STUDY ON THE EFFECT OF TOOL NOSE WEAR ON SURFACE ROUGHNESS AND DIMENSIONAL DEVIATION OF WORKPIECE IN FINISH TURNING USING MACHINE VISION

By

HAMIDREZA SHAHABI HAGHIGHI

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LIST OF ABBREVIATIONS

AE	Acoustic emission
CCD	Charged couple device
2-D	Two dimensional
3-D	Three dimensional
AI	Artificial intelligence
DOE	Design of experiments
TCM	Tool condition monitoring
HSS	High speed steel
RMS	Root mean square
RSM	Response surface method
CMM	Coordinate measuring machine
SEM	Scanning electron microscope
PC	Personal computer
LWDM	Long working distance microscope
ITC	Intensity-topography compatible
FAN	Fuzzy adaptive network
FBFN	Fuzzy basis function network
LDA	Linear discriminant analysis
ANFIS	Adaptive neuro-fuzzy inference system
BUE	Built-up edge
ROI	Region of interest
TWI	Tool wear index

LIST OF SYMBOLS

VB_C	flank wear land width in nose area of relief face of cutting tool
VB_B	flank wear land width in zone *B* of relief face of cutting tool
$N_{i(W)}$	effect of nose wear on the surface roughness of workpiece
$N_{i(C)}$	nose wear of cutting tool
D_d	dimensional deviation of workpiece
VB_N	notch wear width in relief face of cutting tool
VB_Bmax	Maximum flank wear land width
λ	rake angle of cutting tool
α	relief angle of cutting tool
R_{wc}	radial distance of profile of worn cutting tool to the center of nose radius of cutting tool
R_{uc}	radial distance of profile of unworn cutting tool to the center of nose radius of cutting tool
R_a	the value of centerline average of surface roughness
R_q	the value of root mean square of surface roughness
s	standard deviation
$R_{a(r)}$	roughness value measured using real images of workpiece
$R_{a(s)}$.	roughness value measured using simulated images of workpiece
$R_{a(a)}$	roughness value measured using approximation model
$D_{d(r)}$	dimensional deviation using real images of workpiece
$D_{d(s)}$	dimensional deviation value measured using simulated images
$D_{d(a)}$	dimensional deviation measured using approximation model

$VB_{C(m)}$ flank wear width measured using microscope

$VB_{C(2D)}$ flank wear width measured using cutting tool images

$VB_{C(a)}$ flank wear width measured using approximation model

KAJIAN KE ATAS KESAN KEHAUSAN MUNCUNG ALAT PADA KEKASARAN PERMUKAAN DALAM OPERASI PELARIKAN MENYUDAH DENGAN MENGGUNAKAN PENGLIHATAN MESIN

ABSTRAK

Operasi pemesinan merupakan suatu kaedah umum bagi menghasilkan komponen-komponen mekanikal yang dikeluarkan di segenap pelusuk dunia. Permintaan terhadap perkakas mesin dalam setahun dilaporkan mencecah lebih daripada £10 bilion. Walau bagaimanapun, kegagalan mata alat memotong menyebabkan masa-henti proses pemotongan yang tidak dijangkakan lalu mengurangkan produktiviti dan meningkatkan kos pengeluaran. Masa-henti yang disebabkan kegagalan mata alat dianggarkan lebih kurang 20% daripada masa pemesinan. Dijangkakan bahawa kaedah pemantauan keadaan mata alat (TCM) yang tepat dan boleh dipercayai boleh meningkatkan produktiviti antara 10% hingga 40%. TCM yang menggunakan kaedah dalam-proses dan dalam-kitaran mampu menilai kestabilan proses pemesinan, meningkatkan produktiviti, mengurangkan kesan tidak dijangkakan yang boleh merosakkan perkakas mesin, serta meningkatkan kualiti permukaan pada bahagian yang dimesin. Kajian tentang kualiti permukaan dan kejituan dimensi hasil kerja adalah penting kerana kedua-dua parameter ini memberi kesan terhadap prestasi komponen yang dimesin. Walau bagaimanapun, kajian terdahulu, yang dilaporkan dalam literatur, tidak mampu mengenal pasti semua jenis kehausan mata alat yang utama, yang memberi kesan terhadap kekasaran permukaan hasil kerja. Walaupun diketahui bahawa profil mata alat pemotong memberi kesan terhadap kekemasan produk, kesan kehausan muncung pada kekasaran permukaan

