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Powder metallurgy titanium metal matrix composites reinforced with carbon nanotubes and graphite

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ABSTRACT

Carbon nanotubes (VGCF) and graphite (Gr) reinforced Ti metal matrix composites (TiMMCs) were prepared via powder metallurgy. 0–0.4 wt% VGCF/Gr and Ti mixture powders were prepared by rocking mill. The as-premixed powders were consolidated at 1073 K using spark plasma sintering (SPS). Hot extrusion was performed at 1273 K with an extrusion ratio of 37:1. Microstructures and mechanical properties of the as-extruded Ti composites were investigated to evaluate strengthening effects of VGCF/Gr on Ti matrix. Mechanical strength of Ti–VGCF/Gr composites was augmented when VGCF/Gr contents were increased from 0.1 to 0.4 wt%. Yield strength (YS) and ultimate tensile strength (UTS) of Ti-0.4 wt% VGCF composites were increased 40.4% and 11.4% as compared to pure Ti, while those values were 30.5% and 2.1% for Ti–0.4 wt% Gr. The strengthening mechanism including grain refinement, carbon solid solution strengthening and TiC/carbon dispersion strengthening was discussed in detail.

1. Introduction

Titanium (Ti) and Ti alloys have light weight, high strength and good chemical resistance, so they are extensively used as structural materials in aircrafts, automobiles and chemical plants [1–3]. However, the young's modulus, wear resistance and heat resistance of Ti materials are inferior to those of steel and Ni-based alloys [4]. The concept of design metal matrix composites (MMCs) reinforced with innovative materials such as carbon nanotubes (CNTs) has thrown light on development of new materials with outstanding mechanical properties. Due to its extraordinary mechanical properties, ultra-high aspect ratio as well as superior thermal and electrical properties, CNTs are regarded as the 'ultimate fiber' for next-generation composites. Several literatures present significant achievements in Al, Cu and Mg matrix MMCs reinforced with CNTs [5–7]. Few works present Ti metal matrix composites (TiMMCs) reinforced with CNTs.

Ti and its alloys as matrix metal, in combination with the advantages of powder metallurgy techniques, offer an interesting possibility to the development of CNTs reinforced TiMMCs. Until recently, Kondoh et al. [8,9] have observed 27% and 36% improvements in UTS and YS of TiMMCs reinforced with 0.35 wt% multi-wall CNTs (MWCNTs), which was dispersed by wet process and fabricated through powder metallurgy and hot extrusion. However, detailed strengthening mechanism of CNTs in Ti matrix was not mentioned. The primary objective of this work is the study of microstructure and mechanical properties of TiMMCs reinforced with CNTs and graphite (Gr) additives prepared by powder metallurgy route and hot extrusion. The fabrications of the TiMMCs were carried out via mixing the pure Ti powder with different contents of CNTs and Gr reinforcements by designated methods, and the mixture powders were consolidated by spark plasma sintering (SPS) and hot extrusion. The influence of CNTs and Gr contents on microstructures and mechanical properties were studied, and the strengthening mechanism was discussed in detail. Additionally, the distribution behavior of CNTs and Gr in the Ti matrix and the reaction mechanism between CNTs and Gr reinforcements and Ti matrix were investigated.

2. Starting materials

The commercial pure Ti powder (CP Ti, Toho Tec.) was used as starting material. Table 1 showed the characteristics of the CP Ti powder supplied by the provider. The characteristics of MWCNTs (VGCF, Showa Denko) and graphite (Gr, Chuetsu graphite) according to the supplier were listed in Tables 2 and 3. The micrographs of the starting materials were observed by high resolution scanning electron microscopy (JSM-6500F, JEOL). The typical irregular morphology of the CP Ti powder prepared by hydride and dehydride (HDH) method can be observed in Fig. 1a. VGCF is a kind of MWCNTs with about 150 nm diameters and 8 μm lengths, which was employed as reinforcement in the experiments. As a comparison, the flake Gr particle shown in Fig. 1b with a mean diameter of 4.81 μm was also

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Table 1
Characteristics of the titanium matrix powder.

Powder	Impurity content (mass%)					Density (g/cm^3)	Particle size (μm)
CP-450	O	Fe	N	C	Si		
	0.27	0.05	0.03	0.02	0.02	4.51	21.90

Table 2
Characteristics of vapor grown carbon nanotubes (VGCF).

