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MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF PTFE/Al/W SYSTEM

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Abstract. Mechanical and microstructural properties of high density PTFE/Al/W composites consisting of PTFE matrix, aluminum and tungsten particles were investigated. Three types of samples having different porosities and particle sizes of W with an identical weight ratio between PTFE, Al and W were fabricated by Cold Isostatic Pressing. The quasi-static and Hopkinson Bar compression tests were employed to investigate the mechanical properties of these materials. The results demonstrated that the porous PTFE/Al/W composite samples containing fine W particles have higher quasi-static and dynamic fracture stresses than higher density PTFE/Al/W samples containing coarse W particles. ESEM micrographs revealed that deformation occurred mainly in the PTFE matrix while metal particles remain undeformed. We observed nano-fibers of PTFE caused by high strain rate deformation.

Keywords: PTFE, Al, W, porous, granular material, dynamic deformation
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INTRODUCTION

The inclusion of rigid filler particles, such as glass beads, silica particles and metal particles, in a polymeric system is widely studied and used in dentistry [1-4], integrated circuits [5,6] and the defense industry [7]. The influence of fillers on physical and mechanical properties of composites was evaluated. For the most part, these investigations have been concerned with the effects of filler content, size, shape, and processing of a solid composite. None of these papers directly addresses the influence of filler size on the compressive strength of a porous composite system.

There is a need to develop “heavy” energetic materials for some applications. The requirements are a high density and exothermic reaction initiation upon impact. PTFE has an excellent combination of electric and mechanical properties that make it suitable for many applications [8]. It is also one of components of energetic mixtures [9-11] thanks to its unusual physical and thermodynamic properties. A few studies were conducted to investigate the dynamic behavior of composites with PTFE as the matrix [7,12-14]. This paper describes the fabrication of PTFE/Al/W mixtures with varying W particle sizes and densification pressures to introduce the composites with different porosities and different spatial distribution of metal particles. The quasi-static and dynamic compressive strengths of these materials were measured and analyzed. The porous composite containing fine W particles has a higher strength than higher density material with coarse W particles. We explained this behavior by force chains formed by fine metal particles.

EXPERIMENTAL PROCEDURE

The Cold Isostatic Pressing (CIPing) was used to prepare high accuracy samples from a mixture of 17.5 wt% PTFE, 5.5 wt% Al, and 77 wt% W powders. The initial powders had the following average sizes: Al: 2 μm (Valimet H-2); coarse W powder: 44 μm (Teledyne, -325mesh) and fine W powder with particle sizes <1 μm (Alfa Aesar); PTFE: 100 nm (DuPont, PTFE 9002-84-0, type MP 1500J).

The powders (mass about 18 g) were ball milled in a SPEX 800 mill for 2-10 minutes using an alumina ball (mass 3.8 g) Ball milling was used to avoid the agglomeration of particles in the powders. No other treatment of particles or samples was employed to promote the adhesion of the metal particle to the PTFE matrix. A typical sample is about 10 mm high and 10.44 mm in diameter. Three types of composites (Table 1) were prepared. At least three samples, usually five to six, for each type of composite were tested under the same conditions of loading. The density of samples was estimated based on the dimensions of the samples. The porosity was estimated based on the theoretical density of samples.

Quasi-static compression tests were performed using the SATECTM Universal Materials Testing Machine (Instron; Canton, MA) with a 22,000 lb loading capacity. Dynamic testing was carried out using the Hopkinson bar which comprises three 19 mm diameter bars: a 457 mm long maraging steel striker bar, an 1828 mm long maraging steel incident bar and an 1828 long magnesium transmitted bar at strain rates about 500 sec^{-1}. Because the investigated materials have a relatively low strength, a low-impedance magnesium transmitted bar was adopted to obtain low noise-to-signal ratio.

The top of the initial samples and the fractured surfaces after testing were polished, and Au layer was deposited on them using Denton Discovery 18 Sputter System. The morphologies of the samples were examined by a FEI XL30 environmental scanning electron microscope (ESEM) with an accelerating voltage of 20 Kev.

RESULTS AND DISCUSSION

Typical conditions of fabrication and properties of tested Cold Isostaic Pressed (CIPed) samples are presented in Table 1. Note that under the same pressing conditions (pressure, time and sample size), the PTFE/Al/W composite containing fine W particles reached only a density 6 g/cm^3, while the PTFE/Al/W composite containing coarse W particles could reach a density of 7.05 g/cm^3, which is close to the theoretical density (7.16 g/cm^3). At the same pressing condition, the mixture of PTFE and Al can be fully densified [13]. Tungsten particles have a higher strength than Al particles. For this reason the addition of fine W particles into the mixture of Al and PTFE resulted in a lower density of the samples CIPed under the same pressure. One of the initial hypotheses for this behavior was the "closed" porosity of agglomerated fine W particles where PTFE did not penetrate. To avoid this agglomeration we applied separate ball milling of W micron size powder. This procedure only slightly increased the density of the mixture from 6 g/cm^3 to 6.2 g/cm^3 under the same CIPing conditions. It is still significantly lower than the density of the 7.05 g/cm^3 mixture with coarse W particles. It reveals that the agglomeration of fine W particles was not a main contribution to the low density of the porous PTFE/Al/W samples containing fine W particles.

Table 1. Properties of composites and PTFE.

