Int. Journal of Refractory Metals and Hard Materials 42 (2014) 42–46

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals and Hard Materials

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

Relationship between hardness and fracture toughness in WC–FeAl composites fabricated by pulse current sintering technique

R. Furushima *, K. Katou, S. Nakao, Z.M. Sun, K. Shimojima, H. Hosokawa, A. Matsumoto

Materials Research Institute for Sustainable Development, National Institute of Advanced Industrial Science and Technology, 2266-98 Anagahora, Shimoshidami, Moriyama-ku, Nagoya 463-8560, Japan

ARTICLE INFO

Article history:
Received 10 July 2013
Accepted 10 October 2013

Keywords:
Tungsten carbide
Pulse current sintering technique
Iron aluminide
Vickers hardness
Fracture toughness
Hard metal tools

ABSTRACT

WC–FeAl composites having notable mechanical properties as hard metal materials are successfully fabricated by using pulse current sintering technique. The relationship between hardness H_V and fracture toughness K_{IC} of the composites is compared with those of WC–Co materials reported. The comparison suggests successful development of WC–FeAl composites with the characteristics almost equal to WC–Co materials currently used for the hard metal tools. Microstructure of the sintered WC–FeAl is uniform without any grain growth. In the K_{IC}–H_V plot, WC–FeAl composites locate at the same position as that of WC–Co materials. The total mechanical property of WC–FeAl is comparable to WC–Co. The developed WC–FeAl is a very promising candidate to replace WC–Co materials. Fully controlled microstructure is crucial.

1. Introduction

Bonded tungsten carbide (WC) is one of the key materials in industry owing to its superb hardness, low friction coefficient, good electrical conductivity and high oxidation resistance [1]. It has been used extensively for cutting tools, drilling and mining equipment, which require high fracture toughness and high hardness simultaneously. Metallic cobalt (Co) is commonly used as binder to compensate the brittle characteristic of bonded WC [2,3], but it has some problems. The poor corrosion resistance of Co at moderate temperature reduces the oxidation resistance of bonded WC [1,4]. Limited resource and environmental hazard are problems of Co also. A need for a new binder material is high.

Iron aluminide (FeAl) is a promising candidate for the binder material of WC. It consists of only common metals (iron and aluminum) and is environmentally benign. Bonded WC with this material has higher oxidation resistance than WC–Co [5], and is very attractive for application at high temperatures around 700 °C. Schneibel et al., however, reported poor sintering characteristic and significant grain growth in WC bonded with FeAl. The maximum H_V was approximately 800 kgf mm^{-2} for WC–FeAl composites prepared by sintering WC powder and Fe40 at.%Al pre-alloyed powder together in vacuum condition at 1723 K [6].

Pulse current sintering is a promising technique for the densification of materials with poor sintering characteristics. Successful fabrication of hard WC–FeAl composites (more than 1500 kgf mm^{-2} in H_V) has been reported with this technique [7]. Their fundamental mechanical properties such as K_{IC} and transverse rupture strength (TRS) must be examined to apply them for cutting tools. Wear characteristics of tools depend on H_V and chipping frequency of cutting edge is relevant to K_{IC}. TRS has a similar significance to K_{IC} (this parameter is equivalent to K_{IC} for a given critical crack size).

A trade-off relationship is present between H_V and K_{IC} in a ceramics/metal composite [8-18], i.e., H_V increases but K_{IC} decreases with increasing fraction of binder (metallic) contents. Clearly, the structural control is needed to improve the net mechanical properties of the composite. High freedom of microstructure control is expected with the pulse current sintering technique, and is very attractive to improve the net mechanical properties of the composite. The objective of this study is to examine the effectiveness of the pulse current sintering technique on the improvement of mechanical properties of WC–FeAl composite.

