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Analytical stochastic modeling and experimental investigation on abrasive wear when turning difficult to cut materials

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ABSTRACT

Tool wear and tool failure are critical problems in the industrial manufacturing field since they affect the quality of the machined workpiece (unexpected surface finish or dimensional tolerance) and raise the production cost. Improving our knowledge of wear mechanisms and capabilities of wear prediction are therefore of great importance in machining. The three main wear modes usually identified at the tool/chip and the tool/workpiece interfaces are abrasion, adhesion and diffusion. Besides the fact that understanding mechanisms that govern these wear mechanisms are still incomplete, the experimental analysis is very difficult because friction interface features (such as temperature, pressure, particles embedded in the contact ...) are not easily measurable. The objective of this research work is to develop a wear model in which abrasive particles are assumed embedded at the interface between tool and chip. These particles are considered having a conical shape and are characterized by two main parameters in the present approach: the corresponding size and apex angle. Wear particles may be seen as non-metallic inclusions or wear debris generated during the machining process. A probability density function has been adopted to describe the fluctuation of the size and the apex angle of particles in the contact area. The influence of the adopted statistical distribution parameters is also presented. The analytical model gives, as a final result, the volume of the removed material per unit of time. Finally, several wear tests were carried out considering an uncoated carbide tool WC-Co and Ti6Al4V titanium alloy as machined material to validate the proposed model.

1. Introduction

The surface quality of the machined part strongly depends on tool wear. Generally, the main types of wear usually identified are abrasion, adhesion and diffusion modes. These three modes of wear operate in an interactive way and depend on several parameters, which make the understanding of mechanisms governing them still incomplete. In addition, the study of these mechanisms is difficult because friction interfaces (tool/chip and tool/workpiece interfaces area) are not easily measurable during machining operations.

To provide the beginning of an explanation to the mechanism operating during abrasive wear, two fundamental questions raised:

– What is causing this abrasion and how a carbide tool with a very high hardness can be worn by abrasion?
– Which parameters can have a strong influence on the initiation and the spread of abrasive wear?

To answer these questions, some authors have suggested conclusions mainly based on experimental observations Suh [1] supposed that asperities of the rough antagonistic surface are responsible for the process of material removal and hence abrasive wear. Generally, abrasion can be caused by two types of abrasive particles. The first type of particles can be considered as free wear debris at the tool/workpiece contact. In their work, Akasawa et al. [2] showed that this type of particles can be explained by the diffusion wear mode that may lead to a weakening of the cutting tool from which some particles are detached and form wear debris. For instance, considering a WC–Co tool and a carbon steel workpiece [2], carbon atoms of the manufactured steel migrate to the cutting tool and the cobalt (binding part of the substrate WC–Co) migrates to the workpiece. As a consequence, a weakening of the WC grains takes place, thus facilitating the propagation of cracks and the formation of wear fragments.

The second type of abrasive particles is inclusions initially present in the machined material and having a hardness higher or at least equal to the hardness of the tungsten carbide cutting tool. This shows that abrasion depends on the machined material. Marinov [3] reminded that the work material may contain

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exogenous and endogenous non metallic inclusions. Exogenous as soft endogenous inclusions (e.g. sulfides and phosphides) do not play an important role in abrasive wear. On the contrary, hard endogenous inclusions such as silicate and carbides may have a marked effect on the wear evolution. They can easily cut and remove a part of material from the tool surface. Marinov [3] conducted experiments to analyze the influence of cutting conditions and abrasive particle characteristics on the abrasive wear of a K20 tungsten carbide cutting tool. The author considered several specimens prepared by powder metallurgy from a high manganese steel and identified by distinct types of non-metallic inclusions and different levels of concentration. It was shown that the higher the ratio between the non-metallic inclusions hardness and the cutting tool's hardness, the more pronounced the abrasive wear is. Marinov [3] also revealed that the abrasive wear represents in general 25% of the total rate of wear which is in contradiction with a previous study of Ho et al. [4] who found an amount of only 10%. In the case of machining Inconel 718 with a tungsten carbide tool, Focke et al. [5] also confirmed that non-metallic inclusions are the cause of abrasive wear. Jia and fisher [6] focused on the influence of chemical composition of tungsten carbide tools and the nature of abrasive particles. Conducting scratching tests and using several abrasives with different hardness, they confirmed that the abrasion resistance (inverse of the removed volume) of the WC–Co tools depends on their hardness as well as the hardness of abrasive particles. Saito et al. [7] considering different cemented carbide inserts by varying Co content and WC grain size have shown that these two parameters have a significant influence on the abrasive tool wear.