belum diselidik dalam kajian terdahulu. Kebanyakan kajian memberi tumpuan terhadap kesan kehausan-rusuk pada kekasaran permukaan hasil kerja dengan menggunakan kaedah tidak langsung. Penyelidikan ini bertujuan mengkaji kesan langsung kehausan-muncung mata alat terhadap kekasaran permukaan dengan menggunakan imej 2-D pada hujung mata alat dalam operasi pemutaran-kemasan. Reka bentuk faktoran dan kaedah permukaan respons (RSM) digunakan untuk meramal kekasaran permukaan dan sisihan dimensi hasil kerja dalam pelbagai keadaan pemesinan Teknik reka bentuk eksperimen (DOE) berstatistik digunakan untuk mengurangkan saiz eksperimen tanpa memberi kesan terhadap kejituan hasil. Data yang digunakan dalam kajian ini dijana menggunakan kaedah simulasi imej 2-D pada kawasan pemotongan–muncung yang digunakan untuk menghasilkan profil permukaan hasil kerja. Ciri-ciri permukaan dalam imej yang dirangsang disari untuk menentukan kekasaran purata (R_a) dan sisihan dimensi (D_d) hasil kerja. Lebar bahagian kehausan-rusuk dalam kawasan muncung (VB*c*) juga dapat ditentukan daripada kehausan-muncung dan kekasaran permukaan hasil kerja. Kejituan kaedah yang dicadangkan dibandingkan dengan kaedah konvensional dengan menggunakan penguji kekasaran permukaan dan mikroskop pembuat perkakas.

STUDY ON THE EFFECT OF TOOL NOSE WEAR ON SURFACE ROUGHNESS AND DIMENSIONAL DEVIATION OF WORKPIECE IN FINISH TURNING USING MACHINE VISION

ABSTRACT

The aim of this research is to study the direct effect of tool nose wear which is in contact to the surface profile of workpiece directly, on the surface roughness and dimensional deviation of workpiece using a developed machine vision in finish turning operation. The data used in this study were generated using a simulation method whereby 2-D images of cutting tool nose area were used to simulate the surface profile of the workpiece. The surface features in the simulated images were extracted to determine the average roughness (R_a) and dimensional deviation (D_d) of the workpiece. The flank wear in the nose area (VB_C) was also determined from the 2-D image of cutting tool and the surface roughness of the workpiece. The response surface method (RSM) was used to predict the surface roughness and dimensional deviation of workpiece under various machining conditions. The results showed that *R-squared* statistical parameter obtained using RSM for R_a, D_d and VB_C are 0.997, 0.989 and 0.99. The results of proposed method were compared with the conventional methods using surface roughness tester and optical microscope. The deviation between proposed method and microscope for tool wear measurement is about 5.5% and the deviation between proposed method and surface roughness tester was about 3.2%. Proposed method of using 2D image of cutting tool shaped by nose wear could measure and predict R_a, D_d and VB_C. The results showed that the deviation between actual values and the values predicted for R_a, D_d and VB_C are 9%, 11.4% and 12% respectively. The proposed method is easy to carry out in the

workshop area, easy to maintain and easy to understand because assessing the images of cutting tool is easy. Also, this method is flexible to use for different machining process because capturing the 2-D images of most of the cutting tool inserts is possible using this method.

Chapter 1

Introduction

1.1 Background

An important method of production is machining operation, which is used to remove material from a workpiece using a cutting tool. Turning, milling and drilling are some important machining processes that are used to shape products (Sortino 2003). It is well known that machining operations have a significant role in manufacturing process. According to Child et. al. (2000) the demand for machine tools from the producers of machine tools in one year was more than £10 billion.

The economic and technological importance of cutting process have encouraged many researchers to study this field in order to increase productivity, quality of products, stability and safety of the machining while decreasing the costs of production. Tool failure, which is the major cause of unpredictable downtime of cutting process, not only increases production time and cost but also decreases the productivity (Rehorn et. al. 2005). The downtime due to tool failure alone is estimated to be about 20% of machining process time (Kurada and Bradley 1997 b). It has been suggested that a reliable and precise tool condition monitoring (TCM) method can increase the cutting speed between 10% and 50%, thus increasing the productivity between 10% and 40% (Castejon et. al. 2007, Rehorn et. al. 2005).

There are many scientific publications on TCM. Kurada and Bradley (1997 a) reported on vision systems used to detect the wear area of cutting tool directly. Dimla (2000) and Rehorn et. al. (2005) reviewed some studies on TCM that mostly focused on indirect methods. Lanzetta (2001) classified the important types of tool failure in order to make the tool condition monitoring easier.

Automation is a significant goal in advanced machining industries in order to increase productivity and decrease product costs. However, tool wear is a significant limitation to implement the idea of unmanned machining. Manufacturers can decrease production cost and increase productivity if they are able to change worn out cutting tools just in time. Meanwhile, the size of tool wear, which affects the cutting tool, is very small and cannot efficiently be observed using the naked eyes. Thus, a toolmaker's microscope is conventionally used with a magnification more than 30 times to measure the tool wear (Trent 1991). This requires the tool to be removed from the machine, thus disrupting the machining process.

The time of cutting tool replacement is possible to evaluate using the statistical methods (Kerr et. al. 2006) or using TCM methods. Meanwhile, the complicated effects of known and unknown parameters on machine operations have made the tool wear as a challenging scientific study (Tay et. al. 2002). There are lots of scientific reports published that each one was aimed to solve only a part of tool wear study. More than 1400 published work were reviewed by Dan and Mathew (1990), Teti (1995), Byrne et. al.(1995), Sick (2002), Dimla (2000), Rehorn et. al.