2. Experimental procedure

Three kinds of raw WC powders are used in this work: WC-25 (d_{50} = 2.3 µm; Japan New Metals Co. Ltd. Japan), WC-F (d_{50} = 0.73 µm; Japan New Metals Co. Ltd. Japan) and WC-02NR (d_{50} = 0.12 µm; A.L.M.T. Corp., Japan). They are mixed with FeAl pre-alloyed powder (KYORIX, $Fe_{0.6}Al_{0.4}$, d_{50} = 5.6 µm; KCM Corporation Co., Ltd., Japan) and ethanol (100 ml) in a ball mill (the rotation speed 100 rpm). The milling pot is made of stainless-steel and the volume is 420 ml. The milling media are cemented carbide balls (ϕ: 9.35 mm). Fig. 1 shows SEM micrographs of raw powders (three kinds of WC powders and FeAl powder). The volume fraction of FeAl to WC–FeAl (V_{FeAl}) ranges from

* Corresponding author. Tel.: +81 52 736 7603; fax: +81 52 736 7127.
E-mail address: ryoichi-furushima@aist.go.jp (R. Furushima).

0263-4368/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijrmhm.2013.10.008

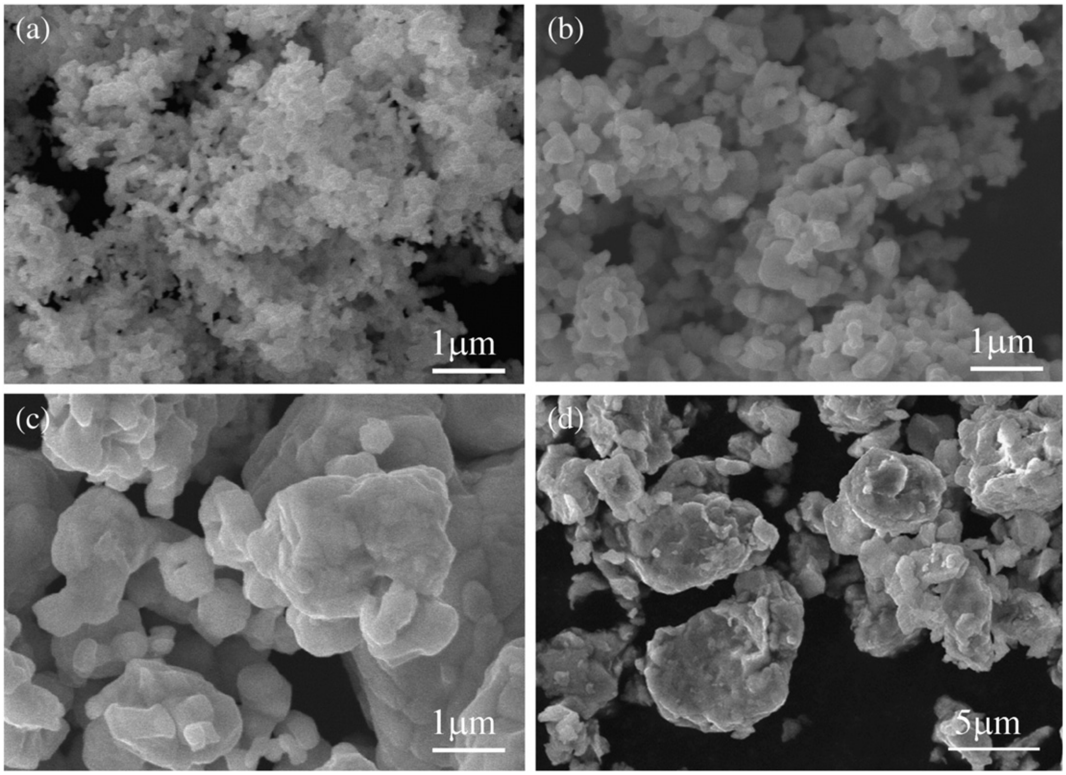

Fig. 1. SEM micrographs of various raw powders. (a) WC-02NR ($d_{50} = 0.20$ μm); (b) WC-F ($d_{50} = 0.75$ μm); (c) WC-25 ($d_{50} = 2.5$ μm); (d) $Fe_{0.6}Al_{0.4}$ ($d_{50} = 5.6$ μm).

