Modeling and Measurement of Wear of Coated and Uncoated High Speed Steel End Mills

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Abstract. A research program was conducted to study tool wear on uncoated and coated (with TiN) high speed steel (HSS) for fluted end mill cutters. These cutters were used to machine AISI 4340 steel at axial and radial engagements of 12.7 mm (0.5 in.). All the machining was carried out using production conditions with the process periodically interrupted to carefully measure the wear condition of the cutting tool. Cutting conditions were carefully chosen so that a linear wear model for the useful life of the cutting tool could be statistically tested. One phase of testing used uncoated tools from 30 different suppliers and the nonstationary linear wear model provided a stochastic representation to determine tool quality using reliability and economic measures. Another phase used the coated tools and a stationary linear wear model to relate force, power, specific cutting energy, and mechanistic model parameters to service life measures. The cutters from each of these phases were carefully examined using optical and scanning electron microscopes so that the dominant wear mechanisms could be identified.

INTRODUCTION

Existing approaches for automation of machining systems rely heavily on the machine operator’s sense to monitor and adjust machining conditions. In a truly automated machining system, the control hardware and software must replace the operator’s sensing capabilities. Of particular importance is the ability to monitor and control tool loads and utilize the load data in optimization of the machining process. Optimization must include tool wear and tool failure effects on both product quality and process economics.

One important factor in the economics of machining operations is the life of the tool cutting edge. Methods do not exist that link cutting tool life with our basic knowledge of wear mechanisms such as abrasion, delamination, and chemical dissolution. The early development of cutting tool materials was accomplished in absence of the complete understanding of wear mechanisms through ingenuity, empiricism, and intuition.

When comparing HSS steel tools with coated HSS tools, other differences in wear occur. The coating provides better wear resistance until the substrate begins to become exposed to the cutting action. When this occurs, wear is accelerated and total failure of the tool soon follows. It is critically important to establish this point in the tool’s life and use a tool change strategy that avoids this catastrophic failure state. An uncoated tool also goes from a gradual wear state to an accelerated wearout period; however, the accelerated wear is more related to an increase in the size of the wear surface that results in greater friction, temperature increases, and, finally, thermal softening of the cutting tool material.

The tool wear mechanisms at the chip-tool–work interface are plastic deformation by shear at high temperature, plastic deformation under compressive stress, diffusion across the tool work interface at high temperature, attrition wear by built-up edge formation, and abrasion wear [1–3]. Abrasion is intuitively considered as a major cause of wear and the literature on the subject often describes tool wear, in general, as abrasive [4], but this is an area that requires further investigation for normal conditions of cutting.

The principal effect of temperature appears to be that it can induce phase changes in some tool materials [5,6]. In addition, the high temperatures temper...
the subsurface layers. The volumetric changes associated with phase transformations can produce micro- and macrocracks and lead to the development of high residual stresses. The high transient temperatures are usually confined to a relatively thin surface layer of material; thus, steep temperature gradients exist. Such temperature gradients can induce high thermal stresses with the possible generation of additional residual stresses and cracks.

The mechanisms of wear are not mutually exclusive. All may play a part in the tool wear process, or for particular conditions, one mechanism may predominate; however, all the mechanisms are dependent on the temperature and state of stress at the tool–workpiece interface. Currently, this temperature and stress state cannot be directly measured; thus, it is difficult to formulate realistic models of the tool wear process. Brief but excellent discussions of the wear of cutting tools have been presented by Trent [4-6] and Opitz and König [7].

Tool wear studies are generally conducted using a number of tools tested under the same conditions. For each tool tested, measurements are made of wear surfaces at periodic intervals during the tool test. The type of measurements needed depend upon the type of tool, work materials, and the wear mechanisms that are anticipated. The service life can be measured in terms of number of parts, time of use, length of cut, and exposure distance. The first three have been commonly used; however, the last has been largely ignored. For end mills, exposure distance $L_e$ is defined as follows:

$$L_e = \frac{\pi R}{180} \left[ \cos^{-1} \left( 1 - \frac{d_r}{R} \right) \right] \frac{L_w N}{f_m}$$

where

$R$ = cutter radius
$N$ = spindle speed
$L_w$ = length of cut
$f_m$ = feed rate
$d_r$ = radial engagement

Exposure distance measures the total distance that a cutting edge is in contact with the work material. Studies that compare this measure with the more commonly used length of cut are nonexistent. This is largely due to the need to know the engagement of the tool with the workpiece at all times during the cutting process. As our machining centers become more autonomous and dependent upon sensor information for intelligent control, engagement measurement will be possible, and exposure distance can be obtained and used for strategic tool changing policies.

Another factor of concern in strategic tool change policies is the inherent variability of tool life. Many studies have been conducted and there is strong evidence that the useful life span of cutting tools can be modeled as a nonstationary linear wear process [8]. This approach ignores the initial wear-in period, which is generally a nonlinear (decreasing wear rate) transition wear period, captures the useful life of the tool as a linear (constant wear rate) wear function, and constrains this function to a wear level below the critical value marking the beginning of accelerated wear (increasing wear rate). In production situations, it is important to characterize the population of cutting tools used in a manner that quantifies tool life variability during this useful tool life period. Often, different vendors supply the tools used and the variation in tool wear among these tools may become important to the economics of the process.

One of the most difficult aspects of tool wear studies is the establishment of the linkage between the process state variables that cause wear and the control state variables that can be changed on the machine tool. This is so difficult that we do not yet have reliable relationships [9]. One necessary step toward obtaining such linkages is to conduct studies where the control state variables are systematically varied for wear tests and the wear zones carefully examined. Such examinations can establish wear mechanisms which may suggest which process state variables (normal stress, temperature, surface tractions, etc.) dominate the wear process. This information can provide useful guidance for more fundamental studies to develop appropriate process models.

The research reported in the remainder of this paper was conducted to obtain specific information regarding the performance of HSS end mills from various vendors and to conduct a systematic investigation of wear on coated HSS end mills. The results presented in this paper were based on the following research objectives:

1. Given a mixed lot of HSS end mills obtained from different vendors, determine whether the nonstationary linear wear model can provide a useful classification of tool quality.
2. Investigate the wear zones of coated HSS end mills and identify the wear mechanisms.
3. Determine how the wear process is related to common control state variables during the useful life of coated HSS end mills.

EXPERIMENTAL WORK

The experimental work consisted of using actual shop floor machining conditions to cause end mill wear plus