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Tribochemical wear of cutting-tool ceramics in sliding contact against a nickel-base alloy

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ABSTRACT

The wear behaviour of a SiAlON and a SiC whisker reinforced Al_2O_3 composite in dry sliding contact against Inconel 718 was investigated. For tribological characterization, the worn contact surfaces were analysed using tribometer data and calculation of wear volume in addition to SEM/EDX analysis. The surface contact temperatures were estimated by finite element simulations.

The tribological behaviour is distinct for each ceramic. The wear in SiAlON undergoes an exponential decay with increasing frictional power due to the formation of lubricous tribolayers that separate both contacting surfaces; once the frictional power is high enough tribochemical wear dominates and delamination of the tribolayers takes place. The wear of Al_2O_3–SiC is lower than that of SiAlON especially at high frictional power, which can be mainly attributed to the chemical stability of the alumina matrix and the formation of stable lubricous tribolayers.

FEM simulations indicated high contact temperatures with steep gradients in the depth.

1. Introduction

Tool life is a crucial factor of cost effective machining of complex components made of high-strength materials such as nickel-base alloys. Thus, tool wear must be reduced as much as possible. Typical parameters that can be optimised to reduce the cutting tool wear are, for instance, the cutting speeds, coolant supply, and feed rates. Furthermore, the right choice of cutting tool materials is decisive. Ceramics have shown a good balanced ratio of performance and price and the development in ceramics has enabled using them in machining various types of steel, cast iron, and superalloys at high speeds and high feed rates [1,2]. During the last three decades their wear resistance was continuously improved by improving their mechanical and thermal properties through modifications of composition, processing and microstructure. Yet, most progress has been achieved on trial-and-error basis and through experience. This study investigates the wear behaviour of selected cutting tool ceramics in contact with Inconel 718 and, thus, aims at understanding the dominant wear mechanisms and the factors affecting them.

The process of cutting metals evokes two types of loads: direct mechanical load at the cutting edge, which induces tool fracture if the load exceeds the material strength and frictional load at the rake face and the flank when a chip is produced ahead of the tool by continuous shearing along a shear plane. If a cutting tool is used correctly, edge fracture should not occur, thus continuous wear dominates and it is divided in two categories: (i) mechanically activated wear, such as abrasion, and (ii) tribochemical wear [3] at high contact temperatures. Tribochemical wear is based on chemical interaction between the rake face and hot chip, often described as diffusion of tool material into the chip, resulting in "crater wear" [4]. These tribochemical interactions are activated at high contact temperatures, depending on the energy dissipation and hence on the cutting speeds, as well as on the chemical affinity of the cutting tool material to the workpiece material [5,6]. The reaction products are typically of lower mechanical strength than their educts, and thus more susceptible to wear [3,7].

At lower cutting speeds, the surface temperature is not necessarily high enough to promote significant tribochemical reactions. The breakup of the adhered workpiece material (built-up edges) and the consequent loss of ceramic-tool particles from edge, flank, and rake face of the tool is bound to take place, taking the form of adhesive wear or attrition, which fall into the category of mechanically induced wear as explained in Ref. [3]. The wear scars produced by

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Table 1
Room-temperature mechanical properties of the investigated materials as provided by the supplier.

Material	Four-point-bending strength [MPa]	Weibull parameter *m*	Hardness HV10	K_{IC} [MPa/m$^{1/2}$] (Anstis)	Elastic modulus [GPa]
SiAlON (α-β -SiAlON)	821.1	3.0	1641	4.8	334
Al_2O_3–SiC	823.3	12.3	2080	4.9	400

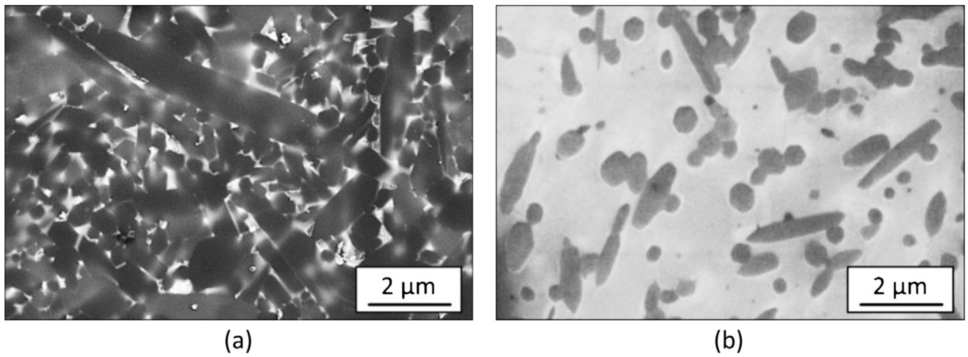

Fig. 1. SEM-micrographs showing the microstructure of the ceramic materials (a) SiAlON, (b) Al_2O_3–SiC.

