Edge effects in sliding wear behavior of ZrO_2-WC composites and WC-Co cemented carbides

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Abstract. A trend in the development of WC based cemented carbides and zirconia based ceramic composites is grain size refinement and more narrow grain size distributions of the starting powder, in order to accomplish higher hardness and abrasive wear resistance. The current work reports the results of dry sliding wear experiments on laboratory-made electrically conductive ZrO_2-WC composites and commercially available WC-Co based cemented carbides, which have been manufactured and finished by rough cutting wire EDM with consecutive execution of gradually finer EDM regimes. Tribological data are obtained using a small-scale pin-on-plate test rig. Wear tracks are analyzed by surface scanning topography and scanning electron microscopy, revealing that the outer extensions of the wear tracks exhibit some differences in wear behavior compared to the central parts.

Introduction

For two materials in sliding contact, one source of stresses is obviously the normal force that acts on the contact. The stresses in a material that are governed by a concentrated contact are described analytically by Hamilton [1]. For the concentrated contact situation a maximum tensile stress occurs at the trailing edge of the sliding contact. This stress can easily be converted to a dimensionless number for determining the mechanical severity of contact [2,3]. Another source of stresses is the thermal expansion due to frictional heating.

This paper focuses on the reciprocating sliding friction and wear behavior of WC-Co cemented carbides and ZrO_2-WC composites against WC-Co cemented carbides. Flat samples of these materials were manufactured and surface finished by wire-EDM and grinding and tested using a small-scale pin on plate tribometer. Detailed investigation of the online monitoring of friction forces as function of the sliding wear path as well as surface viewing of the generated wear tracks by scanning electron microscopy and wear quantification by surface scanning topography, reveal a significant difference between the outer extensions of the wear tracks compared to the central parts.

Experimental

ZrO_2-WC composites. The ZrO_2-WC ceramic composites were obtained by hot pressing of yttria-stabilised ZrO_2 powder mixtures with 40 vol % of WC. Flat samples were manufactured by wire-EDM on a ROBOFIL 2000 (Charmilles Technologies, Switzerland) in demineralised water (dielectric conductivity 5 µS/cm), using a brass wire (CuZn37) electrode with a diameter of 0.25 mm and a tensile strength of 500 MPa. More information on the processing and characterisation of this ZrO_2-based composite, together with the mechanical, physical, microstructural and surface finishing characteristics, is given elsewhere [4,5].

WC-Co cemented carbides. The WC-Co cemented carbides investigated are CERATIZIT grades, manufactured by grinding (JF415DS, Jung, Göppingen, Germany) with a diamond grinding wheel (type MD4075B55, Wendt Boart, Brussels, Belgium). For more details about their mechanical, physical and microstructural properties, together with their surface roughness, one is referred to [6]. In this paper, one rough and one fine EDM cut, as well as ground surface finishes were selected for dry sliding experiments

Wear testing. The wear behavior of wire-EDM'ed ZrO_2-WC composites and ground WC-Co cemented carbides was evaluated using a high frequency tribometer, in which a WC-Co cemented carbide pin was reciprocally slid against test specimen counter plates, in accordance with ASTM G133. The pin material (CERATIZIT grade MG12 cemented carbide with 6 wt. % Co) has a compressive strength of 7.2 GPa, a Vickers hardness HV10 of 1913 kg/mm^2, a fracture toughness of 9.3 MPa m$^{1/2}$ and a stiffness of 609 GPa. The sliding tip of the pins was a hemisphere with a rounding radius and roughness parameters R_a and R_t that were measured to be 4.08 mm, 0.35 μm and 2.68 μm respectively.

The contact load and the sliding velocity were varied in the range of 15 up to 100 N and 0.3 up to 0.9 m/s, with a stroke length of 15 mm. The test duration was associated with a sliding distance of 10 km. Before each test, the specimens were cleaned with acetone. After each test, the wear topography was quantified using surface scanning equipment (Somicronic® EMS Surfascan 3D, type SM3, needle type ST305). The wear scars were examined by scanning electron microscopy (SEM, XL-30 FEG, FEI, The Netherlands), equipped with an energy dispersion X-ray spectroscopy system (EDS).

