euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

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Chemical aspects of single crystal diamond tool wear

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Abstract

Differential interferometric measurements of plunge cut replications of a single crystal diamond tool edge used in precision micro-machining provide high resolution information on the edge recession due to wear. Transitions between wear mechanisms have been observed for modest changes in process conditions. Activation energies for machining of a nominally 65% Ni-Cu alloy have been calculated from both edge recession and crater wear, using modelled temperatures for a range of cutting conditions.

Keywords: diamond, chemical wear, copper-nickel alloys

1. Introduction

Over the last 30 years or so, machines capable of producing optical quality surface finishes on complex shaped components have evolved from exotic systems serving mostly defence industry needs to essential systems enabling a broad range of commercial as well as military products. Brinksmeier [1] recently suggested that the further evolution of machine performance is likely to be slow, adding "…there is an urgent need for a better understanding of the wear mechanism of diamond, i.e. the development of … models that take into account chemical aspects of wear."

Despite decades of study, the mechanisms of single crystal diamond tool wear when precision micromachining of alloys is not well understood. Chemical mechanisms have long been proposed, but much of the literature reports on wear rates well beyond the limits of utility for precision machining of optics. Elsewhere, materials are described having the property of being "diamond turnable" or not, based on a limited number of expensive tests.

For elemental metals, a correlation between electronic structure (ie unpaired d-shell electrons) and chemical wear has been observed by Paul et al [2]. Generalizing the ideas proposed there to alloys of transition metals using linear combinations of atomic orbitals has proved intractable. However, a simple index accounting for d-, s-, and p-shell electrons provides a tool for predicting onset of chemical wear in single phased alloys.

Development of predictive, quantitative models of the chemical aspects of tool wear requires both understanding of the mechanisms at work and high resolution, non-intrusive means for measuring the evolution of tool wear at wear rates relevant to precision machining over reasonable areas of optical surface.

Single crystal diamond tool wear evolves over cutting distance or time, and the later stages of the wear are influenced by that early evolution. It is possible to cut over a short distance and then remove the tool for off-line inspection, for example using an atomic force microscope [1] or scanning electron microscope [3]. However, the processes of preparing the sample for measurement and the difficulty of replacing the tool make questionable any claim of following in detail the evolution of the wear of a specific tool. In Section 2 of this paper we describe a differential interferometric plunge cut replication technique that provides high resolution, low uncertainty measurement of tool edge recession and show examples of results obtained. Section 3 discusses aspects of chemical wear needing basic understanding of the mechanisms.

2. Experimental methods and results

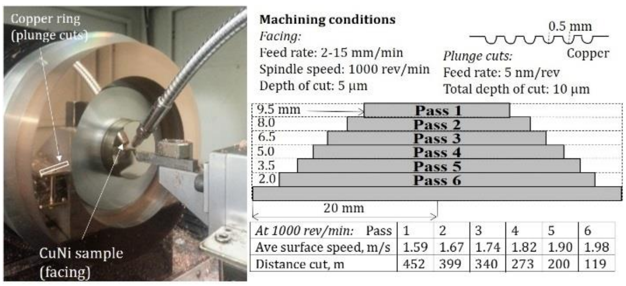

Figure 1. Experimental procedure.

Copper-nickel alloys are convenient because they are single phased at all compositions and commercially available at compositions straddling the predicted onset of chemical wear. Figure 1 shows a typical experimental procedure. A copper nickel alloy sample is centred on the spindle, surrounded by a ring plated with fine grained, low ductility, clean copper. A series of facing passes, interspersed by plunge cuts into the copper ring, generates a terraced part, allowing measurement of surface finish as a function of wear and a replication of the edge of the tool after each pass.

Differential interferometric measurement of plunge cut replications of the tool edge is a development of methods pioneered in the 1980s by Hurt et al [4] and Syn et al [5]. It allows high resolution tracking of the evolution of the tool edge recession. The initial measurement of the tool edge shape is subtracted from the subsequent measurements, after careful alignment of the data sets. To first order, the bias associated with the interferometric measurement in the presence of varying slope is common mode and drops out of the measurement. Fig 2 shows example results of the measured tool edge recession when machining CuNi alloys of varying composition at the conditions given in Figure 1 and with a feed rate of two mm/min.