(2005). Most of these works were focused on TCM especially on tool wear and its effect on products machined.

1.2 Prediction the surface quality of workpiece

Study on surface quality and dimensional accuracy of workpiece is very important because these two parameters affect the performance of the parts machined (Risbood et. al. 2003). Also, the surface profile of workpiece is a suitable parameter to distinguish a worn out cutting tool from an unworn cutting tool (Mannan et. al. 2000). Therefore, the studies reported by Benardos and Vosniakos (2003) were carried out to predict the surface quality of workpiece.

Although, stylus method is reliable for measuring the surface roughness of workpieces accurately, use of stylus is not possible when the vibration exists in the environment. Also, the stylus and its transducer can be easily damaged if excessive force is applied. Therefore, the stylus method is not suitable for use on-line or in-cycle to measure the roughness value (Tay et. al. 2003). Also, this method is not fast and the stylus tip can damage the surface texture of parts machined if the workpieces are soft material e.g. aluminum and plastics (Whitehouse 1994). In contrary, vision methods are able to evaluate different specifications of surface roughness fast and accurate because capturing and assessing the images using vision systems are easy. Also, machine vision does not damage the surface quality of workpieces because this method is a non-contact method.

Benardos and Vosniakos (2003) classified the studies of predicting the surface quality of parts machined into four main groups. These groups are based on:

- The machining theories (these methods are based on metal cutting theories).
- The conventional analysis (these methods use the effect of various machining factors on surface profile of workpiece).
- The artificial intelligence (AI) methods (two important methods are fuzzy-set-based technique and neural network method).
- The design of experiments (DOE) (these methods are based on the statistical methods).

Benardos and Vosniakos (2003) suggested the advantages and limitations of methods mentioned above to predict the surface roughness and dimensional deviation of workpiece as follows:

- The machining theories: Although the background of machining theory methods is well established, these methods have not led to a comprehensive solution yet, and the existing methods using the machining theory have not accurately estimated the surface roughness.
- The conventional analysis: Analysis of machining parameters such as cutting speed, feed, and depth of cut based on the level of understanding of the machining condition is not difficult to carry out, but these methods require doing many experiments.
- The AI methods: The experiments based on intelligent methods are used widely because these methods are not sensitive to noisy data, and these methods do not need to be formulated to solve the problem. However,

according to Benardos and Vosniakos (2003) these methods are not implemented in real applications of predicting the surface roughness because there is no guarantee for their performance.

- The DOE methods: The statistical background of design of experiment methods is well established, and the outputs of these methods are reliable. In a scientific study, the experiments must be planned effectively to achieve the aim of the study. The size of experiments also has to be reduced to save the time and the cost. DOE methods are capable to reduce the size of experiments without decreasing the accuracy of predicting. Thus, many researchers have used these methods widely.

1.3 Effect of nose wear on surface roughness of workpiece using machine vision

It is well known that the nose area of cutting tool is one of the main parameters shaping the surface profile of workpiece (ISO 3685, 1993). Thus, the nose wear, which is formed on the nose area of cutting tool, has an important effect on the surface quality of workpiece. Understanding the effect of tool nose wear on the surface quality of workpiece can help to control the surface quality of workpiece.

Figures 1.2(a)-(b) show the surface profile of workpieces, which are captured using machine vision machined by the unworn and worn cutting tools respectively. Figures 1.2(c)-(d) show the images of cutting tools used to shape the surface profiles shown in Figures 1.2(a)-(b) respectively. Figures 1.2(a)-(d) show the nose radius profile and nose wear of cutting tool form the surface roughness of workpiece as a negative shape of cutting tool profile in turning operation. Also, Figure 1.3 shows that the cutting tool nose profile produces a periodic form on the surface profile of workpiece in turning operation. Thus, one cycle of this periodic profile is sufficient to study the effect of tool nose wear on the surface profile of workpiece.

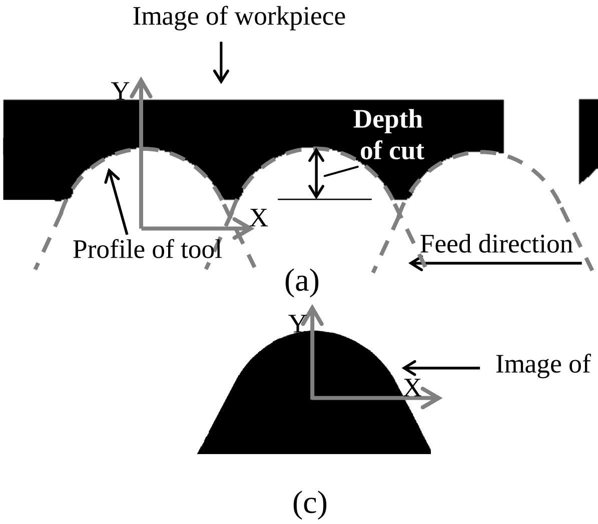

Figure 1.2. (a)-(b) Images of surface profiles of workpieces and (c)-(d) images of cutting tool used.