Purity (%)	Aver. diam. (nm)	True density (g/cm^3)	Aver. len. (μm)	Ash (%)
99	150	2.00	8	0.1

Table 3
Characteristics of graphite (Gr).

Purity (%)	Aver. part. size (μm)	True density (g/cm^3)	Volatile (%)	Ash (%)
99.28	4.81	2.23	0.67	0.05

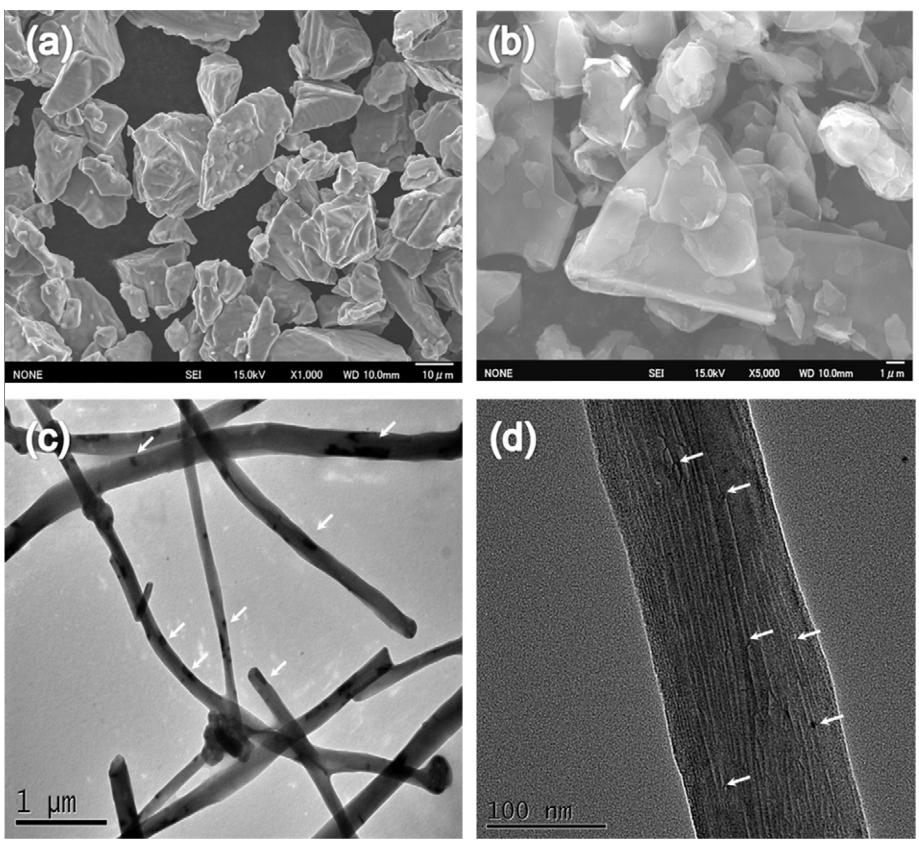

Fig. 1. FESEM and TEM micrographs of the starting materials. (a) CP Ti powder. (b) Graphite particle. (c) Vapor Grown Carbon Fiber. (d) High resolution TEM image.

used as reinforcement. The transmission electron micrograph of VGCF was illustrated in Fig. 1c and d. The arrows indicate the position of nano-defects existing on the surface of VGCF.

3. Experimental procedure

3.1. Powder preparation

In order to achieve an optimal distribution of VGCF and Gr in titanium matrix powder, appropriate VGCF and Gr reinforcements of 0.1, 0.2 and 0.4 wt% were mixed with 200 g of Ti powder, respectively. Mixing was carried out for 120 min in a rocking mill machine (Seiwa Giken); additionally, 0.15 g of lubricant cle-safe® oil was applied to distribute the reinforcements in Ti powder uniformly. For both materials the same blending procedure was employed. SEM images of the powder mixtures Ti–0.4% VGCF and Ti–0.4% Gr were shown in Fig. 2a and b, respectively. It can be observed that VGCF and Gr distributed on Ti particle surface and crevice marked by arrow symbols.

3.2. Consolidation and hot extrusion

The composite powders were loaded into a cylindrical graphite die and consolidated by SPS system (SPS-1030S, SPS Syntex). The sintering temperature was set as 1073 K with a heating rate