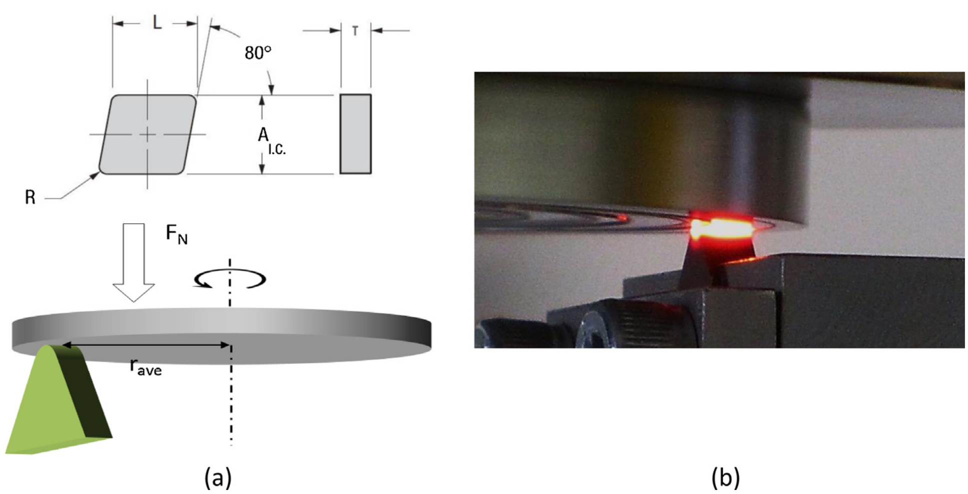

Fig. 2. (a) Schematic drawing of the ceramic samples and the sliding contact setup, L = 12.9 mm; $A_{I.C.}$ = 12.7 mm; T = 3.0 mm und R = 0.8 mm (b) image showing the sliding-contact experiment.

attrition are rough as opposed to the usually smooth wear surfaces produced by tribochemical wear [8–10].

Early studies showed that silicon nitride based ceramics and SiAlONs show chemical instability in sliding contact with ferrous alloys [11,12], in contact with molten steel [13] and nickel base alloys [13], as well as in machining steel [4]. SiAlONs with higher content of alumina show improved corrosion resistance in machining steel and nickel-based alloys [13]. Higher crater wear is often observed in silicon nitride tools when used in cutting ferrous alloys. Alumina-based tools, on the other hand, tend to show better chemical stability with such alloys.

Alumina-based ceramics were found to suffer adhesive wear when cutting grey cast iron at low cutting speeds [9]. Evidence of attrition was found on the cutting edge and was more severe in Al_2O_3 than in Al_2O_3/TiC cutting-tools. Therefore, alumina-SiC composite tool materials find application in machining nickel based superalloys at high cutting speeds and feed rates [14]. A review of studies treating the tribochemical wear in silicon nitride and alumina cutting tools is found in Ref. [15].

Our study focuses on the tribochemical reactions that occur in sliding wear experiments in a wide range of sliding speeds. Furthermore, the dependence of wear rate (evaluated through calculating a wear coefficient) and coefficient of friction (COF) on sliding speed and chemical interaction of contact partners is investigated. A detailed analysis of the tribochemical reaction products that result from low and high sliding velocities is provided, which allows us to correlate the observed mechanisms and the resulting wear rates/COFs.

The role of temperature and tribochemical reactions in tool wear is emphasised in this work. Thus, the analysis of the reaction products by energy dispersive X-ray spectroscopy (EDX) as well as the numerical simulation of the contact temperature is taken into account.

2. Experimental

Two different ceramics were investigated in this work: (i) a SiAlON ceramic based on α-Si_3N_4 and β-Si_3N_4 with additional aluminium and oxygen in their crystalline phase (hereafter denoted by SiAlON) and (ii) a SiC whisker reinforced Al_2O_3 composite ceramic (70/30 Al_2O_3–SiC). Both, SiAlON and the Al_2O_3–SiC composite are commercially available cutting materials (Kennametal Inc.). SiAlON has a glassy phase which amounts to approximately 7 wt.% containing 2.7 at.% ytterbium Yb (instead of the more com-