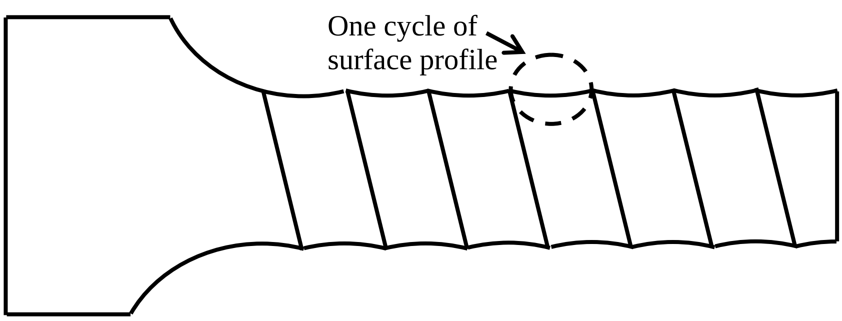

Figure 1.3. Two dimensional schematic shape of a periodic surface roughness of workpiece produced using a lathe machine.

There are various studies in the past on the effect of flank wear land (VB_B and VB_B max) and notch wear as the important types of tool wear on the surface roughness of workpiece (Wong et. al. 1997; Mannan et. al. 2000; Choudhury and Bartarya 2003; Kwon and Fischer 2003; Kassim et. al. 2004; Pavel et. al. 2005). Choudhury and Bartarya (2003) described that in their study roughness value decreased when the flank wear increased. Pavel et. al. (2005) concluded that the surface profile of workpiece is the fingerprint of the cutting tool edge profile. They described that increasing VB_B decreased the surface roughness value of workpiece, and increasing the notch wear increased the surface roughness value of workpiece. Although notch wear is located outside of the contact area of cutting tool and workpiece (ISO 3685), Pavel et. al. (2005) introduced both notch wear and flank wear as the important parameters affecting the surface roughness. However, Wong et. al. (1997) concluded that there is no correlation between flank wear land width and surface roughness of workpiece.

On the other hand, literature survey shows that there are few papers published on the effect of nose wear on the surface roughness of workpiece. Kwon and Fischer (2003) proposed a tool wear index (TWI) method based on rate of both flank wear area and nose wear area to determine the surface roughness of workpiece. However, in the TWI method the surface roughness is a function of time and increases with the machining duration, which does not agree with the findings of Pavel et. al. (2005), Choudhury and Bartarya (2003) and Wong et. al. (1997). Also, Kassim et. al. (2004) reported that all the predominant types of tool wear, based on the machining condition, affect the surface roughness of workpiece; and Wong et. al. (1997) reported that flank wear is not a reliable parameter to predict the surface roughness of workpiece. The reason that only few studies have been carried out in the past to investigate the effect of nose wear, on the surface roughness of the finished products e.g. Kwon and Fischer (2003) can be due to the limitation of the existing methods, which cannot measure the nose wear fast and accurately. Indirect methods such as cutting force monitoring and vibration signatures give the signals that are combination of effect of different types of tool wear on surface quality of workpiece. Thus, the indirect methods cannot be used to study the effect of nose wear on the surface quality alone. Also, Lanzetta (2001) indicated that vision system introduced in the past cannot precisely be used to measure the nose wear of cutting tool using simple subtraction methods. Thus, a method that is precise and fast has to be introduced to assess the effect of nose wear on the surface quality of workpiece.

1.4 Problem statement

In the industries two important problems must be solved. The first is evaluation the quantity of parameters that gives the desirable output. The second is increase of the productivity of system. One important solution to solve theses two problems is the use of models based on scientific background (Benardos and Vosniakos 2003). The problems that based on the literatures were focused on them in this study are as follows:

1.4.1 Effect of nose wear on the surface quality of workpiece

The nose radius area and minor cutting edge together shape the surface profile of workpiece in a turning operation (ISO 3685, 1993). Thus, the tool wear type that affects the nose radius area also affects the surface quality of workpiece. The nose wear is one important type of tool wear that occurs in nose area of cutting tool, thus affecting the surface quality of the product. However, study on the effect of nose wear on the surface roughness is less attended in the papers published in the past. Therefore, the nose wear of cutting tool and the surface roughness of workpiece are evaluated to study their correlation in turning operation as the first aim of this chapter. Also, the small grooves that occur in the corner area of cutting tool can affect the surface roughness of workpiece (ISO 3685, 1993).

Although many optical methods for measuring tool wear and surface roughness have been proposed in the past, these methods either require the tool or the workpiece to be removed from the machine to inspect in the laboratory. In this research, a technique has been developed using machine vision for the measurement of tool nose wear and surface roughness of workpiece in turning operations within the workshop area. The measurement is carried out in-between cutting processes, i.e. in-cycle, without removing either the cutting tool or workpiece from the machine.

