylene (PP)/carbon nanotube (CNTs) (Ahmadi et al., 2014), high-density polyethylene (HDPE)/SiC (Raza et al., 2017), HDPE/CNTs (Gao et al., 2016), polyamide 6/CNTs, and polypropylene(PP)/ethylene-propylene diene monomer (EPDM)/organoclay (Farshbaf Zinati, 2015; Gao et al., 2017; Nakhaei et al., 2016). For instance, studies have shown that CNTs canhomogeneously be dispersed throughout Polyamide 6 (PA6) matrix either through controlled FSP (Gao et al., 2016) or ultrasonic-assisted FSP (Farshbaf Zinati, 2015); Enhanced mechanical properties were reported for HDPE nanocomposite reinforced with multi-walled CNTs when the rotational tool speed is appropriately controlled (Gao et al., 2017); the effect of tool rotational speed on the tensile strength of PP/EPDM/organoclaynanocompositesshowed similar trends (Nakhaei et al., 2016); Enhanced elastic modulus of PE/CNTs/nanoclay composites through FSP was also demonstrated (Rostamiyan and Zaferani, 2017). The effect of processing parameters on FSP of PMMA has been reported in recent studies (Aghajani Derazkola and Simchi, 2017).

However, to the best our knowledge, the effect of alumina nanoparticles on the mechanical properties of PMMA based nanocomposites prepared by FSP has not been studied in detail. This paper presents experimental results on the processing of alumina-reinforced PMMA nanocomposites by FSP and evaluations of the resulting mechanical properties. The main focus of this research is local reinforcement of biomedical fixed part (knee joint) for improvement of mechanical and wears properties which are under stress concentration.

Not only the effect of alumina nanoparticles on the tensile strength, hardness and impact energy were studied, but also the wear behavior of the nanocomposites in a pin-on-disk configuration was investigated. The presented results could be of interest for development of polymer matrix nanocomposites with superior mechanical strength and wear resistance for load-bearing applications.

2. Experimental procedure

A PMMA sheet with 4 mm thickness and properties reported in Table 1 were supplied from local market (Arkema Polymer Industry, USA). The sheet were cut into 200 × 100 mm^2 plates by a laser cutting machine. A flexible clamping system made of high-carbon steel was designed to secure the plates in proper position. The schematic picture of FSP process is shown in Fig. 1a. A non-consumable tools with frustum pin profile was made of high speed tool steel (HSS) and used for FSW which were detailed in Fig. 1b. Alumina powder with an average particle size of 50 nm and purity of 99.9% was purchased from the US Nano Company (US NANO, USA). Fig. 1c shows a SEM image of the

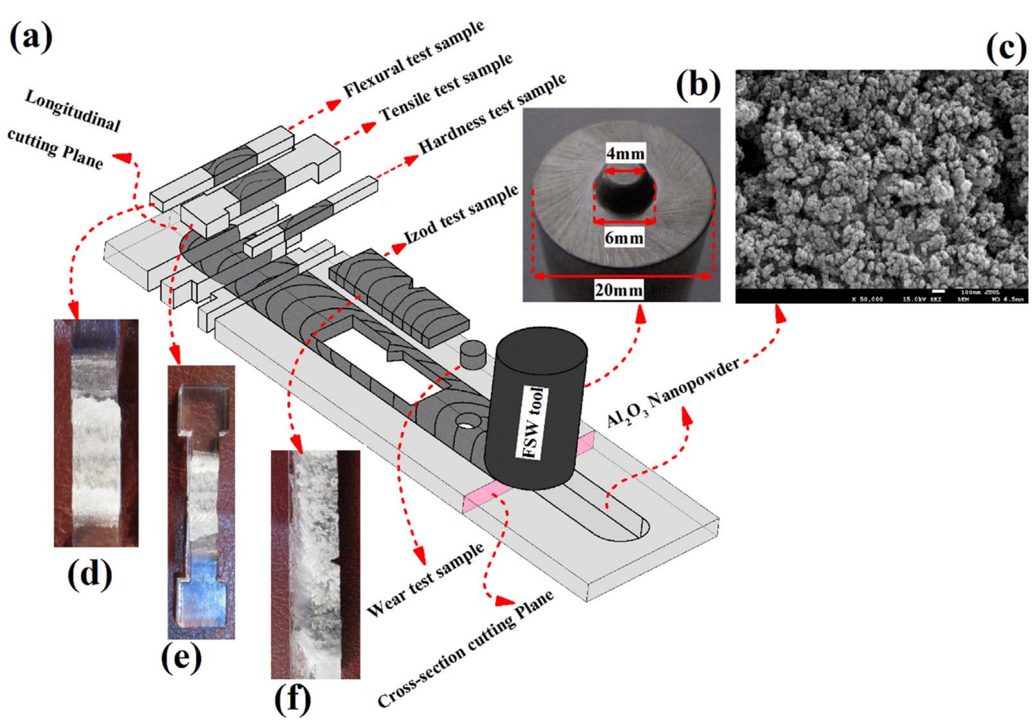

Fig. 1. **(a)** A schematic image of friction stir processing of PMMA based nanocomposites, (b) an electronic image of the utilized tool, (c) SEM image of Al_2O_3 nanoparticle (adapted from http://www.us-nano.com/inc/sdetail/8,4423), and images of the specimens prepared for (d) flexural test, (e) tensile test, and (f) Izod impact.