WEAR BEHAVIOUR OF ADVANCED MULTILAYER COATING PVD-TiAlN IN DRY MACHINING OF AISI D2 HARDENED STEEL

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ABSTRACT

Machining hardened steel is currently receiving increasing attention as a prospective alternative to the grinding and electrical machining (EDM) which mostly accepted as traditional methods of machining materials with hardness (>45 HRC). The reason is that it offers a comparable surface finish, shorter cycle time, fewer process steps, lower production cost and higher flexibility. In order to demonstrate its advances, it is important for a critical hard machining processes enable to run in optimal conditions based on specified objectives and practical constraints. This study was conducted to investigate the life and wear mechanisms of the tool, machined surface integrity such as roughness, microhardness beneath the surface and white layer in end milling of AISI D2 hardened steel (58-62 HRC) in dry machining condition. Sandvik PVD-TiAlN coated carbide cutting tool was used on a vertical machining centre (VMC). The cutting conditions including cutting speed (V_c): 80-120 m/min, radial depth of cut (a_e): 3-5 mm and depth of cut (a_p) is kept constant at 0.5 mm. From the results, it was found that the highest acceptable value of tool life and volume of material removal was obtained at the lowest radial depth of cut of 3 mm and the lowest cutting speed of 80 m/min. This indicates that this value of radial depth of cut and cutting speed is more suitable for machining hardened steel materials. The machined surface experienced microstructure alteration and increment in microhardness on the top white layer of the machined surface. Severe microstructure alteration was observed when the tool became dull. In addition, surface roughness values obtained were within the limit (<4 µm) specified by ISO standard for machining. Thus, the investigation on relationship of tool wear performance and surface integrity in machining AISI D2 hardened steel using coated carbide tool will lead to the development of optimum range of cutting parameters which promoting maximum productivity, maximum tool life and acceptable surface integrity of the workpiece. Hence, a good understanding of the relationship between tool wear performance and surface integrity can be used as the basis of future development of tooling and workpiece respectively. Finally, the potential of cutting performances of coated carbide insert in machining AISI D2 hardened steel could be revealed and have evidences to replace expensive cutting tools such as Polycrystalline Cubic Boron Nitride (PCBN) which its price 4-5 times higher than coated carbide insert.

ABSTRAK

Pemesinan keluli keras kini mendapat perhatian sebagai alternatif kepada proses mencanai dan pemesinan elektrik (EDM) yang kebanyakannya diterima sebagai kaedah tradisional bahan pemesinan dengan kekerasan (>45 HRC). Ini kerana ia mempunyai kemasan permukaan, kitaran masa yang pendek,langkah memprosesan yang kurang, kos pengeluaran yang rendah dan fleksibiliti yang tinggi. Dalam mencapai kemajuan,proses kritikal pemesinan keras dalam keadaan yang optimum sangat penting untuk mencapai objektif tertentu dan mengelakkan kekangan praktikal. Kajian dijalankan untuk menyiasat jangka hayat dan mekanisme alat, permukaan integriti, kekerasan di bawah permukaan dan lapisan putih AISI keluli keras D2 (58-62 HRC) dalam keadaan pemesinan kering. Sandvik PVD-TiAlN bersalut mata alat karbida telah digunakan di pusat pemesinan menegak. Parameter pemotongan yang digunakan termasuk kelajuan pemotongan: 80-120 m / min, kedalaman pemotongan: 3-5 mm dan kedalaman pemotonganadalah malar pada 0.5 mm. Keputusan diperolehi nilai jangka hayat tertinggi alat dan jumlah pembuangan bahan dikedalaman pemotongan paling rendah 3 mm dan kelajuan pemotongan yang rendah 80 m/min. Ini menunjukkan bahawa nilai kedalaman pemotongan dan kelajuan pemotongan ini adalah lebih sesuai untuk pemesinan bahan keluli keras. Permukaan yang dimesin akan mengalami perubahan mikrostruktur dankenaikan kekerasan pada lapisan atas putih permukaan yang dimesin. Perubahan mikrostruktur yang teruk berlakuapabila alat menjadi haus. Disamping itu, nilai kekasaran permukaan yang diperolehi adalah dalam had (<4μm) yang ditentukan oleh ISO untuk permesinan. Oleh itu, hubungan prestasi memakai alat danpermukaan integriti pemesinan keluli keras AISI D2 menggunakan alat karbida bersalut akan membawa kepada pembangunan pelbagai optimum memotong parameter yang menggalakkan produktiviti maksimum, memaksimumkan hayat alat danpermukaan integriti bahan kerja. Oleh itu, pemahaman yang baik mengenai hubungan antara prestasi memakai alat dan permukaan integriti boleh digunakan sebagai asas pembangunan masa depan peralatan. Akhirnya, potensi memotong persembahan mata alat karbida bersalut dalam pemesinan keluli keras AISI D2 boleh mendedahkan dan mempunyai bukti-bukti untuk menggantikan alat pemotong mahal seperti Polycrystalline Cubic Boron NitridePCBN yang harganya 4-5 kali lebih tinggi daripada mata alat karbida bersalut.

