

CASE STUDY IN THERMAL AND WEAR ANALYSES FOR CUTTING TOOLS

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Abstract:

This study represents a case study in thermal and wear analyses for cutting tools, and investigates a relation between temperature distribution and wear characteristic of the tool. This paper presents computer modeling of tool deformation and thermal load during machining using finite element method. The relationship between heat and wear was investigated using both numerical analyses and finite element method.

The results from the thermal analyses indicated that maximum temperatures on the contact area ranged from 163 to 957.5 °C for the uncoated tool while those ranged from 33.6 to 83.4 °C for the coated tool. In other words, the temperatures for the uncoated tool are higher than those for the coated tool. This is expected due to the less contact area resulting from the coating. Therefore, it is worth manufacturing cutting tools with coatings both to extent tool life time and to prevent wear.

It can be concluded that the standardized image processing algorithm should be developed for analyzing wear especially for mass production. It has been proved that the coating material enabled to resist wear, to decrease the cratering and improve the surface topography.

Keywords: Cutting Tool, Finite Element Method, Numerical Analyses, Thermal, Wear

1. INTRODUCTION

Cutting tools are commonly used to perform a wide variety of metal cutting processes such that there exist to be numerous types of them depending upon engineering applications. Modern manufacturers require cutting tools having high quality, long life, low cost with minimal environmental hazards. It is well known that achieving these requirements simultaneously is very difficult, but approaching to them all together is possible with the support of today's high-tech computational capacity and speed. Modeling of cutting tools and simulation of machining processes become a popular and irreplaceable method in research and development as well as in industrial applications. Recently sophisticated complex software programs both employed with finite element method with newly developed mathematical models and installed in super computers have provided researchers relevant data about inherent nature of cutting processes. During any kind of machining processes, the edge of a cutting tool penetrates to the small slice of a workpiece at a certain cutting speed and depth. The external forces acting between the tool and the workpiece occur and the amount of the forces is determined by the cutting speed and the chip thickness.

As a result of processes taking place on the tool and the workpiece, the most of the mechanical energy is converted to heat and the remaining is spent for the formations such as the chip forming process, chip plastic deformation, chip compression ratio, and the tool wear processes. Heat and forces on the workpiece and tool cause deformations resulting in wear on surfaces of tools. The wear type that is dominant in both coated and uncoated cutting tools is crater wear. However, craters that occur in uncoated cutting tools are transformed into chipping or fractures within a short period of machining time.

In this study, two types of uncoated and coated cutting end mills machined after a certain period of machining time have been selected to establish relationships between temperature at the contact area of the tool and tool wear. These types of cutting tools are generally used for a wide range of applications in industry. The temperature distribution was performed by employing finite element analysis package ANSYS, and the tool wear was investigated by using image processing techniques.

There are many research studies available in the literature that their fundamental objectives are to link the temperature distribution and tool wear, and some of them are given in the reference list [1-6]. However, for the evaluation of temperature distribution during machining a different approach in this study is conducted. Instead of determining heat flux rates at the tool-workpiece interface from the thermo-mechanical parameters, heat flux rates within a typical range have been directly used for the thermal analysis such that designers and researchers can figure out heat flux rate by means of various methods and determine the corresponding temperature distribution. This paper presents computer modeling of tool wear, and temperature distribution during machining using finite element method, and focuses on the relationship between the tool temperature distribution and wear.

2. MODEL GEOMETRY

A technical drawing of the cutting end mill with two flutes is shown in Fig. 1. Model geometry of the cutting end mill (Fig. 1) was constructed in SolidWorks by drawing sketches based on the given dimensions. Original images of the uncoated and coated cutting end mill were investigated in order to determine the rake face area by employing image segmentation technique. Then new areas on the cutting tool surfaces were obtained on the model geometry to represent worn zones at the tool tip.

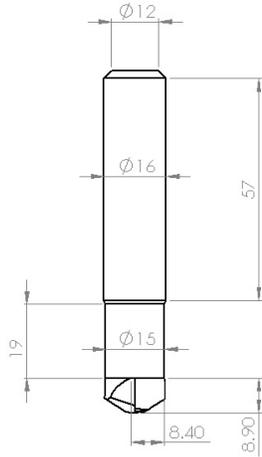


Fig. 1: The technical drawing of cutting end mill.