1.4.2 Developing a method to predict the tool wear and surface quality of workpiece

As mentioned in Subsection 1.1, TCM is a challenging field of study due to the complicated effects of cutting process on cutting tool and surface quality of workpiece. One important part of study in tool condition monitoring has been focused on investigating the tool wear. Evaluating the surface quality, which is a significant parameter in parts machined, is another important goal in cutting process field (Risbood et. al. 2003).

The large number of published work in the field of tool wear and effect of tool wear on the surface quality revealed that introducing a certain method to solve all problems in this field is difficult. This can be due to the complicated interaction between cutting tool, workpiece and machine tool used.

However, detecting the cutting process using on-line and in-cycle monitoring of tool wear is an applicable method to assess the stability of machining, increase productivity, improve the surface quality of workpieces and decrease the unpredicted parameters that can damage the machine tool (Dimla 2000). This means that using a suitable TCM method can increase the productivity of production system (Bradley and Wong 2001).

Rehorn et. al (2005) reviewed about 100 published work on TCM and concluded that the future TCM methods have to be accurate, simple to carry out, easy to install and maintain. Rehorn et. al. (2005) also suggested that advance statistical methods can increase the efficiency of TCM method used. However, replacing the worn out cutting tool just in time is not easy due to the complicated phenomenon of tool wear as a complex process, which is a combination of abrasive, adhesive and diffusive types of wear (Tay et. al. 2002). Therefore, it is essential to focus on developing a system for TCM and surface quality assessment of workpiece that is simple to carry out and flexible to implement in different cutting conditions.

As mentioned in Subsection 1.2, indirect methods are capable to be used on-line and this is the significant advantage of these methods. However, these methods are not easy to be implemented because evaluation of some of unpredicted signals received from cutting process is difficult (Sortino 2003).

Compared to indirect methods, machine vision systems, which can assess the cutting process directly, are suitable for investigating the cutting process directly. These methods are fast and can easily recognize different types of tool wear. Although these methods are able to measure the wear area precisely, vision systems are sensitive to some ambient parameters such as particle dust, ambient disturbance and light intensity (Lanzetta 2001). Also, they cannot be used to measure the wear area when the machining process continues. This is because the wear area of cutting tool is blocked by the chips formed during machining. This setback prevents the implementation of machine vision systems in-process, and most of published literatures using vision methods to monitor the tool wear are either off-line or in-cycle i.e. between cutting cycles. These limitations show that it is necessary to introduce a new algorithm in order to improve the in-process or in-cycle monitoring methods of tool wear.

1.5 Objectives

The objectives of this study are as follows:

1. Measure of tool nose wear and flank wear, surface roughness and dimensional deviation of workpiece developing a machine vision.
2. Study on the effect of nose wear on the surface roughness of turned parts.

3. Prediction of surface roughness and dimensional deviation of workpiece and flank wear using a response surface method (RSM).

1.6 Research scope

The scopes and approaches of his research are as follows:

- Develop a 2-D vision method using image processing to decrease the effect of ambient factors on results of TCM e.g. ambient lighting, ambient vibration, micro dust particles and misalignment of cutting tool.
- Develop a 2-D vision method to measure the nose wear area of cutting tool.
- Develop a 2-D vision method to measure the surface roughness of turned parts.
- Study on the effect of nose wear on the surface roughness of parts machined in turning operation.
- Evaluating the flank wear land width in nose area of cutting tool (VB_C) using top 2-D image of cutting tool.
- Develop a 2-D vision method to measure the dimensional deviation of turned parts.
- Simulation of the surface profile of workpieces using the 2-D images of cutting tools.
- Develop a DOE method to predict the surface roughness and dimensional deviation of turned parts.

1.7 Outline of thesis

The thesis is organized to fulfill the objectives mentioned in Section 1.5 as follows:

- Chapter 1 describes the background on the importance of cutting process, importance of the TCM methods and problem being investigated. Also, in Chapter 1 the objectives and the scopes of this work are introduced.
- In Chapter 2, past literatures published in TCM and prediction of the effect of tool wear on surface quality, using direct methods and indirect methods, are reviewed.
- In Chapter 3, the algorithms used to fulfill the objectives of this study are described.
- In Chapter 4, the results of this study is presented and discussed.
- In Chapter 5, the conclusion of this thesis is made. Also, the recommendations and suggestions for future study on the effect of tool nose wear on the surface roughness of workpiece in turning operation are given.

Chapter 2

Literature review

2.1 Introduction

Tool wear is an important field of study in machining because it affects the surface quality of the machined parts. Also, surface quality and dimensional deviation are two important characteristics of a part machined because they affect the performance of the part (Risbood et. al. 2003). The surface quality affects some important characteristics of parts machined such as tribological characteristics, fatigue strength, corrosion resistance and aesthetic appeal of the products (Kohli and Dixit 2005). Dimensional deviation can also affect flatness, straightness, circularity, cylindricity, parallelism, perpendicularity, angularity and concentricity of products (Dotson et. al. 2003).

