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Effect of $MoSi_2$ content on the lubricated sliding-wear resistance of ZrC–$MoSi_2$ composites

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Abstract

The effect of $MoSi_2$ content (5, 10, and 20 vol.%) on the lubricated, sliding-wear behaviour of ZrC–$MoSi_2$ composites at room temperature is investigated and modeled. It was found that the resistance to sliding wear decreases markedly with increasing $MoSi_2$ content, with a greater rate of mild wear, an earlier transition from mild to severe wear, but essentially the same rate of severe wear. The analysis of the wear results using a mechanistic model indicated that the worsened sliding-wear resistance with the increase in $MoSi_2$ content derives from the decreased hardness and increased internal effective tensile stresses of the ZrC–$MoSi_2$ composite, which speed up the accumulation of damage induced by plastic deformation within the grains and shorten the onset of the grain-boundary fracture condition and subsequent grain pullout. Reduction of the $MoSi_2$ content thus emerges as an effective approach for making the ZrC–$MoSi_2$ composites more sliding-wear resistant under lubrication at room-temperature. These results may have important implications because ZrC holds promise for use in tribological applications requiring both wear resistance and electrical contact, and $MoSi_2$ is its commonest sintering additive.
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Keywords: ZrC; Sliding wear; Contact-mechanical properties; Tribology

1. Introduction

The favourable mechanical and thermal properties of ZrC make it one of the select group of compounds on the current short list of ceramic materials for extreme environments.[1] Not surprisingly, much of the current research on ZrC is focused on evaluating its use as a high-temperature aerospace material (leading edges, acreage thermal protection systems, scramjet flow-path components, rocket propulsion components, *etc*.). However, although they have been less explored, ZrC also possesses a unique combination of properties for tribological applications. In particular, it is not only harder (∼25.5 GPa) and stiffer (elastic modulus ∼392 MPa) than the common advanced ceramics (Al_2O_3, ZrO_2, Si_3N_4, *etc*.), but is also more refractory (melting point ∼3540 °C) and a better thermal conductor (∼40 $W\,m^{-1}\,°C^{-1}$).[2] Thus, ZrC would alleviate and resist the frictional heating in sliding-contact applications better than other advanced ceramics, which make it particularly useful for the fabrication of a great variety of tribocomponents (bearings, wear parts, valves, seals, rollers, *etc*.). Another feature that distinguishes ZrC from the majority of common triboceramics is that its high electrical conductivity (∼$10^6\,S\,m^{-1}$ [2]), similar to that of many metals, enables its use in tribological applications that require electrical contact, such as brushes, microelectromechanical devices, circuit breakers, motor vehicle starters, *etc*. In this context, ZrC could potentially provide electrical tribocomponents with the superior sliding-wear resistance not achievable today with metals, which cannot compete with ceramics in this important mechanical property.

Unlike other mechanical properties, the sliding wear of polycrystalline ceramics is controlled by average microstructural characteristics. This underscores the need to investigate the effects of microstructure on the sliding-wear resistance of ZrC if this is to be used for fabricating tribocomponents. One of these microstructural features is the vol.% of second phases because ZrC is intrinsically unsinterable in the pure state, and has to be densified with the help of additives. For this reason, in the present wear study we explore the role of the $MoSi_2$ content

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(5, 10, or 20 vol.%), doubtless the commonest sintering additive for ZrC. We find that reduction of the $MoSi_2$ content should be an effective approach to making ZrC–$MoSi_2$ composites more sliding-wear resistant under lubrication at room-temperature, and support this finding using a wear-mechanistic model.

2. Experimental procedure

Commercially available submicrometre powders of ZrC and $MoSi_2$ (in both cases Grade B of H.C. Starck, Berlin, Goslar, Germany) were used as starting materials. Three powder batches were prepared by combining the ZrC and $MoSi_2$ powders in relative concentrations of 95–5, 90–10, and 80–20 vol.%, respectively (abbreviated hereafter as ZrC–x%$MoSi_2$, where x refers to $MoSi_2$ content in vol.%). The individual powder batches were attrition milled (01-HD, Union Process, Akron, OH, USA) for 3 h at 600 rpm using WC/Co balls (6.7 mm diameter) with a charge ratio of 24:1 to reduce particle size and promote intimate mixing of ZrC and $MoSi_2$. The milled powders were hot-pressed (HP20-3560-20, Thermal Technology LLC, Santa Rosa, CA, USA) at 1900 °C for 1 h at 30 MPa pressure. The hot-pressing protocol was the same than used previously by others in ZrB_2,[3] except for the final temperature and pressure. The surfaces of the hot-pressed samples were polished to a 1 μm finish and were characterized by scanning electron microscopy (SEM; S-3600N, Hitachi, Japan). Several micrographs of representative regions within the microstructures were recorded for grain size analysis, which was performed by an image analysis system using at least 300 grains for each ZrC–$MoSi_2$ composite.