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LIST OF ABBREVATIONS

EDM	-	Electrical Discharge Machining
PCBN	-	Polycrystalline Cubic Boron Nitride
PCD	-	Polycrystalline diamond
TiN	-	Titanium Nitride
TiAlN	-	Titanium Aluminium Nitride
TiCN	-	Titanium Carbon Nitride
PVD	-	Physical Vapour Deposition
CVD	-	Chemical Vapour Deposition
AlCrN	-	Aluminium Chromium Nitride
CrN	-	Chromium Nitride
MRR	-	Material Removal Rates
VMR	-	Volume Material Removal
V_c	-	Cutting speed
a_p	-	Axial radial depth of cut
a_e	-	Radial depth of cut
T_L	-	Tool life
R_a	-	Average surface roughness
LOC	-	Length Of Cut
BUE	-	Built-Up edge
V_B	-	Flank wear
KT	-	Crater wear
TiAlCrN	-	Titanium Aluminium Chromium Nitride
TiAlSiN	-	Titanium Aluminium Silicon Nitride
HRC	-	Hardness Rockwell C
SEM	-	Scanning Electron Microscope
HV	-	Hardness Vickers
VMC	-	Vertical Machining Center
EDAX	-	Energy Dispersive X-Ray Spectrometer

CHAPTER 1

INTRODUCTION

1.1 Recent trends in manufacturing by machining

The recent developments in science and technology highly emphasized in the field manufacturing industries. The manufacturing industries are trying to decrease the cutting costs, increase the quality of the machined parts and machine more difficult materials. Machining efficiency is improved by reducing the machining time with high cutting speed machining. However, when cutting hard material such as steels, cast iron and super alloys, softening temperature and the chemical stability of the tool material limits the cutting speed (Kishawy et al., 2000).Therefore, machining hardened steel parts has become more pronounce in manufacturing process, particularly in mould and die industries and subsequently mostly contributed in making automotive and aerospace components. Due to the hardness of the material, abrasive processes such as grinding and polishing have been typically required, but advances in machine tool and cutting tool materials has allowed machining hardened steels to become a realistic replacement for many grinding applications. Despite of having outstanding machinery, no one could not expect the failure of tool life for certain conditions in machining operation. Thus, it will become most apparent when machining hard materials such as hardened steel (Lajis et al., 2008).

With the advent of several advanced diffcult-to-cut materials, and with the availability of heat resistant has posed a great challenge in industries. Hardened steel is one of these diffcult-to-cut materials(Chen et al., 2007). During the last few years, numerous studies have been conducted to improve the machinability of this kind materials and to explore and develop new techniques to minimize machining costs maintaining the quality requirements of the machined direct manufacture of components from hardened steel are expected to be substantial especially in the context machining costs and leads times compared to traditional route of machining in the annealed state followed by heat treatment, grinding or electrical discharge machining (EDM), and manual finishing. However, there are several issues related to this process that require further investigation, and the major issue among these is the high temperatures at the tool-chip and tool-workpiece interfaces in conjuction with the plastic deformation, both strongly affecting the surface integrity and the quality of the machined product.

In today machining issues, the studies have been done to evaluate the machinability of the AISI D2 hardened steel by using the cutting tool insert-coated carbide. The reason is hardened steels AISI D tool group is extensively used in making moulds and dies, but the machinability of this group is very poor. But despite the extensive use and potential scope of AISI group D tool steel for cold forming operations, most information about the machinability of AISI group D tool steel is highly is needed (Koshy et al., 2002). Milling of hardened steel AISI D2 is usually a finishing process, therefore a stable cutting process must be guaranteed first. A very important indicator of the performance of metal cutting operation is the productivity or volume material removed per unit time. The productivity enhancement of manufacturing processes imposes the accelerations of the design and evolution of improved cutting tools with respect to the achievement of a superior tribological attainment and wear resistance. The trend to increase productivity has been the instrumental in invention of newer and newer cutting tools with respect to material and design (Fox-Rabinovich et al., 2005).

Other than cutting tool improvement and development, dry cutting is beneficial because of the elimination of the cost the cutting fluid as well as the high cost of fluid disposal. Hence, in dry cutting; the increasing need to boost productivity, to machine more difficult materials and to improve quality in high volume has been the driving force behind the development of cutting tool materials. For these reasons, hard coating for cutting tools has been of the one important aspect of cutting tool research development. These hard coatings are thin films that range from one layer to hundreds of layers and have thickness that range from few nanometres to few millimetres. These hard coatings have been proven to increase the tool life through slowing down the wear phenomenon of the cutting tools. This increase in tool life allows for less frequent tool changes, therefore can reduce the manufacturing cost, but also reducing the setup time as well as the setup cost. In addition, to increasing the tool life, hard coating deposited on cutting tools allows for improved and more consistent surface roughness of the machined work piece. The surface roughness of the machined work piece changes as the geometry of the cutting tool changes due to wear, and slowing down the wear process means more consistency and better surface finish (Derflinger et al., 1999; Chen et al., 2011).

Machining efficiency is improved by the reducing the machining time with high cutting speed. When cutting the hard material such as steels, cast iron and super alloys, softening temperature and the chemical stability of the material limits the cutting speed. Therefore, it is necessary for tool materials to possess good high-temperature and mechanical properties. While many ceramic materials such as TiC, Al_2O_3 and TiN posses high temperature strength, they have lower fracture toughness than that of conventional tool materials such as high-speed steels and cemented tungsten carbides. The machining of hard and chemically reactive materials at higher speeds is improved by deposited single and multi layer coatings on conventional tool materials to combine the beneficial properties of ceramics and traditional tool materials. The majority of cutting tools is use today employ in chemical vapour deposition (CVD) or physical vapour deposition (PVD) hard coatings. The high hardness, wear resistance and chemical stability of these coatings offer proven benefits in terms of tool life and machining performance. Coated hard metals have brought great influence in increasing productivity since their introduction. Since then coatings have also been applied to high speed steel(HSS) especially in end millings. Coatings acts as diffusion barrier; they prevent the interaction between chip formed during the machining and the cutting material itself. The compounds which make up the coatings used are extremely hard and so they are abrasion resistant (Kovalev et al., 2009).