The methods used to monitor tool wear can be broadly divided into two groups: (i) Indirect methods and (ii) direct methods (Pfeifer and Wiegers 2000). Rehorn et. al. (2005) and Dimla (2000) reviewed about 180 published works on tool condition monitoring (TCM) that are mostly focused on indirect methods. Cutting force monitoring, acoustic emission (AE), vibration signatures (acceleration signals), tool tip temperature monitoring and spindle motor current monitoring are some examples of indirect methods for monitoring tool wear. Cutting force measurement and vibration signals method are two of the indirect methods used widely to evaluate the tool wear in batch production (Dimla 2000). Indirect methods are capable for on-line use to assess the tool wear, and this advantage is the reason for their wide application (Sortino 2003). The basis of indirect methods is comparison between the received signals from the current cutting process and the optimized signal as the threshold. However, evaluation of signals received from indirect methods is not simple because of the unpredicted parameters that can affect the output signals (Pfeiffer and Wiegers 2000).

On the other hand, machine vision systems are well known as the direct methods of TCM. Some studies on tool wear using vision systems were reported by Kurada and Bradley (1997 b). The vision systems are suitable for assessing the tool wear and surface quality of workpiece. The vision systems are also able to recognize the tool wear pattern in different cutting process directly.

This chapter aims to survey the literatures focused on TCM and prediction of effect of tool wear on the surface quality of products using direct and indirect methods. In Section 2.2 the important types of tool wear are reviewed. Section 2.3 briefly discusses some early studies on TCM methods, Sections 2.4 and 2.5 discuss about TCM using indirect and direct methods respectively, and Section 2.6 discusses about some indirect and direct methods employed to predict the surface roughness and dimensional deviation of workpiece.

2.2 Important types of tool wear

The important types of tool wear are flank wear, nose wear, crater wear and notch wear as shown in Figures 2.1(a)-(b). Most of studies on TCM in the past have been focused on flank wear and crater wear. This can be due to the recommendation of ISO 3685 (1993) standard that introduced the flank wear and crater wear as the criteria of tool life.

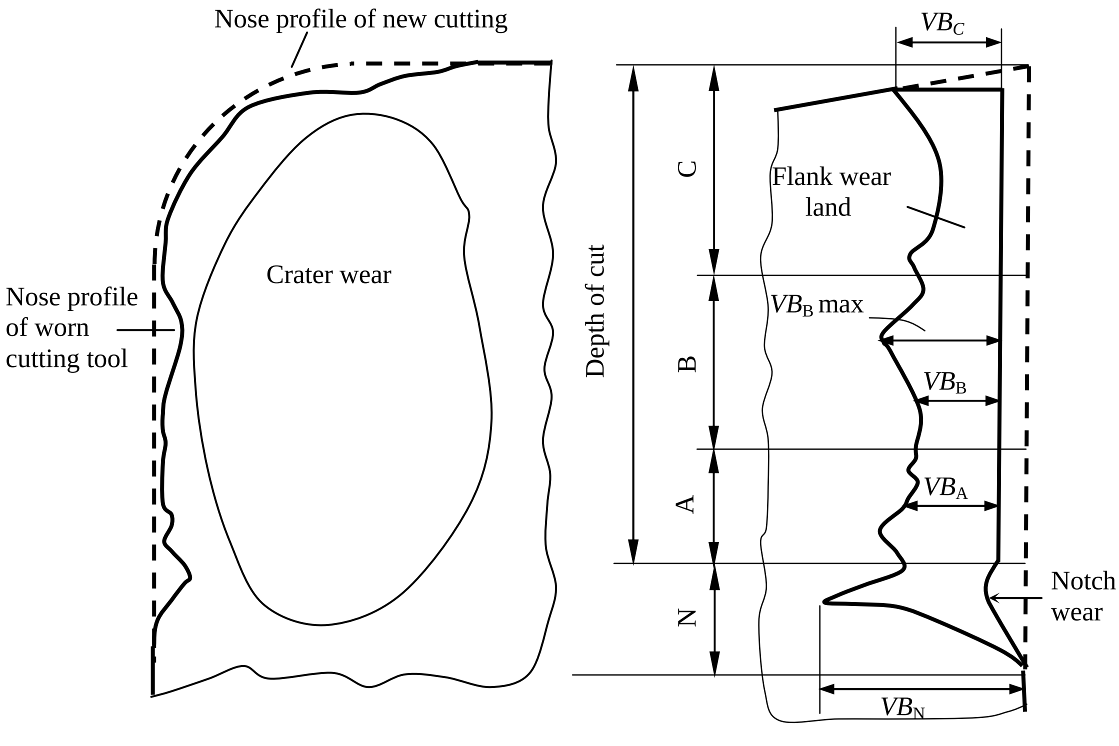

Figure 2.1. (a) Top view of crater wear and nose profile and (b) flank wear land and notch wear of cutting tool based on ISO 3685 (1993).