Sliding-wear testing was performed at room-temperature using a multi-specimen tribometer (Falex, Faville-Le Vally Corp., Sugar Grove, IL) configured in the ball-on-three-disks geometry. In this testing configuration a commercial, bearing grade Si_3N_4 ball (NBD 200, Cerbec, East Granby, CT) of radius 6.35 mm was rotated in contact with three flat disk specimens (thickness 2 mm, diameter 4 mm) aligned with their surface normals in tetrahedral coordination relative to the rotation axis and mounted onto a bearing assembly to ensure equal distribution of the applied load. Paraffin oil (Heavy Grade, Fisher Scientific, Fair Lawn, NJ) with a viscosity of $\sim 3.4 \times 10^{-5}$ m^2/s (~34 cst) at 40 °C was used as the lubricant to avoid any tribological effects such as friction-induced heating or triboreactions, and thus to study the vol.% $MoSi_2$ effect only. The contact load was 120 N and the rotation speed was 100 rpm, corresponding to a sliding velocity of ~0.04 m/s. The wear tests were interrupted at intervals, and the diameters of the circular wear scars on each disk were measured under optical microscopy (two orthogonal measurements per disk, three disks per ZrC–$MoSi_2$ composite). After each interruption the specimens were put back in the tribometer in exactly the same position using a precision fixture. The wear-scar diameter was used to quantify the extent of wear damage. Finally, the wear damage was observed under SEM.

Conventional Vickers indentation tests (MV-1, Matsuzawa, Tokyo, Japan) were performed to evaluate the hardness and toughness of the ZrC–$MoSi_2$ composites. Tests were performed with 98 N load, and the hardness and toughness values were determined using the standard procedure and formulas[4,5]; elastic modulus (E) values determined by the rule-of-mixture were used in the toughness calculations ($E_{ZrC} = 392$ GPa,[6] and $E_{MoSi_2} =$ 440 GPa [7]).

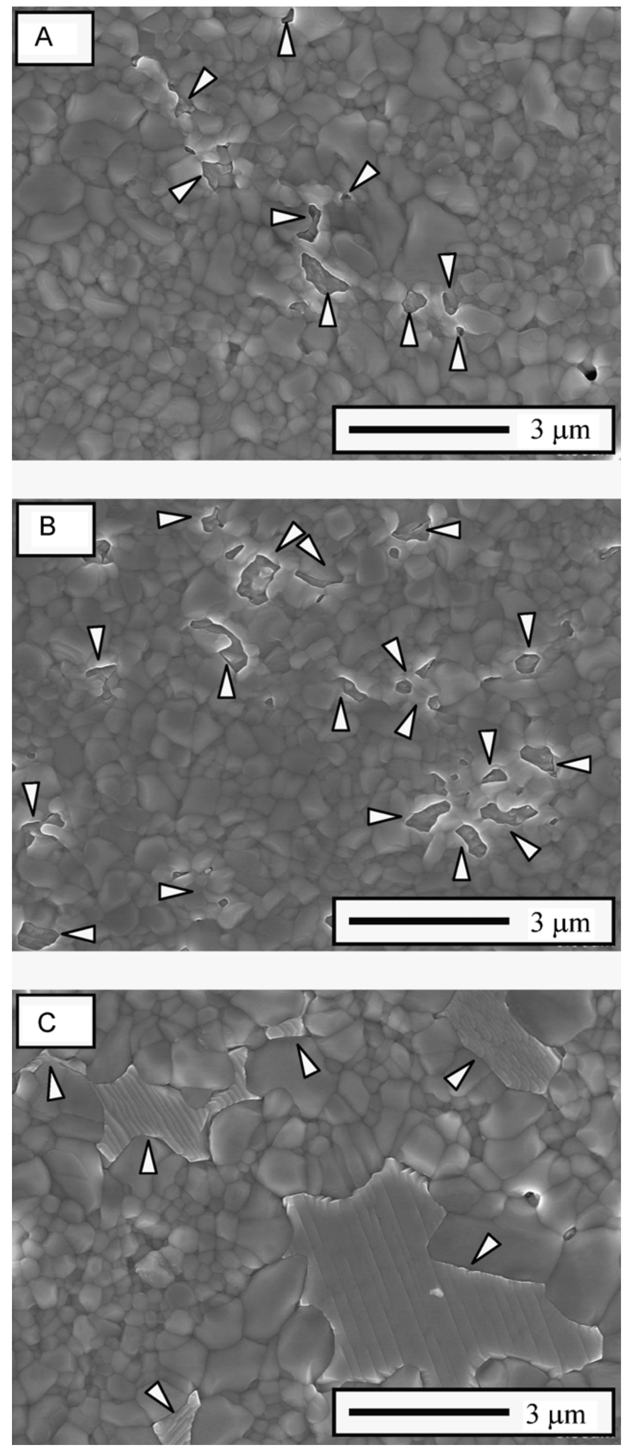

Fig. 1. SEM micrographs of the polished and thermally etched (1 h at 1500 °C in Ar) cross-sections of the ZrC–$MoSi_2$ composites prepared in this study: (A) ZrC–5%$MoSi_2$, (B) ZrC–10%$MoSi_2$, and (C) ZrC–20%$MoSi_2$. The $MoSi_2$ phase is marked with arrows.

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