3. THERMAL ANALYSES

3.1 Thermal Modelling

During metal cutting processes, heat is generated due to mostly friction between tool and workpiece, causing temperatures around contact areas to increase. The generated heat which amounts to almost 98 percent of the mechanical energy consumed in the milling operation is conducted to the cutting tool, the workpiece, and the chip. One of the most fundamental purposes of many research studies regarding heat transfer and wear is to reduce the heat partition into the cutting tool to increase the tool life and thus surface quality. To determine the amount of heat generation, there are numerous models available in the literature, but most of them are very complex and difficult to employ particularly when milling is considered. This is not surprising because experimental validations of milling processes are almost impossible since any temperature measurement involves with the installation of thermocouples in rotating tool at the cutting location. An infrared camera can be used but the camera view is generally blocked with the use of coolant. The most essential feature in any thermal analysis of machining processes is to determine the rate of heat flux on the contact areas of the cutting tool which generally depends on parameters such as cutting force, cutting velocity, chip velocity, and cutting tool geometry. However, in this study, instead of determining the heat flux rate from mechanical measurements, a different and simple approach for the thermal analysis is employed to determine the temperature distribution of the cutting tool such that the temperature distribution on the tool is figured out for a wide range of heat flux rates. Surfaces where the heat flux is applied are contact areas between the cutting tool and the workpiece during machining. These surfaces can be characterized by analyzing images captured from high-resolution 3D digital microscope with a high intensity halogen lamp and image processing capabilities. Table 1 shows cutting edges of two images of uncoated and coated cutting end mills. Using conventional image processing techniques, total areas and

dimensions of the cutting edges were examined, and contact areas were measured to be 13.64 mm² and 1.3 mm² for uncoated and coated cutting end mills, respectively. The surface geometries were drawn on to solid modeling of the cutting end mills, as shown in Table 1. Both models were then meshed using ANSYS CFX meshing.

Table 1: Original images and solid modeling of uncoated and coated cutting end mills.

Tool Type	Original images after 25 min. machining	Solid Modeling
Uncoated		
Coated		

3.2 Meshing

The first step in any finite element modeling is meshing which means the discretization of domain. Meshing plays an essential role in obtaining precise results. If a proper care is not taken, serious errors may emerge or solution simply may not converge. Therefore the strategy in this study is to obtain high-density mesh on areas where the cutting end mill is contacted with workpiece. The entire end mill was meshed with tetrahedral elements in which each solid element has four nodes. The size of the elements was reduced dramatically for regions requiring high resolution.

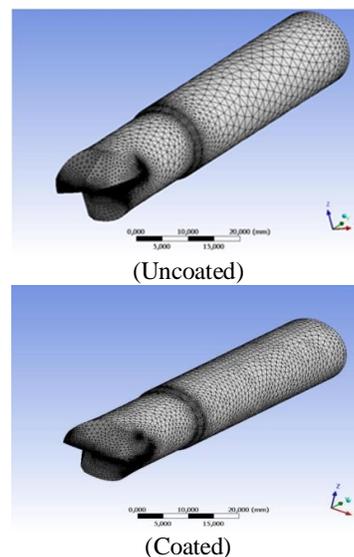


Fig. 2: Meshes of solid uncoated and coated cutting end mill geometries

Fig. 2 shows the mesh distributions of the uncoated and coated cutting end mills using ANSYS Meshing. The model geometries of the uncoated and coated end mills contain 449858 elements with 86253 nodes and 193281 elements with 997612 nodes, respectively. Note that the number of elements for the coated end mill is higher than that for the uncoated end mill. This is certainly due to the smaller contact area for the coated end mill. The highest values of skewness for the uncoated and coated end mills are less than 0.63, which is interpreted as good.

3.3 Thermal Evaluation

The cutting end mill is analyzed without making any simplifications in the solid geometry of the model. Therefore, no changes have been made on the solid model, and actual dimensions were used. The thermal analysis of the cutting end mill is carried out by considering it as a solid boundary in which heat is transferred from the tool-chip contact surface to the convection boundary through conduction taking place in the model. Some relevant input parameters associated with the thermal analysis of the tool are presented in Table 2. The same thermal boundary conditions were used for both the uncoated and coated end mills to obtain a reference state. All equations together with the boundary conditions and the input parameters are solved numerically by using finite element analysis package ANSYS for thermal analysis.

Table 2: Relevant input parameters for thermal analysis.