1.1.1 Machinability and surface integrity in machining

Numerous investigation have been carried out to improved the machinability (tool life and tool wear performance) and surface integrity (surface roughness, surface topography and surface metallurgy) of the hardened steels. In machining process, the tool may experience repeated contact loads during interrupted cut, and the workpiece may chemically interact with the tool material. The response of a tool material to the above tribological condition dictates its performance. Moreover, the damages of a cutting tool are influenced by the stress state and temperature at the tool surfaces, the cutting conditions with the presence or not cutting fluid. In machining, the tool damage mode and the rate of damage are very sensitive to changes in the cutting operation and the cutting conditions. To minimize machining cost, it is not only to find the most suitable tool and work combination for a given machining operation, but also to reliably predict the tool life.

AISI D2 hardened steel have a poor machinability due to its low thermal conductivity, which causes a high chemical reactivity caused by the elevation of the temperature in the field cutting (Sun et al., 2009), indeed, the quality of machined surface, is becoming more and more important to satisfy the increasing demands of sophisticated component performance. However, surface integrity is one of the most relevant parameters used for evaluating the quality of machined surface, indeed the quality and performance of the product is directly related to the surface integrity achieved by final machining. Surface integrity is influenced by a set of parameters. Various researchers have analyzed the influence of cutting parameters on surface state such as (Daymi et al., 2011; Kishawy et al., 2000; Umbrello et al., 2009 and Amin et al., 2001). However, surface integrity including several criteria such as roughness, microstructural changes, residual stress, microhardness and plastic deformation at the surface. The microstructure at the surface layer can be changes as a result of chemical changes caused by the tool, enlargement and elongations of the grains are observed by Hughes et al.(2004).

Surface metallurgy includes the existence of microcracks, untempered, and overtempered martensite imposed by the machining process, pull-out of carbides from the grain boundary, intergranular attack, pits, tears, laps, protrusions, plastic deformation and changes in the microhardness (Kishawy et al., 2000).These factors determine the behaviour and service failures of the components produced. Otherwise, the choice of manufacturing processes is based on cost, time and precision. Precision of a surface is one of the topographical features which divided by two criteria: dimensional accuracy and surface finish. However, another criterion has become increasingly important: the performance of surface. The terms of performance has different meanings depending on the contex, but is most likely linked to fatigue, corrosion, wear and strength(Davim, 2010b). It is usually assumed that performance is directly related surface integrity.

Therefore, the main interest in this study is to obtain longer tool life and high productivity or high volume material removed in hard milling of AISI D2 using coated carbide tool. With rapidly growing trends in developing advanced processing technologies, manufactured components/products are expected to demonstrate superior quality and enhanced functional performance. Material removal processes continue to dominate among all manufacturing processes. The functional performance of components from material removal processes is heavily influenced by the quality and reliability of the surfaces produced both in terms of topography as well as metallurgical and mechanical state of the subsurface layers (Jawahir et al., 2011).

1.2 Problem Statement

Problems arise in machining hardened still is due to its high hardness and toughness as well as its inhomogeous microstructure, which contributes to accelerated tool wear and chipping. Besides that, increasing material removal rate (MRR) (i.e increasing cutting speed,V_c and radial depth of cut,a_e) leads to produce higher productivity, however, it influences the tool wear deterioration rapidly, hence, reduces tool life due to mechanical stress and temperature increases. Figure 1.1shows problems in hard machining. The progress of tool wear affects to the surface integrity on the workpiece as well.

In machining hardened steeel, Polycrystalline Cubic Boron Nitride (PCBN) tool usually common used in machining hardened steel because its great cutting performance and also excellent tool properties such as higher wear resistance and hardness. However, due to the high cost and expensive which are about 4-5 times higher than coated carbide tools. Therefore, there is a keen interesting of utilizing multilayer coated carbide tools such as TiAlN/AlCrN and AlTiN. It is the most possibly can replace the expensive cutting tools such as PCBN, which are particularly produce high productivity and efficiency in hard machining.