When the relief face of a cutting tool rubs against the workpiece, flank wear is created on this face. Therefore, this type of tool wear is made by an abrasion mechanism. Flank wear decreases the accuracy of the parts machined because it causes deflection of the cutting tool (Stephenson and Agapiou 1997). Flank wear land width (VB_B) shown in Figure 2.1(b) is the criterion of tool life. When the wear patterns formed on relief face of cutting tool are regular, VB_B =0.3 mm is the criterion of tool life, and if the wear patterns formed on relief face of cutting tool are not regular, VB_B max=0.6 mm is the criterion of tool life.

Crater wear is another important type of tool wear that forms a rake on the cutting tool face. This rake can be produced by chemical reaction or metal diffusion due to high temperature on cutting tool face. Although crater wear increases the effective angle of cutting tool that can decrease the cutting force, severe crater wear makes the cutting tool weak.

Notch wear is produced by chemical reaction between cutting tool faces and coolant or atmosphere (Stephenson and Agapiou 1997). When notch wear grows on the cutting tool face, it can cause breakage of the cutting tool due to the grooves produced on the tool tip that weakens the cutting tool structure. Therefore, according to ISO 3685 (1993) severe notch wear is also a criterion of tool life. In this case, the notch wear width VB_N = 0.3 mm is the criterion of tool life when the cutting tool is regularly worn on the relief face. On the other hand, if the cutting tool is not regularly worn on the relief face, the cutting tool shall be replaced when VB_N exceeds 0.6 mm.

Nose area of cutting tool is where the nose wear occurs. When severe nose wear is formed catastrophic tool failure can occur (Dimla 2000). Nose wear is a combination of flank wear and notch wear (Jurkovic et. al. 2005, Stephenson and Agapiou 1997). Figure 2.1(a) shows the nose wear, which consists of flank wear and notch wear, as the important type of tool wear. Kwon and Fischer (2003) reported that the nose wear affects the surface quality of workpiece in turning operation. This finding agrees with ISO 3685 (1993) standard that introduced the tool corner radius as one of the main factors that affects the surface roughness of workpiece in a turning operation.

2.3 Overview of the methods of TCM and early studies

There are a number of different methods used to evaluate tool wear. These methods can be grouped into two general groups:

- Indirect methods
- Direct methods

Vibration signatures (acceleration signals), cutting force monitoring, acoustic emission (AE), tool tip temperature monitoring and spindle motor current are some examples of indirect methods of tool wear monitoring. Among these, vibration signals and cutting force measurement methods are used widely to evaluate the cutting process in batch production (Dimla 2000). Indirect methods are capable to be used on-line to assess tool wear (Pfeifer and Wiegers 2000). This advantage has encouraged the industries to adopt some of these methods. The indirect methods are based on comparison between the received signal of current cutting process and optimized signal of cutting process. When the received signals are out of optimized signal bound, the system will send a signal to change the cutting tool (Pfeifer and Wiegers 2000). Thus, the threshold signals must be investigated before using these methods to monitor the cutting process.

Although indirect methods based on vibration signals and cutting force signals have been used widely for TCM, Sortino (2003) reported that it is not simple to design the indirect methods to apply in a real condition. This can be due to lack of knowledge about some signals received from the cutting process using indirect methods. In addition, these methods are costly to monitor the cutting process because they are complex and are not simple enough to use in a workshop easily (Sortino 2003, Pfeifer and Wiegers 2000).

Machine vision systems that mostly use the Charged Couple Device (CCD) camera are well known as the direct methods to evaluate the tool wear (Kurada and Bradley 1997 a). Machine vision systems using computer to process the captured images of cutting tools are suitable to assess the tool wear and surface texture of specimen due to their ability to recognize different forms and structures of objects. Also, machine vision methods are capable of saving and processing huge amount of information via captured images. The vision systems are able to record and evaluate the micro detail of objects precisely. In addition, machine vision systems can be used for different types of cutting processes such as turning, drilling, milling and grinding. The types of workpiece materials used, cutting tools and parameters of machining do not affect the output of vision systems. Since they are non-contact methods, they do not cause damage to the parts measured (Lanzetta 2001). Machine visions can measure the objects directly using two dimensional (2-D) or three dimensional (3-D) methods. In some studies, machine vision was used to monitor the tool wear directly (Lanzetta 2001, Dawson and kurfess 2005, Devillez et. al. 2004), and in some other studies machine vision was used to evaluate the cutting tool condition via surface texture (Mannan et. al. 2000, Kassim et. al. 2004).

Lighting is an important factor in all machine vision applications. The type of illumination used depends on the output required. There are two main types of lighting:

- Front-lighting
- Back-lighting

In front-lighting method, both of illumination source and camera are in front of the specimen. The output of this method is an image of the object surface. When the specimen is placed between camera and the source of light, this method is called back-lighting. Back-lighting is used when it is necessary to capture an image of specimen contour. Front-lighting is the method used to study the flank wear (Pfeifer and Wiegers 2000; Kurada and Bradley 1997 a), crater wear (Prasad and Ramamoorthy 2001; Dawson and Kurfess 2005) and their effect on surface roughness (Mannan et. al. 2000, Kassim et. al. 2004). Meanwhile back-lighting is the method which has been used to measure the nose wear in off-line mode (Kwon and Fischer 2003).