Name	Dense coarse W	Porous fine W	Porous coarse W	Pure PTFE
W Particles Size (μm)	<44	<1	<44	-
CIPing Pressure (MPa)	350	350	20	350
Density (g/cm^3)	~7.05	~ 6.00	~ 6.00	~2.1
Porosity (%)	1.6	14.3	14.3	4.5
Quasi-static Strength (MPa) (10^{-3} s^{-1})	18	24	5	3
Dynamic Strength (MPa) (500 s^{-1})	24	44	18	20

To investigate the behavior of materials with the similar porosity and different particle sizes of W, porous PTFE/Al/W samples containing coarse W particles were fabricated with the porosity similar to the porosity of samples with fine W particles. This goal was accomplished by significantly reducing the CIPing pressure to 20 MPa.

The data in the Table 1 illustrate that the samples with fine W particles and higher porosity had higher compressive strength than higher density samples with coarse W particles. This is an unusual phenomenon because typically the more porous the material is, the weaker strength it has. When comparing the porous composite containing coarse W particles with the higher density composite, we found that higher porosity lead to lower strength when the components are identical. When comparing the porous composite containing coarse W particles with the porous composite containing fine W particle, we found that the difference in the particle size of W is a major contributor to their difference in strength.

The similar behavior was observed under drop weight tests conditions [15]. We explain the higher strength phenomenon at higher porosity by the influence of force chains between metal particles when they have small diameters. Two-dimensional numerical analysis of drop weight tests revealed that small particles create force chains affecting the global strength of porous granular materials [16,17]. They can serve as an ignition site within the composite granular energetic material [18,19]. No significant force chains exist in the densified composite containing large W particles with the same volume.

Quasi-static compression tests demonstrated a consistently different pattern of fracture shown in Fig.1. It is natural to expect that porous materials in compression tests fail due to axial cracks caused by tensile stress concentration at the vicinity of pores [20]. It is interesting that the more porous PTFE/Al/W containing fine W particles failed mainly because of shear cracks.

It can be seen from Table 1 that the composite materials have relatively low strengths. That is because metal particles had low aspect ratio (length/diameter ratio of filler particles) and thus generally not able to support stresses transferred from the polymer, and thus weaken the composite materials. The weak interface between the matrix and the filler also contributed to the low strengths. The dynamic strength of composites with course W is very close to that of pure PTFE (Table 1). It means that the major contribution to the strength of these composites was from the PTFE matrix, rather than from the metal particles. This speculation is consistent with the microstructure of the deformed

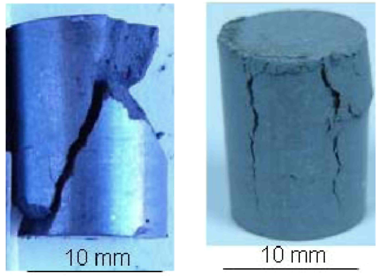

FIGURE 1. Specimens after quasi-static testing: (a) shear crack in the porous PTFE/Al/W composite sample with fine W particles; (b) axial crack in the porous PTFE/Al/W composite sample with coarse W particles.

samples. Figure 2 shows that the continuous PTFE matrix was heavily deformed and fractured under high strain rate deformation. PTFE fibers were stretched out probably due to the local adiabatic heating leading to crazing formation. Metal particles, i.e. Al and W particles, kept their original spherical geometry.

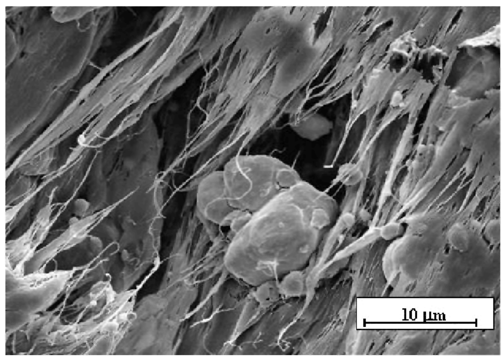

FIGURE 2. SEM image of the dense W/Al/PTFE sample containing coarse W powder after Hopkinson bar test.

A detailed view of one of PTFE fibers is shown in Fig. 3. These fibers have a diameter as low as 60-100 nm, so termed nano-fibers. PTFE nano-fiber formation has been observed by Brown et al. [21] under different conditions of deformation. The formation of these thin fibers is connected with the crazing phenomenon, with fibers providing additional resistance for a propagating crack.

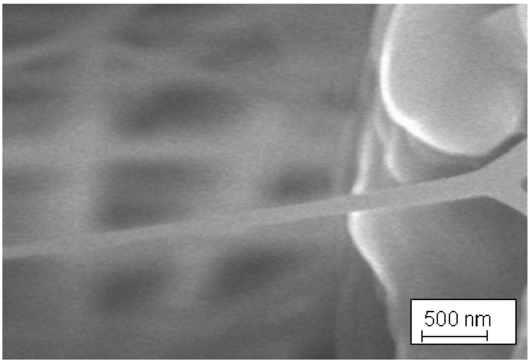

FIGURE. 3. A detailed PTFE fiber formed by opening crack in high strain rate deformation.

CONCLUSIONS

Quasi-static and high strain rate mechanical properties of composite systems consisting of PTFE, Al and W particles were investigated. Three kinds of sample with varying size of W particles and varying porosity were tested to determine the effect of particle size on the density and the ultimate compressive strength of the materials.

Fine W particles-filled samples with a higher porosity have a higher compressive strength than coarse W particles-filled ones, which had a higher density. We attribute this phenomenon to the existence of force chains between fine W and Al particles in the composites.

Microstrutural observation of heavily deformed samples revealed that most of the plastic strain is accommodated by a soft PTFE matrix with practically undeformed metal particles. The formation of PTFE nano-fibers is attributed to local adiabatic heating.

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