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A wear model for silicon nitride in dry sliding contact against a nickel-base alloy

Iyas Khader [a,b,*], Alexander Renz [b,c], Andreas Kailer [b]

[a] Department of Industrial Engineering, German-Jordanian University, P.O. Box 35247, 11180 Amman, Jordan
[b] Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstraße 11, 79108 Freiburg, Germany
[c] Luleå University of Technology, 971 87 Luleå, Sweden

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ABSTRACT

The properties of silicon nitride ceramics allow their broad application in extreme tribological conditions. High-temperature sliding contact of Si_3N_4-base materials against metals will be found more often in future applications, in which the ceramic's wear resistance becomes clearly necessary.

In this study, the dry sliding behavior of silicon nitride against Inconel 718 is investigated. Wear experiments were carried out at sliding velocities ranging from 1 to 20 m/s. A finite element wear simulation was constructed by relying on experimentally measured wear rates and COF. The simulations enabled quantifying localized temperature and contact stress fields as a function of geometrical changes due to progressive wear.

The experiments showed a transition in wear mechanisms depending on the sliding velocity and frictional power. Cross-sectional analysis of the ceramic samples provided information on the tribochemical processes and the dominant wear mechanisms. Combining analytical and numerical results enabled proposing a schematic wear model. The agreement of this model with common theories of wear is discussed.

1. Introduction

The application of engineering ceramics in machining high strength alloys such as nickel-base superalloys is widely used. While the effect of mechanical load on the sharp edges of the tool may be mitigated through proper tool design and usage, tribological load by sliding remains as an origin of wear and can be considered as the crucial factor in limiting the lifetime of the tool. In an early review of the application of engineering ceramic tools in machining Stachowiak and Stachowiak [1] explained tool wear to originate from mechanically activated mechanisms by abrasion and adhesion, and tribochemical wear driven by chemical interaction between the tool, workpiece, and surrounding media at high contact surface temperatures. These tribochemical interactions are activated at high contact surface temperatures, depending on the energy dissipation and hence on the sliding speeds, as well as on the chemical affinity of the materials to each other [2]. A recent review on tool wear mechanisms in general can be found in Olortegui-Yume and Kwon [3] and specifically in machining nickel-base alloys in Zhu et al. [4]. A review on the influence of tool materials on the machinability of nickel-base alloys is given by Pervaiz et al. [5]. Whereas, the synergetic and/or competing mechanical and chemical wear mechanisms involved in ceramic cutting tools were addressed by [6,7].

The mechanical and physical properties of silicon nitride indicate good resistance to thermal shock. Nevertheless, previous research work has indicated chemical instability of silicon nitride ceramics in some systems such as in contact with molten copper in the presence of oxygen [8] and molten steel [9], and in sliding contact against ferrous alloys [10]. It also showed susceptibility to tribochemical wear in machining steel [11], especially chromium containing steel alloys [12], whereas, in machining Inconel 718 nano-grained silicon nitride showed high wear rates due to nose wear according to [13]. Diffusion tests in vacuum were conducted by Addhoum and Broussaud [14] using SiAlON (an Si_3N_4-base ceramic with additional content of aluminum and oxygen) against Inconel 718 and Waspaloy static interaction couples. The authors described the formation of a liquid phase corrosion layer at temperatures exceeding 1100 °C with precipitation of TiN at its interface in the metal side and the presence of nickel, iron, and chromium silicides in the corrosion layer. On the other hand, Si_3N_4 was mentioned in [15] to have a rather high resistance to interaction with nickel even in its molten state. Renz [16] conducted diffusion

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[*] Corresponding author at: Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstraße 11, 79108 Freiburg, Germany.
E-mail address: iyas.khader@gju.edu.jo (I. Khader).

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tests in air on SiAlON against Inconel 718 and Nimonic 90 static interaction couples and reported the formation of chromium and titanium oxides at high temperatures. Bhattacharyya et al. [17] tested commercial SiAlON inserts by machining Incoloy 901 and found wear by attrition and diffusion to control the tool life up to certain cutting speed.

In order to obtain accurate information on the tribological behavior of any material combination in contact, tribological experiments under controlled environments have to be designed and conducted. Supporting the experiments, numerical modeling offers the possibility of estimating quantitative data such as contact surface temperatures and localized stress fields, both of which are almost impossible to measure in situ. In a recent study by Renz et al. [18] the dry sliding behavior of two cutting tool materials, namely, a SiAlON and a silicon carbide (SiC) whisker reinforced alumina (Al_2O_3) composite, against Inconel 718 was studied in detail. The authors pinpointed a combination of mechanically activated and tribochemical wear mechanisms involved in the wear of the ceramic samples tested in dry sliding contact experiments.

