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The sliding wear of TiC and Ti(C,N) cermets prepared with a stoichiometric Ni_3Al binder

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ABSTRACT

TiC and Ti(C,N) based cermets offer several improved characteristics relative to conventional WC-based "hardmetals", such as lower mass and improved oxidation resistance, which are combined with high toughness, hardness and wear resistance. In the present work the tribological behaviour of TiC and Ti(C,N) cermets has been evaluated under reciprocating sliding conditions. The cermets were produced using an *in-situ*, reaction sintering procedure to form the stoichiometric Ni_3Al binder, with the binder contents varied from 20 to 40 vol%. Wear tests were conducted using a ball-on-flat geometry, with a WC–6 wt% Co sphere as the counter-face material, for loads from 20 to 60 N. The wear response was characterised using a combination of optical profilometry, scanning electron microscopy, energy dispersive X-ray spectroscopy, and focused ion beam microscopy. Initially, two-body abrasive wear was observed to occur, which transitions to three-body abrasion through generation of debris from the cermet and counter-face materials. Ultimately, this wear debris is incorporated into a thin tribolayer within the wear track, which indicates a further transition to an adhesive wear mechanism. It was found that specific wear rates of the cermets increased with both applied load. The highest wear resistance was found for intermediate Ni_3Al contents.

1. Introduction

Traditionally, tungsten carbide–cobalt (WC–Co) cemented carbides have been widely applied in demanding wear environments [1]. However, WC–Co has a number of performance limitations, such as poor oxidation and corrosion resistance, together with a high density [1]. As a consequence, titanium carbide and carbonitride (TiC and Ti(C,N), respectively) based cermets have received considerable recent attention due to a combination of favourable properties [2–5]. These include high hardness, wear resistance, corrosion/erosion resistance, and fracture toughness [2–5]. TiC and Ti(C,N) cermets also have a good strength to weight ratio due to their low densities [2–5]. These cermets have been used in applications that benefit from such properties, including cutting tools and wear resistant coatings [6,7]. Ti(C,N) based cermets incorporate the benefits of both TiC and TiN, in the sense that in general the hardness increases proportionally with the percentage of TiC, while the wear properties improve with the amount of TiN [4]. TiN also has a superior thermal conductivity than TiC, which makes Ti(C,N) based cermets more thermal shock resistant than those based solely on TiC [4]. Typical metallic binders that have been used in the TiC and Ti(C,N) based cermets include nickel and cobalt [8], while more recently nickel aluminides and stainless steels have also been examined [9–11]. In particular, nickel aluminides based on the nominal stoichiometry Ni_3Al have many attractive properties, including a high oxidation resistance up to ~1100 °C, due to the aluminium oxide (Al_2O_3) layer that forms [12,13]. Ni_3Al alloys also exhibit the ability to retain their strength and stiffness to elevated temperatures [14], which is a characteristic that is also transferred to related cermets [15].

In cermet systems the bulk mechanical properties, such as the fracture toughness and hardness, are invariably determined by the binder volume fraction and composition, as well as related microstructural parameters (*e.g.* the ceramic grain size, contiguity, and metallic binder mean free path). For a constant grain size, the bulk hardness typically increases while the fracture resistance decreases, with both decreasing binder volume fraction and binder mean free path [16,17]. These parameters also influence the wear response, such that typically an increased binder content results in a reduction in the wear resistance [18,19]. Similarly, reducing the grain size also often increases the wear resistance, as there is a reduced tendency towards cracking and fragmentation of the ceramic phase [20].

Many applications of cermets require resistance to wear under dry sliding conditions, including mechanical seals, bearings, *etc.* [21,22]. As a consequence, the dry sliding response of a variety of WC–Co and

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TiC-based cermet systems has been examined. Bonny and co-workers have assessed various WC–Co materials, with differing surface finishes, under aggressive dry-sliding conditions with high elastic modulus WC–6 wt% Co based counter face pins [23,24]. Their work demonstrates the importance of the surface finish on minimising the volumetric (or specific) wear rate, with smoother surfaces providing nearly an order of magnitude reduction in the wear rate (*e.g.* polished *versus* electrodischarge "as-machined"). Typical wear rates for these studies varied between 0.15 and 4.5×10^{-7} mm^3/Nm. These researchers also assessed the influence of grain size refining Cr_3C_2/VC additions on the wear response of WC–10 wt% Co [25], sliding against a WC–6 wt% Co counter face pin. It was demonstrated that these additives halved the average wear rate (for 10 km of sliding) from $\sim 0.16 \times 10^{-7}$ mm^3/Nm to $\sim 0.08 \times 10^{-7}$ mm^3/Nm. Onuoha et al. reported wear rates between 4 and 23×10^{-7} mm^3/Nm for a range of TiC-304L stainless steel cermets, with up to 30 vol% steel, sliding against a WC–6 wt% Co sphere [11]. The wear mechanisms in these general studies are invariably complex, and typically include carbide fracture and fragmentation, metallic binder extrusion, and the formation of tribolayers on the wear track surface, often with high oxygen incorporation. These features usually infer a combination of abrasive and adhesive wear in cermet systems.

In other studies, relatively softer counter face materials have been examined. For example, Manoj Kumar and colleagues have investigated the fretting reponse of $Ti(C_{0.7}N_{0.3})$–20 wt% Ni based cermets with various carbide additions, sliding against a bearing grade steel counter face sphere [26,27]. They demonstrated specific wear rates between 2.7 and 36×10^{-7} mm^3/Nm, with the best response obtained using WC additions to the carbonitride.