Results and discussion

Friction and wear depth. Typical and representative wear data for wire-EDM'ed ZrO_2-WC composite flat/ WC-Co pin combination as function of sliding distance are presented in Fig. 1. The applied normal force (F_N) and the concomitant tangential friction force (F_T) were recorded continuously as function of sliding distance (s), as illustrated in Fig. 1(a), respectively by means of a load-cell and a piezoelectric transducer. The friction force appears either positive or negative, depending on the sliding direction. One sliding cycle, i.e., a double sliding stroke, contained 50 sample values. The F_T/F_N forces ratio is defined as the coefficient of friction (μ), which can be differentiated in a static (μ_{stat}) and a dynamic (μ_{dyn}) component, Fig. 1(b). Simultaneously, the combined wear depth (Δd), resulting from the pin penetrating the counter plate, was acquired by an inductive displacement transducer. From the vertical displacement curves, instantaneous wear rate curves (k_d) were derived by

$$k_d(s) = \Delta d(s)/(F_N \cdot s). \quad (1)$$

The friction coefficient and wear loss are noticed to increase abruptly during initial sliding and gradually ascend further due to growing pin on plate contact surface, whereas just the opposite behavior is observed for the wear rate. After a running-in stage, the tribosystem reaches a steady state with an almost exponential variation of wear depth and wear rate as function of sliding distance and, at the same time, a short drop down and subsequently gradual recovery in the friction coefficient. The fluctuations in the friction curves, both in the initial and steady state regime, indicate a more pronounced adhesion of both contact surfaces [5]. The dynamic and static component of friction are found to vary similarly as function of the sliding distance, however at a different level. The instabilities in the friction curves during the first sliding km can be related to the changes in the sliding contact surface and removal of the wire-EDM induced recast layer.

Detailed investigation of the curves shown in Fig. 1(b), allowed to infer that peaks in the friction force curves mostly occur at reversing the sliding direction, i.e., at the outer edges of the sliding contact surface.

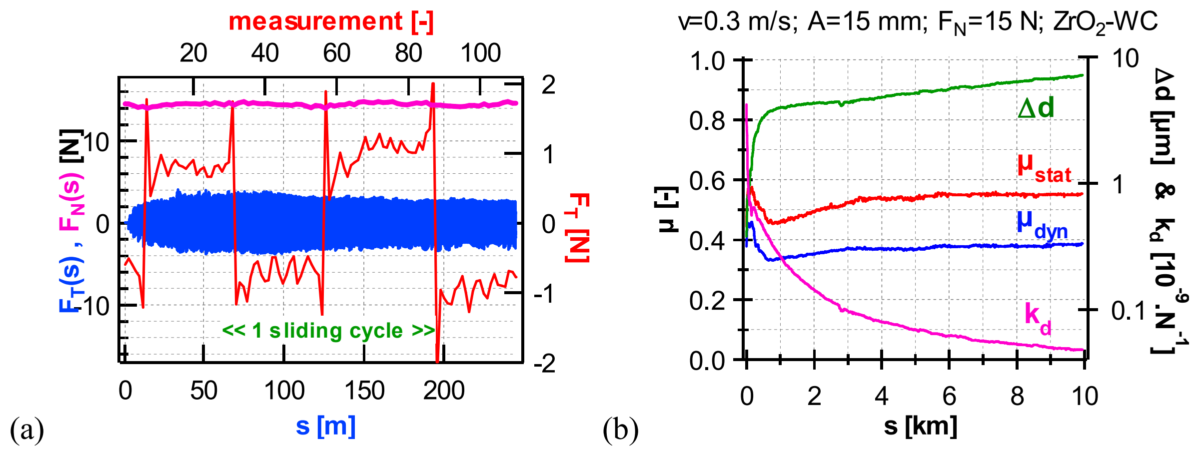


Fig. 1: real-time normal force and friction force (a) and wear depth, wear rate, static and dynamic friction coefficient (b) for wire-EDM'ed ZrO_2-WC flat/ WC-Co pin pairs sliding at 0.3 m/s, under a 15 N contact load

Wear surface analysis. Wear experiments were carried out under the condition of a constant total sliding distance of 10 km. The 3D wear track surface topography for a WC-Co cemented carbide after sliding against WC-Co cemented carbide pin under a 50 N contact load is presented in Fig. 2. The wear depth distribution in the centre of the track appears quite uniform, with values around 20 μm. The outer edges of the track, however, exhibit a more inhomogeneous wear depth pattern, with higher damage. Similar observations were made for the ZrO_2-WC ceramic composites.

