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# Reciprocating wear behaviour of TiC-stainless steel cermets

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ABSTRACT

TiC based cermets have been prepared with three different grades of stainless steel binder (304L, 316L and 410L). The cermets were densified by vacuum melt infiltration, at 1500 °C, which allows the steel binder content to be readily varied from 5 to 30 vol%. The cermets were assessed for their hardness and indentation fracture resistance using Vickers testing. The reciprocating wear response was evaluated using a ball on flat geometry, with a WC-Co counter face sphere. It was shown that the coefficient of friction increases with increasing steel binder content, and also with increasing load and wear time. Similarly, the specific wear rate increases with both steel binder content and applied load, but was largely independent of the steel grade used.

## 1. Introduction

Many demanding applications in the chemical, aerospace, automotive, mining, and oil and gas industries require the use of materials that show a good combination of wear and corrosion resistance. Invariably, ceramic–metal composites, or cermets, are employed in these industries due to their unique combination of high wear resistance, hardness, and strength characteristics, combined with good aqueous corrosion resistance [1–3]. The most widely employed cermet-type materials are the tungsten carbide-cobalt (WC-Co) cemented carbides, or 'hardmetals', which have been extensively used as cutting tools, and also in the drilling and mining industries [4,5]. WC-Co based coatings are also widely used as hard chrome replacements [6,7]. However, cemented carbides based on WC suffer from having exceptionally high densities (~13–15 g/cm$^3$), relatively poor mechanical properties at elevated temperatures, and only moderate oxidation and corrosion resistance. Titanium carbide (TiC) based cermets have proven to be a good substitute for these conventional 'hardmetals' in many applications, due to having low densities (less than 50% of WC-Co), high chemical and thermal stability, relatively high hardness, and good wettability with many metallic binder materials. Several metals have been utilised as ductile binders with TiC, such as Ni, Mo and Fe [8–11]. Due to the relatively low cost, potential for heat-treatment, and good strength and ductility, Fe-based alloys are now being studied and applied more widely [9,12,13]. TiC based cermets have been reported to show high abrasive wear resistance [14]. Degnan and colleagues noted that it is the load bearing capability of the TiC retained at the sliding surface of the composite, and its ability to reduce metal to metal contact during sliding, that is responsible for the improved wear performance of TiC composites at low level of ceramic loading [15].

When thinking specifically about ferrous alloys, stainless steels are widely used for their corrosion resistance, while they also typically possess good mechanical properties. However, one significant limitation of austenitic stainless steels (e.g. 316L) is their poor wear resistance. These materials are generally quite soft, and thus are susceptible to many common forms of wear and contact damage [16]. The potential is therefore present to generate steel-containing composites were a hard ceramic phase is incorporated, ranging from moderately dilute metal matrix composites (MMCs) through to high ceramic loadings in a cermet structure. A variety of powder metallurgy based approaches have been developed to fabricate these types of composites. Bolton and Gant used a conventional press-and-sinter method to produce steel MMCs with relatively low carbide additions (i.e. 5 wt% TiC or niobium carbide) [17]. Akhtar and Guo produced TiC-465 stainless steel composites, with the TiC content varied between 50 and 70 wt%, using a similar press and sinter approach, where sintering was performed at 1400 °C for 1 h [18]. Melt-infiltration can also be used to fabricate cermets, where the ceramic content can exceed 90 vol% [19]. It is also possible to produce clad layers of steel MMCs onto various substrates, as demonstrated by Axen and colleagues [20]. They incorporated TiC particles into a surface layer on a carbon steel through $CO_2$ laser heating. In terms of the tribological characteristics of these types of composite, Pagounis and co-workers reported that the wear resistance of stainless steel can be improved dramatically through the incorporation of ceramic particles such as carbides and oxides [21]. Akhtar and Guo reported that their materials, with 50–70% TiC addition to a stainless steel binder, exhibited a significant improvement in wear resistance [18]. Tjong and Lau also reported a significant

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improvement in the micro hardness, sliding wear and abrasion wear resistance by addition of 20 vol% of a related material, titanium diboride ($TiB_2$), to 304L stainless steels [22].

For the present study, we have developed a family of TiC-based cermets utilising a variety of austenitic and martensitic stainless steels as binder (i.e. grades 304L, 316L, and 410L), using a simple melt infiltration/sintering technique, with the binder contents varied from 5 to 30 vol%. The primary aim of this study is to investigate the microstructure, mechanical, and wear behaviour of these new TiC stainless steel composites. A companion paper will report in more detail on the microstructural effects of the wear process in terms of damage accumulation [23].