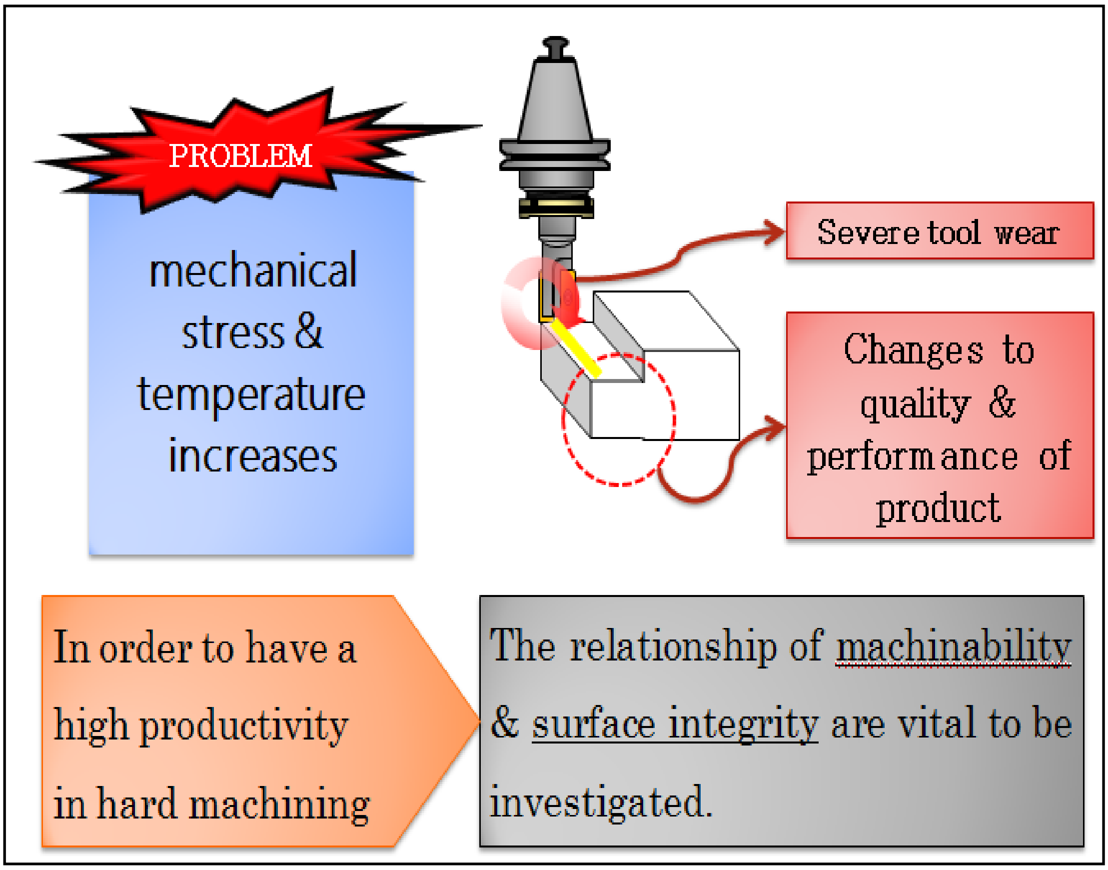


Figure 1.1:Problems in hard machining (Jasni., 2012)

Therefore, it is vital to study the relationship between tool wear performance and surface integrity in machining of AISI D2 hardened steel using coated carbide tool leads to the development of optimum range of cutting parameters in order to get the maximum productivity, maximum tool life and acceptable surface integrity of workpiece (i.e. surface roughness, microhardness and microstructure). Yet, a good understanding of the relationship between tool wear performance and surface integrity can be used as the basic future development of tooling and work piece respectively. So, the potential cutting performances of coated carbide insert in machining the AISI D2 hardened could be revealed. Coated carbide tools improve wear resistance, increase tool life and enableto utilize higher cutting speeds used. Therefore, there is a keen interest in the utilization of coated carbide tools that can mostly replace expensive cutting tools (i.e. PCBN and ceramic) particularly in high productivity of hard machining. Besides, from the investigation work of worn inserts for the coated carbide tools revealed that the coatings were rapidly removed from the substrate when high speed machining applied. As the coating was removed so quickly, its effectiveness could be questioned.

1.3 Purpose of Study

This project is undertaking to relate the tool performance and surface integrity in machining of AISI D2 hardened steels using advanced multilayer coated carbide tool PVD-TiAlN. The objectives of this project are as below:

i. To investigate the effect of cutting variables (i.e cutting speed and radial depth of cut) on tool wear performance and tool life of the cutting tools;
ii. To identify the effect of cutting variables (i.e cutting speed and radial depth of cut) on surface integrity of the workpiece(i.e microstructure analysis; microhardness; machined workpiece surface roughness);
iii. To explore the coating characteristics including the thickness of coating, oxidation resistance and the microhardness of the coating.

1.4 Significances of Study

The study was conducted to evaluate the machining characteristics of AISI D2 hardened steel in a high speed CNC milling operation by using tungsten carbide coated PVD-TiAlN. This research concentrates on the effect of cutting variables on tool wear performance, tool life and machined workpiece surface roughness.Machining database developed is likely to benefit the machining practitioners and industries as it would help them in selecting optimum values of the cutting parameters. An optimal selection of cutting parameters will satisfy the economic objectives which are maximizing production rate and minimize the production cost.Then, a good understanding of the relationship between tool wear performance and surface integrity can be used as the basic of future development of tooling and work piece respectively. So, the potential cutting performances of coated carbide insert in machining the AISI D2 hardened could be revealed. The results can be use to have a better understanding in today advanced machining technology.

1.5 Scopes of Study

The scope of this project is to perform machining operation for AISI D2 steel by using PVD-TiAlN coated carbide cutting tool by using a high speed CNC Vertical Milling (Mazak Tech). The parameters varying are cutting speed and radial depth of cut while feed and depth of cut are kept constant.

This work was carried out with the aim to evaluate the performance of coated carbide tools when end milling of AISI D2 hardened steels at various of cutting speed and radial depth of cut. The effect of the varying cutting speed and radial depth of cut on the tool wear, tool life and surface integrity machined work piece were investigated.

In order to realize the objectives of the study to be successful and reasonably implemented, the following significance study have been derived:

a) Cutting speed (>80 m/min), feed (0.05 mm/tooth), axial depth of cut (0.5mm) and radial depth of cut (>5 mm).

b) Using a Vertical Milling CNC (Mazak Tech) machine to carry out the machining experiments.

c) Coated carbide inserts with multilayer coating PVD-TiAlN (Sandvik Coromant) was selected as the cutting tools for machining the work piece.

d) Conducting the machining operation on AISI D2 hardened steel (having a typical hardness range of (58-62 HRC) as workpiece material.

e) The experiment was carried out under dry cutting condition.

f) Conducting experimental trials to investigate and evaluate the following responses:
    i. Tool life and tool wear using Tool Maker Microscope.
    ii. Surface roughness measurement using Mitutoyo SJ-400.
    iii. Microhardness measurement using Vickers Microhardness machine.
    iv. Surface/sub-surface damage including white layer using Scanning Electron Microscope (SEM)
    v. Surface morphology of cutting tool wear and machined work piece using Field Emission Scanning Electron Microscope (FE-SEM).

g) Analyzing data of gathered through experiments for both coated carbide inserts (PVD-TiAlN) with;
    a) Evaluation and comparison of the effect of cutting conditions on the machinability of the work material.
    b) Observation of machining characteristics of cutting tools due to the cutting conditions.