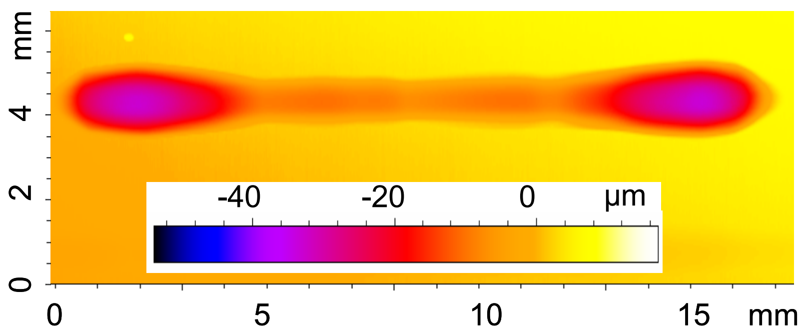
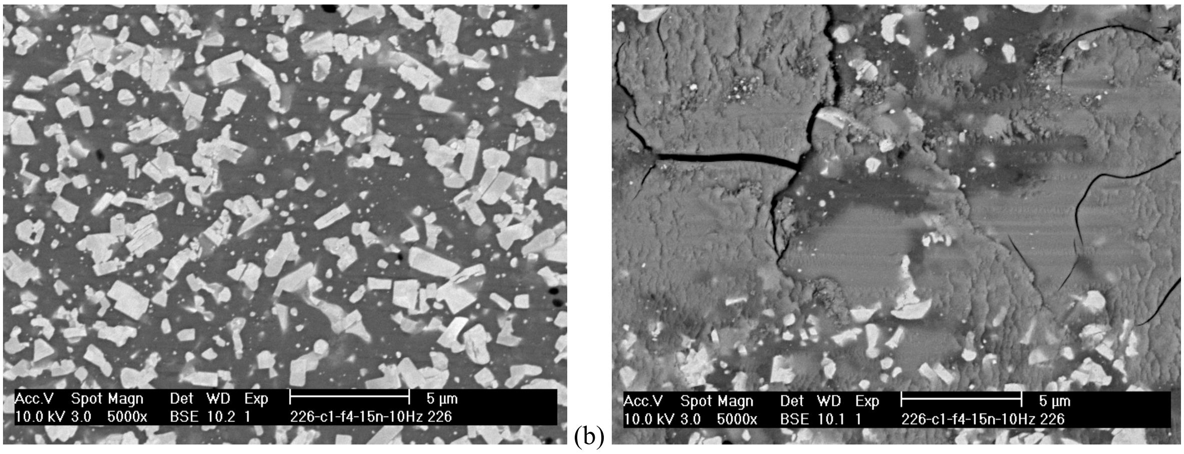


Fig. 2. Wear scar topography for WC12Co(V) cemented carbide, slid against WC6Co(Cr/V) pin (v=0.3 m/s, s=10 km, F_N=50 N)

Optical investigation of wear tracks of both ZrO_2-WC and WC-Co surfaces reveals a polishing impact as a result of the sliding contact with the WC-Co pin. This is confirmed by normal roughness profiles, yielding much lower R_a- and R_t-values after wear testing, compared to the initial surface roughness.

SEM topographies at the centre and at the outer extensions of the wear track on a wire-EDM'ed ZrO_2-WC surface, after sliding 10 km against WC-Co pins, are compared in Fig. 3. The microstructure in the central part of the track mainly corresponds to the base material, i.e. the original microstructure is still visible and no microcracks are detected. Polishing and abrasion appear to be the primary wear mechanisms. At the edges of the wear track however, a thin wear debris layer with very fine ZrO_2 and WC can be observed. Furthermore, the occurrence of microcracks is obvious. This phenomenon was also found at the central area of ZrO_2-WC wear tracks, however only for higher contact loads [5]. The microcracks in the debris layer are induced by tangential stresses due to the reciprocal sliding movement of the cemented carbide pin on the ZrO_2-WC surface.

The differences in wear damage and wear mechanisms within the wear surface area of ZrO_2-WC composites and WC-Co cemented carbides can be explained in terms of friction force peaks and accumulation of tensile surface stresses at the outer ends during oscillating sliding contact with the WC-Co pin, shifting load-dependent wear transition behavior towards lower contact loads.



(a) (b)

Fig. 3: SEM surface views in the central part (a) and at the outer extension (b) of a wear track on a wire-EDM'ed ZrO_2-WC composite after sliding 10 km at 0.3 m/s under a 15 N contact load

Conclusions

Dry reciprocative friction experiments on ZrO_2-WC composites and WC-Co cemented carbides sliding against WC-Co pins, revealed significant differences in wear behavior between the outer extensions and the central part of the wear tracks. The central ZrO_2-WC wear track appears to be less prone to the formation of a debris layer and microcracking compared to the outer ends of the wear track. The wear damage in the wear tracks of both WC-Co cemented carbides and ZrO_2-WC composites is quite higher compared to the central part. These differences can be explained in terms of friction force peaks as the sliding direction reverses and accumulation of tensile surface stresses at the outer ends during oscillating contact with the WC-Co pin, shifting load-dependent wear transition behavior towards lower contact loads.

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