## 2. Experimental procedures

### 2.1. Sample preparation

It is generally assumed that the wear behaviour of cermet materials is a direct function of both the material hardness and toughness [24], and that an optimum wear response is obtained when both of these properties are fully maximized [25]. In view of this, the processing techniques used in the production of TiC-based cermets should be careful selected. A method that minimises residual porosity and effects a homogenous distribution of the carbide phase within the metallic binder phase, with no interfacial debonding, should be employed. These benefits are achieved when using vacuum melt-infiltration/sintering in the production of the TiC stainless steel cermets, which ensures highly dense cermets ( > 98% of theoretical density), even when very low amounts of binder are employed (even as low as 5 vol%). The general details of the melt infiltration process for production of the cermets has been reported in detail previously [26–28], and will only be briefly outlined here. The TiC powder used in the current study was obtained from Pacific Particulate Materials Ltd. (Vancouver, BC, Canada), and had a manufacturer quoted mean particle size of ~1.3 μm; this was confirmed through independent particle size analysis, with a measured mean of ~1.25 μm, and a clear bimodal distribution [29]. The 304L (Stock #: 11085, Lot #: K19M09), 316L (Stock #: 11089, Lot #: A04S008) and 410L (Stock #: 11088, Lot #: I23M43) stainless steel powders were all obtained from Alfa Aesar (Ward Hill, MA, USA), and each had a nominal particle size of −100 mesh. Chemical composition analysis of the as-received TiC powder, determined using inductively coupled plasma optical emission spectroscopy (ICP-OES; Model Varian Vista Pro, CA, USA) is presented in Table 1. The W and Co constituents are believed to arise from a milling stage used by the manufacturer for particle size reduction. ICP-OES was also used to analyse the metallic constituents of the three stainless steel powders, as demonstrated in Table 2. In this instance the powders match the specifications typically reported for these steel grades. The C and N contents were determined using combustion infrared (Model Leco CS-444, Leco Instruments, St. Joseph, MI, USA) and inert gas fusion methods (Model Leco TC-436, Leco Corporation, St. Joseph, MI, USA), respectively.

In order to fabricate the cermets, TiC powder pellets were uniaxially compacted in a hardened steel die at ~45 MPa (using ~7.35 g of powder), and then vacuum sealed in polyethylene bags and cold isostatically pressed at ~208 MPa. After compaction, a known amount of steel powder is applied on top of the pressed disks (held in alumina crucibles), which were then melt-infiltration/sintered in a graphite resistance furnace (Materials Research Furnaces, Suncook, NH, USA). The vacuum sintering cycle was conducted at 1500 °C, held for 60 min, with nominal heating and cooling rates of 10 °C/min and 25 °C/min, respectively. Using this approach, samples with 5–30 vol% steel content could be prepared for each of the steel grades.

**Table 1**
ICP-OES chemical analysis of the TiC powders used in the present work (in wt%). C comprises the balance.

| Element | Ti | W | Co | Fe | Ta | Ni | Cr |
|---|---|---|---|---|---|---|---|
| Concentration | 76.79 | 2.22 | 0.23 | 0.17 | 0.026 | 0.024 | 0.014 |

### 2.2. Materials characterisation

The sintered densities of the cermet samples, as a percentage of theoretical, were determined using Archimedes immersion method in water. For subsequent microstructural evaluation and wear testing, the samples were first ground flat using a coarse grit diamond peripheral wheel, and then polished to a mirror-like finish (starting with a 125 μm diamond impregnated pad and finishing with 0.25 μm diamond paste). Microstructural assessment was then conducted using both optical microscopy (Model BX-51, Olympus Canada, Richmond Hill, Ontario, Canada) and scanning electron microscopy (SEM; Model S-4700, Hitachi High Technologies, Tokyo, Japan), equipped with energy dispersive X-ray spectroscopy (EDS; Model Inca X-Max$^N$, Oxford Instruments, Abingdon, UK) for chemical microanalysis. The mean TiC grain size in the sintered materials was determined using the linear intercept method [30] from digital SEM images, while both the TiC–TiC contiguity and steel binder mean free path (MFP) were determined using Gurland's method [31]. The contiguity value, $C$, for each sample were determined by generating a series of parallel, horizontal lines on digital micrographs, and then counting the numbers of carbide/carbide ($N_{c/c}$) and carbide/binder ($N_{c/b}$) interfaces intercepted. Contiguity is then determined following [31]:

$$C=\frac{2N_{c/c}}{2N_{c/c}+N_{c/b}} \quad (1)$$

Using the information obtained for the TiC grain size and contiguity, the binder MFP, $d_b$, can then determined following [31]:

$$d_b=\frac{1}{1-C}\left(\frac{V_b}{V_c}\right)d_c \quad (2)$$

where $V_c$ and $V_b$ are the volume fractions of carbide and binder, respectively. For cermet-type structures the binder MFP is effectively a quantifiable measure of the nomalinal dimensions of the metallic ligaments separating the carbide grains.

The hardness of the materials was determined using Vickers indentation (Model V-100A, Leco Corporation, St. Joseph, MI, USA) with a 1 kgf applied load, held for 15 s, in order to avoid any sample cracking. The indentation fracture resistance (IFR) of the various cermets was determined using Vickers indentation method, with a 50 kgf applied load. Both median and Palmqvist-type sub-surface cracking patterns can be anticipated for these materials, depending on the load and binder volume fraction. For median cracking, IFR values were determined using the equation developed by Anstis and colleagues [32]. For the Palmqvist-type cracking a modified version of the equation formulated by Shetty and co-workers was employed [33], consistent with our recent work [34]. To ensure the validity of the measurements of both hardness and IFR values, a minimum of six indentations were made for each test procedure and material.

### 2.3. Reciprocating wear testing

A reciprocating wear test procedure, using a ball-on-flat geometry, was employed in the present study, and is consistent with our recent publications on related cermet systems [27,34]. The tests were conducted using a universal micro tribometer (Model UMT-1, Bruker Corp., Campbell, CA, USA) on cermet samples prepared with 10, 20 and 30 vol% of each of the three steel grades. A 6.35 mm diameter WC-Co counter-face sphere (Grade 25 with 6 wt% Co, equivalent to ~10.2 vol% Co) was used, sliding against the sample in a reciprocating motion. The wear tests have a fixed stroke length of 5.03 mm, while an