Cutting conditions also have a strong influence on abrasive wear [8]. The effect of temperature, for example, has been studied by Usui et al. [9] who developed an empirical model to analyze abrasive and adhesive wear. Kramer et al. [10] considered that mechanisms controlling the total wear rate (including abrasive wear) depend on cutting conditions. The authors confirmed that mechanical wear processes, such as abrasion, are dominant at low cutting temperature and for cutting speed. Thus, abrasive wear depends, indirectly, on the chip sliding velocity and the tool/chip contact length.

Abrasion manufacturing, in general, and the abrasive wear of the cutting tool, in particular, can be studied by means of different techniques. In the case of a conventional machining, cutting tool wear is a combination of a complex several mechanisms. Separating the specific action of one of these wear modes is very difficult to manage. Moreover conventional tribological tests cannot reproduce severe machining conditions (high contact pressure, high temperature, high strain rate…). Nevertheless, some authors (e.g. Kagnaya et al. [11]) used tribological tests like scratch tests, pin-on-disk tests, etc. to predict abrasion tool wear in machining. By this way (knowing the restricted area of such an analysis), one can capture influences of the sliding distance, the applied pressure or the nature of the used lubricant (in the case of an assisted process) as well as material properties and characteristics (hardness, impurities concentration, thermomechanical behavior,) on the abrasive wear. As a consequence, cutting tool behavior may be analyzed and tool life may be predicted from tribological bench tests.

One of the first empirical equations based on conventional tribological tests, governing wear process was given by Rabinowicz [12] and through the well known Archard equation [13]. In these models, the removed volume of material increases linearly with the normal applied load and the sliding distance and decreases as the workpiece's hardness is increased. Through Abrasive wear tests, Khruschov et al. [14] showed that the abrasion resistance varies linearly with the hardness. Tabor and Powell [15] performed scratch tests with spherical indenters and proposed a relationship where the abrasive wear is proportional to the normal load and to the sliding distance; it was also found inversely proportional to the hardness and the Young's modulus of the counter surface.

Thanks to these studies, answers can be proposed to the two above questions. Abrasion wear is caused by abrasive particles present at the tool-chip and tool-workpiece interfaces. Particles can be either non-metallic hard inclusions present (initially) in the machined material or debris generated by other wear modes (adhesion or diffusion modes). Parameters such as hardness, contact pressure, sliding velocity, contact length and temperature have a great influence on the abrasion wear process. However, the temperature will not be considered in the development of the proposed study which takes into account only the mechanical abrasive wear mode.

In the present paper, a new analytical abrasive wear model is proposed and applied to analyze physical wear phenomena occurring during the machining of titanium alloy Ti6Al4V by WC–Co carbide tools. The paper is organized as follow:

- First of all, a Representative Volume Element (RVE) describing the contact area is presented and general equations are formulated. Then, it addressed the description of the proposed model based on an analytical approach including a statistical description of particles embedded in the contact area. Special attention has been paid on the particles morphology and contact pressure.
- A sensitivity study is proposed in order to highlight the effect of model parameters on the cumulative overall abrasive wear.
- Finally, experimental cutting tests with WC–Co inserts machining refractory titanium alloys are presented and discussed. The tested materials are characterized by a fine sized microstructure (grain size in the order of 1 μm) with a high hardness level, in order to exhibit abrasion phenomenon

To validate the modeling, machining tests were performed without lubrication (dry cutting) under different cutting conditions. Uncoated WC–Co tools with different geometries were chosen to study the wear behavior of the insert. Cutting forces, pressure, friction and tool damage were deeply analyzed. A part of the experimental study focuses on SEM and EDS post-mortem analyses of the wear patterns exhibited by the inserts during machining tests. Results were then compared qualitatively to the theoretical modeling developed in this work. Experiments revealed that during machining the α-β alloy, different tool wear modes can be exhibited depending on the considered cutting condition. It was clearly shown that diffusion was not fully activated even for high levels of cutting temperatures, while abrasion and excessive chipping were the most important failure mechanisms for WC–Co cutting tools. The paper discusses all factors leading to such occurrences and studies the influence of cutting conditions and some microstructure parameters on the tool effectiveness and failure modes.

2. Problem description

2.1. Representative volume element RVE

During machining, the chip flows on the tool's face with a sliding velocity denoted by V_c and exercising above an apparent pressure denoted by P_0. By adopting a homogenization procedure, it was assigned to each material point of this contact chip–tool interface a representative volume element RVE shown in Fig. 1. Within this RVE we denote by *Nbr* the number of potentially abrasive particles per unit area present at the tool/workpiece