1.6 Expected Study

Machining AISI D2 hardened steels at the higher cutting speed will cause rapid chipping at the cutting edge which leads to catastrophic failure of the inserts. A higher cutting speed also results in rapid cratering and/or plastic deformation of the cutting edge. This is due to the heat generated which tends to be concentrated at the cutting edge closer to the nose of the inserts. The heat affected zone is very small when cutting AISI D2 hardened steel. The smaller heat affeced area produced is a result of the shorter chip/tool contact length. It is mainly for this reason that the cutting speeds are limited. The rapid tool failure and chipping at the cutting edge has resulted in poor surface finish of the machined surface. It has caused not only higher surface roughness values but also higher microhardness values and severe microstructure alteration.

AISI D2 hardened steels are generally used in mould and die industries, which are requires the great reliability, and therefore the tool life and surface integrity must be maintained. According to the several researchers, when machining any component it is essential to satisfy surface integrity requirements. However, during machining and grinding operations, the surface of AISI D2 hardened steel is easily damaged because of their poor machinability. In order to get better performance in machining of AISI D2 hardened steel, continously increasing demand for higher metalworking productivity is propelling the development of new manufacturing methods. Effective implementation of these new techniques, such as dry machining and hard machining, requires advanced carbide and cermet cutting tools. The performanace of the advanced cutting tool materials can be enhanced by better and more resistant coatings; development of these new cotings shows a clear trends towards complex multicomponent and multilayer configurations.

CHAPTER 2

MACHINABILITY AND SURFACE INTEGRITY

This chapter explains briefly about the wear and surface integrity in the metal cutting process. Special attention is directed toward the tool wear performance, coated carbide tool and surface integrity such as surface topography and metallurgy. Thus, the aim is to illustrated the fundamental concepts that would be used to explain the results of this study.

2.1 Tool Wear

Tool wear leads to tool failure. According to several authors, the failure of cutting tool occurs as premature tool failure (i.e tool breakage) and progressive tool wear. Figure 2.1 shows some types of failures and wear on cutting tools.

Generally, wear of cutting tools depends on tool material and geometry, workpiece materials, cutting parameters (i.e cutting speed, feed rate and depth of cut), cutting fluids and machine-tool characteristics.

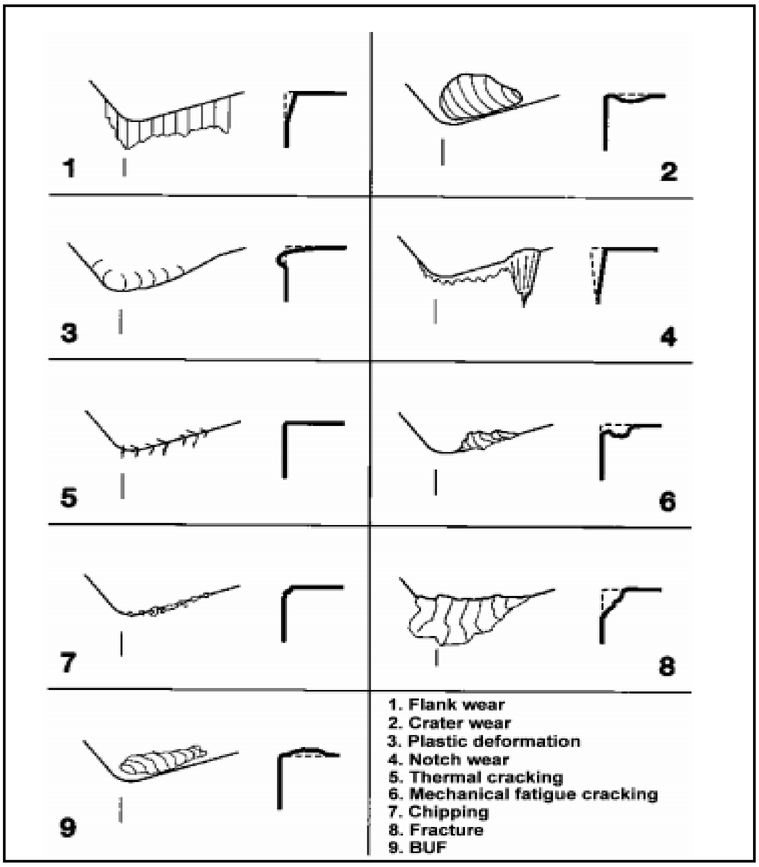


Figure 2.1: Types wear on cutting tools (Modern Metal Cutting, A practical Handbook, Sandvik Coromant).