In the present work, a new family of TiC and Ti(C,N)-based cermets have been prepared with a nominally stoichiometric Ni_3Al binder through a simple *in-situ* reaction sintering process [28,29]. Ni_3Al contents have been varied from 20 to 40 vol%, while various Ti(C,N) compositions have also been assessed. The influence of composition upon the sintering response has been examined, paying particular attention to microstructural development. Reciprocating wear testing has been utilised to assess the wear resistance under aggressive, dry-sliding conditions, using a high hardness WC–6Co counter face material. Such sliding conditions can be envisioned in a variety of applications, especially for replacement of hard chromium coatings in aerospace environments (*e.g.* landing gear, wing flap tracks, *etc.*) [30–32].

2. Experimental procedure

The TiC (lot no. PL20125339; $D_{50}=1.25$ μm) powder was obtained from Pacific Particulate Materials (Vancouver, BC, Canada). The $TiC_{0.7}N_{0.3}$ (lot no. L25809; $D_{50}=2.10$ μm), $TiC_{0.5}N_{0.5}$ (lot no. L29865; $D_{50}=1.74$ μm), and $TiC_{0.3}N_{0.7}$ (lot no. L25747; $D_{50}=1.72$ μm) powders were all obtained from Treibacher Industrie AG (Althofen, Austria). Typical scanning electron microscopy (SEM; Model S-4700, Hitachi High Technologies, Toyko, Japan) images of both the TiC and $TiC_{0.5}N_{0.5}$ powders are shown in Fig. 1. These images confirm the general size characteristics of the powders, with the TiC showing a broadly bimodal distribution, as reported previously [33]. Chemical analysis of the TiC and Ti(C,N) powders, to determine any secondary metallic constituents, was performed using inductively coupled plasma optical emission spectroscopy (ICP-OES; Varian Vista Pro (Radial View), Varian, Inc., Mulgrave, Australia).

The Ni_3Al binder constituents, in the form of Ni (lot no. L10W013; 2.2–3.0 μm) and Ni/Al 50/50 wt% (lot no. D28 × 029; $D_{50}=38$ μm) powders, were obtained from Alfa Aesar (Ward Hill, MA, USA). Powder mixtures were ball milled with 0.5 wt% polyvinyl butyral resin in acetone, using yttria stabilized zirconia milling media, at a media:powder ratio of 10:1 by mass. The mixture was then left to evaporate in a fume hood for a period of 24 h before being sieved through a 75 μm mesh. The sieved powders were uniaxially pressed at 45 MPa (with ~0.6 ml hexane to act as a volatile binding aid during compaction) into disks (~31.75 mm diameter $x \sim 4$ mm thick). The disks were then sealed in plastic bags and cold isostatically pressed (CIPed) at 207 MPa. For sintering, the CIPed samples were placed on top of bubble alumina in an alumina crucible, with sintering performed at 1550 °C for 1 h under dynamic vacuum (~20 mTorr). A heating rate of 10 °C/min was used, while the nominal cooling rate was 25 °C/min (below ~800 °C a slower, natural furnace cool was maintained).

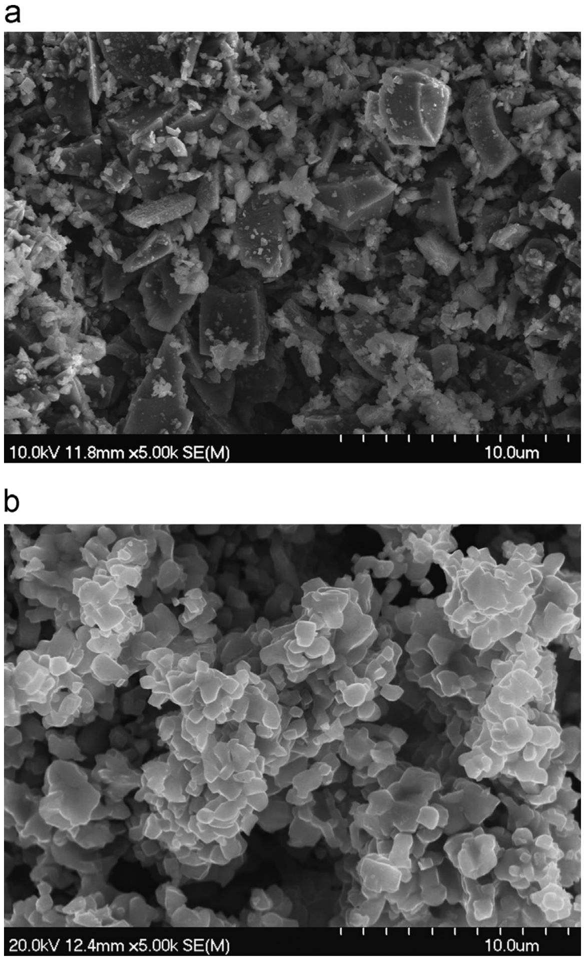

Fig. 1. Typical representative SEM images of the ceramic starting powders used: (a) TiC and (b) $TiC_{0.5}N_{0.5}$.

The density of the sintered cermets was determined using Archimedes' principle, in water, at room temperature. Materialographic preparation for microscopy and subsequent testing involved sequential grinding and polishing, starting with a 125 μm diamond impregnated resin pad and finishing with 0.25 μm diamond paste. Microstructural characterisation was performed using SEM, with associated compositional analysis conducted using energy dispersive X-ray spectroscopy (EDS; Inca X-max^N, Oxford Instruments, Concord, MA, USA). Further chemical analysis was performed using an electron microprobe analyser (JEOL 8200 Superprobe, JEOL Ltd., Tokyo, Japan), using wavelength dispersive X-ray spectroscopy (WDS). The grain size distributions and average grain sizes were determined using the mean lineal intercept method [34], from digital SEM images, with a commercial digital image-processing package (Image Pro, Media