0.15 to 0.45. The weight ratio of powder/ball is 2:15. The milled suspension (approximately 9 vol.%) is dried in a rotary evaporator at 55 °C under reduced pressure.

The dried WC–FeAl powder is packed into a graphite die with a cross section of 5 mm in width and 30 mm in length, and consolidated under a pressure of 40 MPa in a vacuum (10 Pa) using a pulse current sintering equipment (Dr. Sintering Series SPS-515S, Sumitomo Heavy Industries Techno-Fort Ltd., Japan). The average heating rate is 60 °C/min and the maximum temperature ranges from 1140 to 1170 °C. The holding time is 3 min for all samples.

The sintered WC–FeAl is machined into specimens of the dimension $2 \times 4 \times 30$mm with a planar grinding machine (grading wheel of 240 mesh roughness). After the density measurements by the Archimedean method, the specimens were edge chamfered. Three-point bending test is used to determine the transverse rupture strength (TRS) on the specimens of half size ($2 \times 4 \times 15$ mm) with the span of 10 mm. The load is applied by a universal testing machine (Autograph AGS-G 1 kN, Shimadzu Corp. Kyoto, Japan) with the crosshead speed of 0.5 mm/min. A buffing machine is used to polish the surface of the specimen after bending tests with 6 and 1 μm diamond slurries. Vickers hardness (H_V) is measured on the polished surfaces following the ASTM B294 standard with a Vickers hardness tester (HV114, Mitutoyo Corporation, Japan) at the load of 30 kgf for 15 s. Five indentations are made for each sample to measure the length of indentation diagonals.

The fracture toughness K_{IC} is calculated with the Palmqvist model proposed by Niihara et al. [18]

$$K_{IC} = 0.0089\left(\frac{E}{H_V}\right)^{0.4}\frac{P}{a(C-a)^{0.5}} \tag{1}$$

where E, P, a and C denote Young's modulus, applied load, half-length of indentation diagonal and crack, respectively. Eq. (1) is applicable for $C/a < 2.5$. Young's modulus E is obtained from velocity measurements for longitudinal and shear waves in the specimen by ultrasonic pulse echo method using the following equation,

$$E = {V_S}^2\rho\frac{3{V_L}^2-4{V_L}^2}{{V_L}^2-{V_S}^2} \tag{2}$$

where, V_L, V_s and ρ denote velocities of longitudinal and shear waves and apparent density of the specimen, respectively.

Finally, the microstructure is observed on the polished surface with a scanning electron microscope (ERA-8900FE, ELIONIX INC., Japan). An energy-dispersive X-ray spectrometer (EDS) is used for mapping elements such as Fe and Al. X-ray diffraction (XRD) analysis (X'pert-MPD, PANalytical, Netherlands) is used to identify the phases in sintered composite (Cu-Kα, diffraction angle 20°–90°).

3. Results and discussions

3.1. Microstructure and density of WC–FeAl composite

Fig. 2 shows SEM micrographs of sintered WC–FeAl composites. The dark and bright features correspond to FeAl and WC, respectively. Grain growth of WC and FeAl not observed for any sample examined. The pulse current sintering is effective in densifying the WC–FeAl composites without the grain growth.

Fig. 3 shows EDS maps of a sintered WC–FeAl composite made from the WC-F ($d_{50} = 0.75$ μm) powder with $V_{FeAl} = 0.25$. The black features in the SEM image (Fig. 3(a)) correspond to Fe and Al or Al and O elements from the maps (Fig. 3(b)–(d)). The locations match well for Al and O, and Fe is distributed in small spaces enclosed by WC grains. These results suggest that a part of FeAl powder is oxidized in milling or drying process.

Table 1 shows density data for various WC–FeAl composites. The relative density is calculated from the ratio of true density of the WC–FeAl powder to apparent density of the sintered composite. The