This research aims to study the effect of nose wear, which is located on the profile of cutting tool, on surface roughness using direct methods that was not studied in the past. Thus, the back-lighting method, which is a suitable method to use to capture the images of tool contour, was employed to assess the tool wear of cutting tool.

According to literature survey in this study, the effect of cutting speed on tool life of cutting tool was one of the earliest studies reported in the field of metal cutting process. The study carried out by Taylor (1907) showed that the effect of cutting speed on tool life is significant and the manufacturer has to use the optimum cutting speed. The cost of tooling and downtime of machining can be decreased using the optimum cutting speed. The optimum cutting speed *V* is given by:

$$\log V = \log C - n \log T \tag{2.1}$$

i.e. $$VT^n = C \tag{2.2}$$

where *T* is cutting time to produce a standard flank wear land width (e.g. 0.6 mm for irregular wear pattern on the relief face). *C* and *n* are constant of material and machining condition respectively.

Since access to the very old work published in the field of tool wear in cutting process was not easy, the literature survey on the history of tool wear in this work is not comprehensive. However, the published works that are introduced in this section shows the trend of study in cutting process. The trend shows that the goal of these studies were focused on understanding the effect of machining parameters on the tool wear that affects the machined parts and productivity. Since the cutting speed is not the only parameter that has to be observed to increase the product quality and decrease the tool wear rate, other investigators followed Taylor's method to study on the other important parameters of machining. Some of these studies are briefly described in this section. Hake (1955) proposed a method based on radioactive γ ray to measure the effect of wear on the cutting tool. Shaw and Dirke (1956) studied on the nature of wear pattern of the cutting tool to understand the effect of wear on the tool life of cutting tool. Taylor (1957) suggested using the area of tool wear to improve the accuracy of measuring the wear pattern.

Opitz and Gappisch (1962) studied the effect of cutting speed on the formation of built-up edge (BUE), flank wear and cater wear in cutting process. They concluded that in low cutting speed BUE occurred, in medium cutting speed 'moderate flank wear' occurred and in high cutting speed 'high rate flank wear' and crater wear was observed. However, high or low cutting speed for different material is different i.e. a cutting speed that is assumed high for high speed steel (HSS) cutting tool material is a moderate cutting speed for a ceramic cutting tool material.

Takeyama and Murato (1963) studied on the effect of temperature on the tool life. They suggested that tool condition can be monitored using cutting tool temperature when machining the workpiece. Meyer and Wu (1966) proposed an optical method to measure the crater wear of cutting tool. The method was carried out using a high axial resolution lens in order to record some photograph from the crater area of cutting tool. They described that other researchers used other methods e.g:

- Weighing the cutting tool before and after machining.

- Measuring the depth of crater wear using the stylus method.
- Gradual lapping down of top surface of crater wear area.
- Use of radioactive isotopes method.

The results showed that the proposed method, which is an optical method, could successfully be used to measure the depth of crater wear.

Mukherjee and Basu (1966) used a regression method in order to model the effect of machining variables on the flank wear. The variables used in this study were: Duration of machining, feed rate, cutting speed and depth of cut. The output response was flank wear that was measured using a toolmaker's microscope. The results showed that regression method can be used to model the effect of machining parameters on the flank wear. Also, they concluded that cutting speed affected the flank wear rate significantly.

Bhattacharyya and Ham (1969) proposed a mathematical method to model the flank wear. They varied some different machining parameters to model the mechanism of forming the wear pattern on the relief face of cutting tool. The parameters varied were: Cutting tool material, cutting tool angle and duration of machining. The parameters that were kept constant were: Cutting speed, depth of cut, feed and workpiece material. They concluded that the proposed method could effectively be used in similar machining conditions. Thus, modeling the flank wear rate is not possible using machining condition that is different from the experiments carried out.

Bhattacharyya and Gonzalez (1970) proposed a regression model to predict the surface roughness and determine the optimum machining condition. The variables used were: Feed rate, cutting speed, length of workpiece to be machined, diameter of workpiece and tool life. The method used was successful in predicting the surface roughness and optimizing the machining process in the known field of variables.

Sundram (1978) proposed a method to predict the surface roughness of workpiece. Also, the model constructed was used to determine the optimum machining conditions. The variable parameters chosen were: Surface roughness value, power consumption of machine tool used, cutting speed, feed rate and depth of cut while other machining parameters were fixed. A relatable design method, which is a type of statistical DOE method, was used to design the experiments. A stepwise regression method was also used to analyze the data obtained from machining process. Sundram concluded that the goals of proposed study were fulfilled using the proposed method successfully. Thus, Sundram suggested using the concept of proposed method to solve the similar problems using machining condition that is desirable.

Tlusty and Massod (1978) studied on the chipping and fracture of cutting tool as the catastrophic types of tool failure. They used two methods to study the tool failure: A plain stress-strain analyses method and fractographic method. However, they mentioned that due to neglecting some other parameters such as effect of temperature on the output, this method cannot be mentioned absolute.