The current study focuses on the wear behavior of a gas-pressure sintered silicon nitride in dry sliding against Inconel 718. Gas-pressure sintered silicon nitride is lately gaining much more importance in engineering applications, especially in cutting and forming tools and dies, due to its less expensive yet more versatile manufacturing technique as opposed to its hot-pressed counterpart. The high cost incurred by the fabrication of hot-pressed silicon nitride in addition to the intrinsic limitations imposed by the process in producing parts with complex geometries both have kept its application limited. Moreover, studying a simple silicon nitride ceramic provides fundamental knowledge needed in developing tailored Si_3N_4-base material systems for various applications. This work combines experimental work and finite element simulations, by which the ceramic-metal contact was modeled to obtain information on localized temperature and contact pressure fields as functions of progressive wear. Macroscopic wear was implemented within the finite element framework in the commercial software ABAQUS by modeling smooth surfaces in contact and through a bespoke subroutine to account for wear. The effect of wear on the contact conditions is correlated with the experimental outcomes, thus, enables a better understanding of the wear mechanisms, and friction behavior observed in the experiments.

2. Experimental

A commercially available Si_3N_4-base ceramic (SN-GP black, FCT Ingenieurkeramik GmbH, Germany) was tested in unlubricated sliding contact experiments against Inconel 718 (EN material no. 2.4668) disks (initial average surface roughness $R_a = 1.06 \pm 0.13$ μm), Fig. 1a. The ceramic samples were provided by the manufacturer in a CNGN-type insert geometry, Fig. 1b. The tests were run in the configuration shown in Fig. 1c.

SN GP black is a commercial Si_3N_4-Y_2O_3-Al_2O_3 material system. Its microstructure consists of β-Si_3N_4 grains and ca. 10 wt% secondary glassy phase of the sintering additives and less than 1 wt% Ti. The β-Si_3N_4 grains have a length-to-diameter ratio of $L/D = 7.4$. The microstructure of SN-GP black is shown in a backscattered mode scanning electron microscope (SEM) image in Fig. 2. The temperature dependent properties of SN-GP black were obtained from a series of experiments aimed at characterizing the material in [19]. The chemical composition of Inconel 718 is listed in Table 1.

The side faces of the ceramic samples were ground. The samples were then fixed into a tribometer using a special fixture designed to withstand the tangential forces emerging in dry sliding contact. A 3 mm line contact is created between the edge of the insert-like ceramic sample (R = 0.8 mm, see schematics in Fig. 1b) and the flat surface of the Inconel 718 disk. From the Hertzian contact theory the resulting semi contact width at an applied

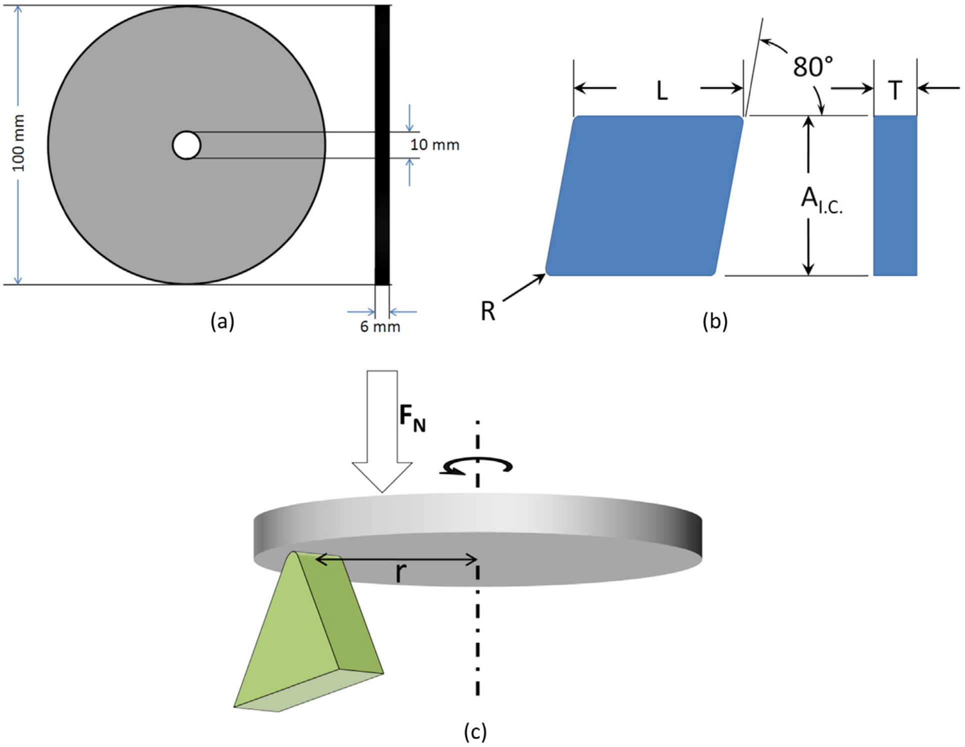

Fig. 1. Schematic drawings of (a) the Inconel 718 disk, (b) the SN-GP black ceramic samples (L = 12.9 mm; $A_{I.C.}$ = 12.7 mm; T = 3.0 mm, and R = 0.8 mm), and (c) the pin-on-disk test configuration.