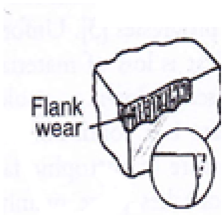
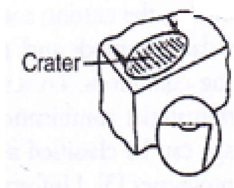
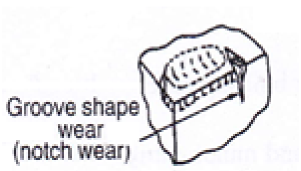
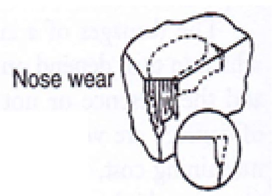
2.1.1 Tool Wear Types

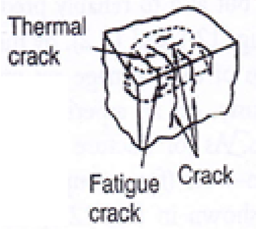
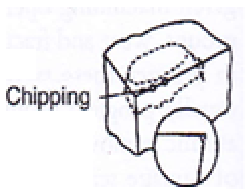
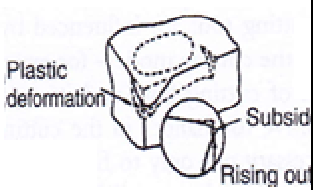
Normally, wear is an undesirable and to be minimized. Tool wear occurs when the machine surfaces rub together and a loss material from one or both surfaces results in a change in the desired geometry of the system(Shaw, 2005). Tool wear adversely affects tool life, the quality of the machined surface and its dimensional accuracy, and consequently, the economics of cutting operation.

Wear is a gradual process, much like the wear of the tip of an ordinary pencil. The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids, and the characteristics of the machine tool. Tool wear and the changes in the tool geometry during cutting manifest themselves in different ways, generally classified as flank wear, crater wear, nose wear, notching, plastic deformation of the tool tip, chipping, and gross fracture.

There are lot types of tool wear such as crater wear, flank wear, crater wear, notch wear, nose wear thermal cracks, chipping and plastic deformation. Table 2.1 illustrates some types of failures and wears on cutting tools.

Table 2.1: Tool failure mode and cause (Grzesik, 2008)

Failure	Cause
Flank wear 	Flank wear is observed on the flank or clearance flank as a result of abrasion by the hard constituents of the workpiece material. This failure mechanism is commonly observed during machining of steels.
Crater wear 	Crater wear observed on the rake face of cutting tools. It is primarily caused by chemical interaction between the rake face of a tool insert and the hot chip. Many thermally activated phenomena such as adhesion, diffusion or dissolution may be involved in the wear process.
Notch wear 	Notch wear is often attributed to the oxidation of the tool material from the sides of major and minor cutting edges, or to abrasion by the hard, saw-tooth outer edge of the chip. The workpiece materials tend to have high work-hardening and generate high tool-tip temperatures.
Nose wear 	Nose wear termed also tool-tip blunting, results from insufficient deformation resistance of a tool material in a given machining operation.
Thermal crack	Thermal cracks develops when the repeated heating and cooling associated with interrupted cutting (thermo-

	mechanical fatigue), creates high temperature gradients at the cutting edge. With prolonged time, lateral cracks may appear parallel to the cutting edge.
Chipping 	Chipping of the tool, involves removal of relative large discrete particles of tool material. Tool subjected to discontinuous cutting condition are particularly intended to chipping. Built-up edge formation also has a tendency to promote tool chipping. A built-up edge is never completely stable, but it periodically breaks off.
Plastic deformation 	Plastic deformation takes place as a result of combined high temperatures and high pressure on the cutting edge. High speeds and hard workpiece materials mean heat and compression. The typical bulging of the edge will lead to higher temperatures, geometry deformation, chip flow changes and so on until a critical stage is reached.

Wear on the flank of the cutting tool is caused by the friction between the newly machined workpiece surface and the contact area on the tool flank. Because of the rigidity of the workpiece, the worn area, refered to as the flank wear land, must be parallel to the resultant cutting direction. The width of the wear land is usually taken as a measure of the amount of wear and can be readily determined by means of toolmaker’s microscope (Boothroyd & Knight 2006). Tool wear leads to the tool failure. Generally, wear of the cutting tools depends on tool material and geometry, workpiece materials, cutting parameters such as cutting speed, feed rate and depth of cut. Other than that, wear of the cutting tool also depend cutting fluids and machine tool characteristics (Davim, 2010a).

Tool wear is caused by the continuous action of the chip removal process, and can be located in two tool zones.

- Wear on the rake face, which usually gives rise to a crater like pattern;
- Wear on the flank or clearance, due to the high friction of tool edge with the fresh machined surface. It looks like a typical abrasion pattern.

All tool wear types are described in the corresponding ISO standards. In milling, the standard ISO 8688-2 describes the main wear patterns and localization, shown in Figure 2.2.

- Flank wear (V_B): the loss of particles along the cutting edge, that is, in the intersection of the clearance faces of end-milling tools. Three different measurements are possible:

  -Uniform flank wear (V_{B1}): the mean wear along the axial depth of cut.

  -Non-uniform flank wear (V_{B2}): irregular wear in several zones of the cutting edge.

  -Localized flank wear (V_{B3}): wear usually found in specific points. One type is that placed just in the depth of cut line, the notch wear (V_{BN}), typical of materials susceptible to mechanical hardening.

