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Microstructural evolution during the combustion synthesis of TiC–Al cermet with larger metallic particles

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Abstract

Carbon black powders were incorporated into coarse aluminum and titanium powders, and the mixture was used for a combustion front quenching test. The microstructural evolution in the quenched sample was analyzed with scanning electron microscope (SEM) and energy dispersive spectrometer (EDS). In addition, the combustion temperature and rate were measure, and the phase constituent of the final product was inspected by X-ray diffraction (XRD). The results showed that the combustion reaction started with the melting of the Al particles and formation of Al_3Ti around the Ti particles, and it proceeded in a reaction–dissolution–precipitation mechanism. After melting of the Al and formation of Al_3Ti, the Ti, especially C particles dissolved into the Al liquid and forming Ti–Al–C solution, as a result, TiC grains precipitated out of the saturated liquid solution. With an increase in temperature, Al_3Ti then decomposed and TiC also precipitated from the melt. In the final products, besides TiC particles and Al matrix, a small amount of Al_3Ti was also founded. Also, previous results were explained, and a model corresponding to this mechanism was drawn.

Keywords: TiC–Al cermet; Self-propagating high-temperature synthesis; Microstructural evolution; Synthesis mechanism; Combustion front quenching method

1. Introduction

TiC–Al cermet is a new kind of advanced engineering materials with promised performance. It combines metallic properties (ductility and toughness) with ceramic characteristics (high strength and modulus), leading to greater strength in shear and compression and to higher service temperature capabilities [1]. Interest in TiC–Al cermet in the aerospace and automotive industries, and other structural applications, has increased over the past 20 years because of its high strength-to-weight ratio [2–8].

Traditionally, cermets have been produced by such processing techniques as powder metallurgy, performs infiltration, spray deposition and various casting techniques, e.g. squeeze casting, rheocasting and compocasting [2]. All these techniques are based on complicated process and high-energy requirement. Self-propagating high-temperature synthesis (SHS), developed by Merzhanov and Borovinskaya [9] in the late 1960s, is an innovative processing technique to produce cermets and a feasible way for the in situ fabrication of compositions [10]. SHS refers to a process in which materials with a sufficiently high heat of formation are synthesized in a combustion wave, which after ignition, spontaneously propagates throughout the reactants and converts them into the products. It has many attractive advantages, such as high purity of products; low processing cost, and energy and time efficiency. A wide variety of materials, such as borides [10], carbides [11], intermetallics [12,13], and composites [14] have been produced by this method.

Considerable effort has been made to investigate the combustion synthesis of TiC. The combustion synthesis of titanium carbide from elemental powders has been theoretically and experimentally studied by Holt and Munir [11], calculations of the adiabatic temperature of combustion of graphite and titanium powders to form TiC_x have been made to show the effects of stoichiometry, dilution and the initial temperature of the reactants. Fan et al. [15] investigated the mechanism of combustion synthesis of TiC–Fe cermet by means of combustion wave front quenched method, and a ternary-reaction–diffusion/solution–precipitation model was proposed. The microstructural evolution during SHS of TiC–Fe cermet was also studied [16], at same time, the role of addition of Fe

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[17] as well as the formation of layer-shaped pores was also investigated [18]. Much effort has been exerted toward studying the SHS of TiC–Al cermet, Choi and Rhee [19] studied the effect of aluminum addition on the combustion reaction of titanium and carbon by using differential thermal analysis (DTA) and differential scanning calorimetry (DSC). They concluded that aluminum serves not only as a diluent but also as a reactant and suggested that the heat of reaction between titanium and aluminum initiates the titanium–carbon reaction in the titanium–carbon–aluminum system. Gotman et al. [10] have prepared an Al matrix composite reinforced with 30 vol.% TiC via SHS, Microstructural analysis of the reaction products showed that the composite contained the Al_3Ti phase, indicating that full conversion of Ti had not been achieved, in the TiC/Al composite a certain amount of Al_4C_3 was detected. Lee and Chung [20] studied the ignition phenomena and reaction mechanisms of the SHS of Ti–C–Al system. A possible reaction mechanism was proposed, firstly, Al melted and $TiAl_x$ compounds formed at the interface between the Al melt and the Ti particles, and Ti dissolved into the Al melt by diffusion through the $TiAl_x$ layer. Ignition was believed to have occurred by the reaction of Ti and C at the interface by the diffusion of Ti through the Al melt to the interface. Choi et al. [21] were the first to report the fabrication of Al-based composite reinforced with fibrous TiC formed by SHS reaction. Microstructural analysis of the products from the Ti–C–Al reaction without preheating showed that small amounts of an aluminum carbide phase were present. Brinkman et al. [22] investigated the production of Ti–C–Al grain refiner alloy by SHS route, they found that the Ti/C ratio did not affect the phase composition after reactive synthesis in the 30 wt.% Ti alloys and the formation of Al_4C_3 was suppressed with a high cooling rate after the exothermic formation reactions. Zhang et al. [23,24] suggested that the mechanism of reaction synthesis of TiC in SHS of Ti–C–Al system was a solution–precipitation, accordingly, they divided the whole process of synthesizing TiC into four stages, a heating and melting stage, an initial reaction stage, a complete reaction stage, and a cooling stage.