Thermal conductivity of the tool k (W/m °C)	48
Convection heat transfer coefficient h (W/m ² °C)	50
Ambient temperature away from the tool T_{∞} (°C)	25
Heat flux rates q_0 (MW/m ²)	1, 2, 3, 4, 5, 6, and 7

4. WEAR ANALYSES

The coated tools have similar surface structure except the coating layer observed in different surface topography and colour. However the precise measurements have indicated that the coating process caused the same surface of the cutting tool a higher density of material with an irregular geometry. The irregularities caused by the coating process were observed using 3D nanometrology methods to inspect the critically surface structures of the coated and uncoated tools in detail [6]. 3D digital microscope monitors high quality recorded images easily, since the optical image is projected directly on the charge-coupled device (CCD) in a digital camera.

Images of the cutting tools were taken using a CCD camera. The resolution of CCD camera is 54 Megapixels. Before all image analyses, images were resized into 650×650 pixel sizes in order to standardise images. The captured images of the uncoated and coated cutting tools were analysed using the image processing technique such as segmentation. Segmentations of the images for uncoated and coated tools were analysed using the techniques developed

by the authors [7]. For former, RGB images were converted into gray level. A threshold is applied to the images and all images were binarised. For latter, RGB images were converted into YCbCr color. Then a threshold is applied and the images were binarised. Filtering is carried out by removing small objects from binary images. All connecting components were removed and the images were labelled. The exterior boundaries of the objects were traced and marked. Then the number of pixels in the marked areas was computed.

5. RESULTS AND DISCUSSION

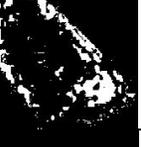
The temperature distribution for uncoated and coated cutting end mills are calculated for seven different heat flux values of 1, 2, 3, 4, 5, 6, and 7 MW/m². The order of magnitude of these heat flux rates are determined based on a study published by Jam et al. [1]. The average temperatures at the contact area of the uncoated tool ranged from 163 to 957 °C, as shown in Table 3. This increase in contact temperatures is expected due to mostly the increasing heat flux rates. The more heat entering the tool, the more energy it receives. Thus, the temperature at the contact surface increases gradually, and it can be said that there is about a sevenfold increase in the average temperature at the contact area. The temperature distribution for the coated cutting end mill shows the same behavior with the uncoated cutting end mill. The average temperatures at the contact area for the coated tool ranged from 33.6 to 83.4 °C, and the temperature increased about twofold of the temperature corresponding to the heat flux of 1 MW/m². For both cases, temperatures at the contact area are in a typical range given in studies published by Jam et al. [1], Liu et al. [5], and Ghani et al. [2]. As it can be seen from the following table, temperatures range from 163 to 957.5 °C for the uncoated tool while those range from 33.6 to 83.4 °C for the coated tool. In other words, the temperatures for the uncoated tool are higher than those for the coated tool. This is expected due to the less contact area resulting from the coating.

Table 3: Average temperature at contact area for different values of heat flux rates.

Tool Type	Heat flux rates q_0 (MW/m ²)	Average temperature at contact area (°C)
Uncoated	1	163.0
	2	301.4
	3	429.0
	4	557.0
	5	691.1
	6	823.7
	7	957.5
Coated	1	33.6
	2	43.3
	3	51.4
	4	59.4
	5	67.4
	6	75.4
	7	83.4

Images were analysed using image segmentation methods. Image segmentation results are given in Table 4.

Table 4. Image segmentation results.

Image Processing Application	Processed Images	
	Uncoated	Coated
Resizing Original Image		
Converting RGB to YCBCR		
Thresholding and binarising		
Filtering and removing small objects from binary image		
Removing all connecting components		
Tracing the exterior boundaries of objects		

6. CONCLUSION

This study purposes to establish a relationship between the temperature distribution and the tool wear for cutting end mills. The methodology developed for the thermal analysis is based upon heat flux on contact areas. This perspective is so simple and efficient that designers can figure out how temperature is distributed depending upon the heat flux rates. The temperature distribution for the cutting end mills during milling process is considered to be steady state heat conduction and the finite element modeling is carried out by using ANSYS software packages. On the other hand, the tool wear behavior of the cutting end mills was investigated by means of various image processing techniques. The two methods showed that there is a fundamental link between temperature and wear. It can easily be seen from the results found that surfaces which have the highest temperature are worn much and thus the increasing surface area allows more heat transferred to the

tool. Therefore, the tool wear can be kept at minimal by preventing more heat entering the tool and thus temperature to increase.

The results from the presented study can be seen as a further step in the direction of a wide-ranging analysis of the surface structure characterization of the coated tool with different materials using both the contact readings and 3D digital microscope capturing of the magnified surface images by CCD.

It can be concluded that the standardized image processing algorithm should be developed for analyzing wear especially for mass production. It has been proved that the coating material enabled to resist wear, to decrease the cratering and improve the surface topography.

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