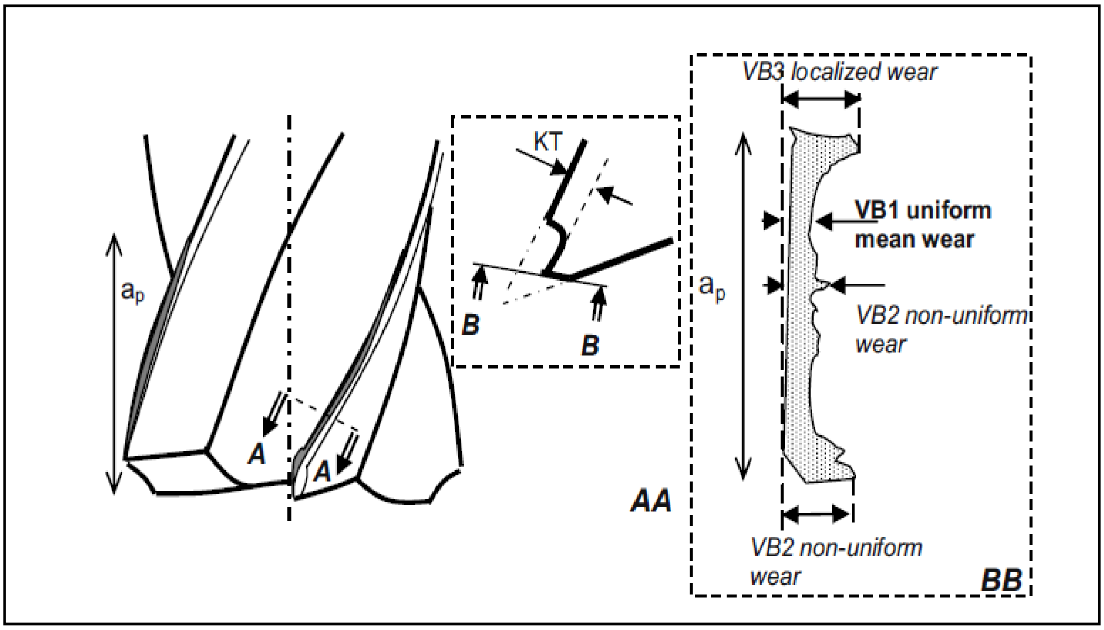


Figure 2.2:Wear of endmilling tools, from ISO 8688-2

- Wear on the rake face (KT): this is located on the internal flutes of endmills. The most typical is the crater wear (KT1), a progressive development of a crater oriented parallel to the major cutting edge.
- Chipping (CH): irregular flaking of the cutting edge, at random points (see Figure 2.2 and 2.3). it is very difficult to measure and prevent. It consists of small portions breaking away from the cutting edge due to the mechanical

impact and transient thermal stresses due to cycled heating and cooling in interrupted machining operations.

- Uniform chipping (CH1): small edge breaks of approximately equal size along the cutting edge engaged on material.
- Non- uniform chipping (CH2): random chipping located at some points of the cutting edge, but with no consistency from one edge to another.
- Flaking (FL): loss of tool fragment, especially observed in the case of coated tools.
- Catastrophic failure (CF): rapid degradation of tool and breakage. Mean flank wear size is the usual tool life criterion, due to it implying a significant variation of tool dimensions and therefore in the dimension of the machined part. Values of 0.3-0.5 mm are the maximum accepted, the former for finishing and the latter for roughing. Chipping greater than 0.5 mm is also a tool life criterion. In low machinability alloys several wear types appear simultaneously, adding and multiply their negative effects. (See Figure 2.4).

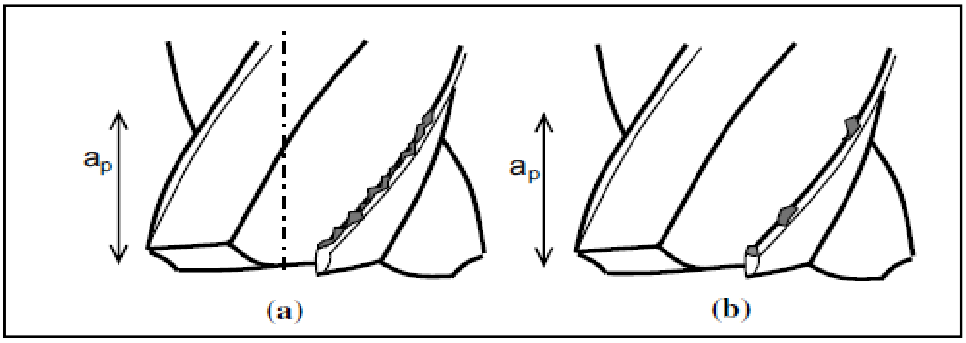


Figure 2.3:Chipping: (a) *CH*1, and (b) *CH*2

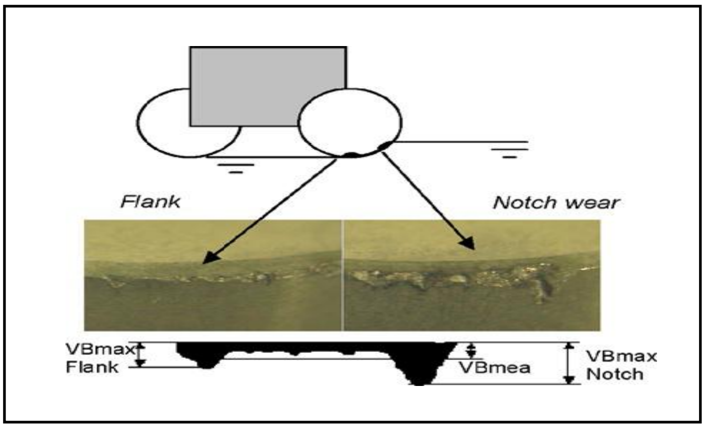


Figure 2.4:Two wear types when machining the material

2.1.2 Tool Wear Evolution

Tool wear curves illustrate the relationship between the amount of flank (rake) wear and the cutting time, $T_m$or the overall length of the cutting path,L. Figure 2.5 (a) shows the evolution of flank wear V_{Bmax}, as measured after a certainlength of cutting path. Normally, there are three distinctive regions that can be observed in such curves. The first region (labelled I in Figure 2.5(a)) is the region of primary or initial wear. The relatively high wear rate (an increase of tool wear per unit time or length of the cutting path) in the region is explained by accelerated wear of the tool layers damaged during manufacturing or re-sharpening. The second region (labelled II in Figure 2.5(a)) is the region of steady-state wear. This is the normal operating region for the cutting tool. The third region (labelled III in Figure 2.5(a)) is known as the tertiary or accelerated wear region. Accelerated tool wear in this region is usually accompanied by high cutting forces, temperatures and severe tool vibrations. Normally, the tool should not be used in this region.