Clearly, the above-mentioned results are based on the observation of the characteristics of combustion synthesis and of its products. According to the Refs. [19–24], it can be seen that the combustion-synthesized products of Ti–C–Al system are TiC and Al, during the reaction, there is Ti–Al alloy existing, but the kinds of Ti–Al alloy they got are different. More detailed experimental observation and a description of the microstructural evolution are still lacking. In addition, it is possible that the size of the reactants used in a test greatly affects the combustion process and mechanism. Therefore, it is necessary to observe more carefully the microstructural evolution and to study further the mechanism of TiC–Al combustion synthesis, but both high combustion temperature and rate make the observation very difficult, if a sample that was combusting in a self-propagating mode were quenched and reactants used was relatively coarser, the initial, intermediate, and end reaction products would be frozen in the quenched sample, thus microstructural evolution could be observed and analyzed by scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS). The objective of the present work was to investigate more carefully the microstructural evolution in the combustion synthesis of coarser titanium and aluminum powders and finer carbon black than that used in preceding test.

Using a combustion front quenching method (CFQM), Rogachev et al. [25] have observed microstructural transitions on Ti–C and Ti–B specimens with a quenched combustion front, and the CFQM was also used by Lebrat et al. [26] for the mechanistic studies of combustion synthesis of Ni_3Al and Ni_3Al-matrix composites. Subsequently, the CFQM was developed and used by Fan et al. for investigating mechanisms of self-propagating combustion synthesis of TiC [27], TiC–Ni composite [28], TiC–Fe composite [15–18], NiAl [12], and NiAl–Cu [13]. Based on the mechanism which was proposed by Fan et al. [12], Gennari et al. [29,30] investigated the self-propagating high-temperature reaction in nickel–aluminum powder mixtures by computer simulated experiments using a mono-dimensional model and the effect of process parameters on SHS of intermetallic compounds by computer simulation. Anselmi-tamburini et al. [31] investgated the mechanism of the combustion synthesis of zirconia and yttria-doped zirconia in oxygen and air, by quenching the reacting samples at various stages of combustion and examining the microstructure, they proposed a mechanism for the combustion process in this system. In another study, Li [32] investigated the combustion parameter profiles in the combustion zone for NiAl stoichiometry, created by computational means, and established the correlations of the temperature with the fraction reacted, the density, the thermal conductivity, and the reaction rate profiles in the combustion zone.

In the present work, the microstructural evolution of combustion synthesis of TiC–Al cermet was studied using CFQM. The combustion temperature and rate of the reaction was measured; also, the phase constituents of combustion-synthesized product were inspected by XRD. Based on these experimental results, the microstructural evolution and mechanism of the combustion synthesis was discussed, and a model for the combustion synthesis was established.

2. Experimental procedures

About 51.5 wt.% titanium powder (135–154 μm in diameter), 12.9 wt.% carbon black (0.033–0.079 μm in diameter) and 35.6 wt.% aluminum powder (135–154 μm in diameter) were mixed thoroughly for the following tests.

2.1. Measurements of temperature–time profile and wave rate of the combustion synthesis

The mixture was compressed forming a compact (18 mm in diameter and 20 mm in length) with a relative density of about 70%. Then a small hole (2 mm in diameter and 8 mm in depth) was drilled in the bottom of the compact, and a thermocouple pair of W–3% Re versus W–25% Re (0.1 mm in diameter) was inserted into the hole and linked up with an *X–Y* recorder by means of which a temperature–time curve could be recorded, as shown in Fig. 1. The compact was ignited in a