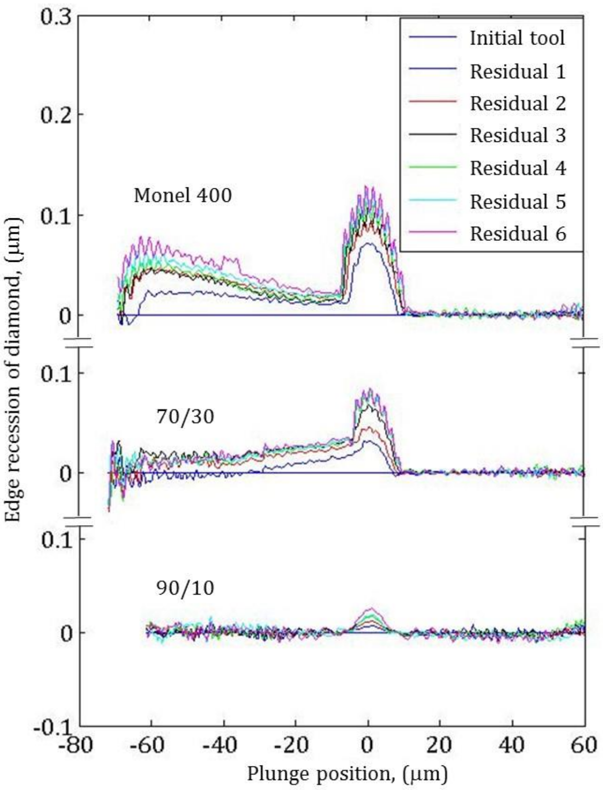

Fig 2. Measured edge recession for different CuNi alloys. The nose of the unworn tool defines zero plunge position, with the leading edge at approximately -70 μm.

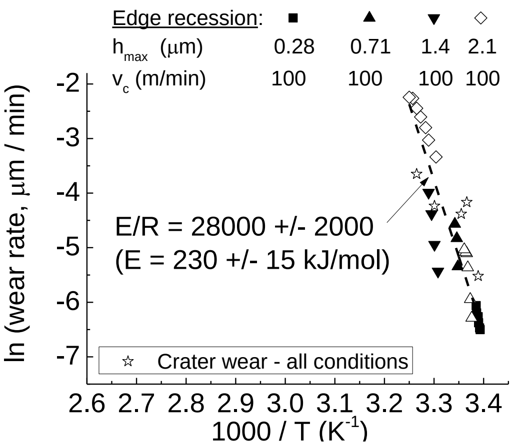

Figure 3. Estimated activation energy for cutting Monel 400.

We observe variations in tool wear rates that correlate with the d-index model. We note transitions between dominant wear mechanisms as a function of process parameters. For example, for the conditions of Fig 2 when cutting Monel 400, the largest wear is nose wear, with some edge recession. Increasing the feed per revolution from two to five μm the nose wear becomes insignificant, but the leading edge wear increases by approximately 20%.The lower feed rate measurements show the formation of Pekelharing-like grooves at both the nose and near the leading edge. At higher feed rates, these grooves are not apparent.

Observed rake face crater wear can also be quantified using interference microscopy. Using modelled temperatures from finite element analysis [6] and wear rates from edge recession and from crater wear, activation energies can be calculated.

Evolution of surface characteristics during tool life suggests complex interactions between tool condition, machine tool dynamics, and optical surface function. Preliminary results (initial estimates in [6] updated and extended in Fig 3) for a population of cutting conditions show consistency across the data sets for Monel 400.

3. Toward prediction of chemical wear

Prediction of diamond wear using models that account for chemical wear [1] requires an understanding of the mechanisms and the transitions between mechanisms. We have demonstrated high resolution measurements of tool edge recession. The Arrhenius equation provides portability of results, but requires new understanding of how the pre-exponential factor and the activation energy change, for example, with alloy composition. Temperature measurement at the scale and conditions of experiments described here is difficult. Modelling provides numbers but validation of those models, and especially the effect of the boundary conditions, is lacking in this domain. Although the effect of crystallographic orientation on abrasive wear of diamond is well known, there is no literature on low temperature anisotropy in chemical etching of diamond. Such improved understanding and data for activation energies will allow quantitative predictions of chemical wear rates.

Acknowledgements

This research has been support in part by NSF Grant CMMI 1162209

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