In practice, the cutting speed is of prime concern in the consideration of tool wear. As such, tool wear curves are constructed for different cutting speeds keeping other machining parameters constant. In Figure 2.5(b), three characteristic tool wear curves (mean values) are shown for three different cutting speeds, V_1, V_2, and V_3. Because V_3 is greater than the other two, it corresponds to the fatest wear rate. When the amount of the wear reaches the permissible tool wear, $V_{Bc,}$ the tool is said to be worn out.

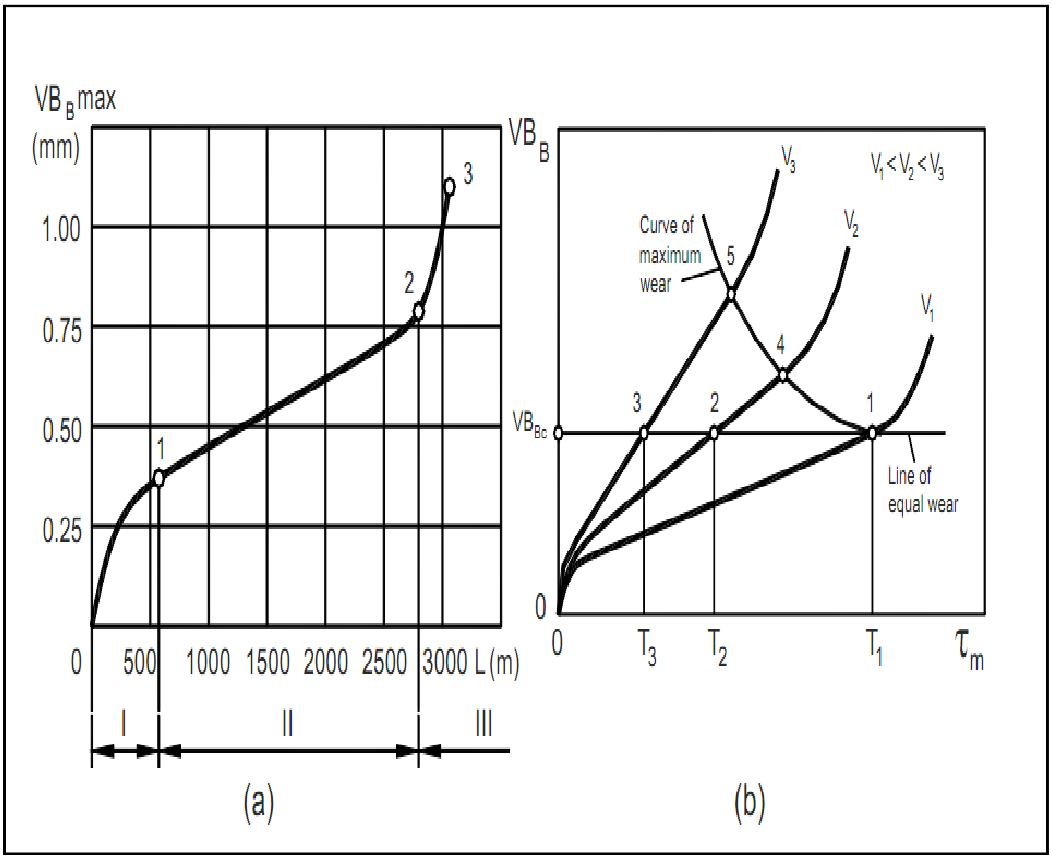


Figure 2.5: Wear curves: (a) normal wear curve, (b) evolution of flank wear land VB_B as a function of cutting time for different cutting speeds (Davim, 2008).

Typically VB_{Bc} is selected from the range 0.15-1.00 mm depending upon the type of machine operation, the condition of machine tool and the quality requirement of the operation. It is often selected on the grounds of process effiency and often called the criterion of the tool life. In Figure 2.5(b), T_1 is the tool life when the cutting speed V1 is used, T_2-when V2, and T_3-when V3 is the case. When the integrity of the machined surface permits, the curve of maximum wear instead of the line of equal wear should be used (Figure 2.5(b)). As such, the spread in tool life between lower and higher cutting speeds becomes less significant. As a result, a higher productivity rate can be achieved, which is particularly important when high speed CNC machine are used.

2.1.3 Mechanism of tool wear

The general mechanisms that cause tool wear, summarized in Figure 2.6, are: (1) abrasion, (2) diffusion, (3) oxidation, (4) fatigue and (5) adhesion. Most of these mechanisms are accelerated at higher cutting speed and consequently cutting temperatures (Davim, 2008). In the context of cutting tool wear three groups of causes can be qualitatively identified: mechanical, thermal and adhesive. Mechanical types of wear, which include abrasion, chipping, early gross fracture and mechanical fatigue, are basically independent temperature. Thermal causes with plastic deformation, thermal diffusion and oxygen corrosion as their typical forms, increase drastically at high temperatures and can accelerate the tool failure by easier material removal by abrasion or attrition.

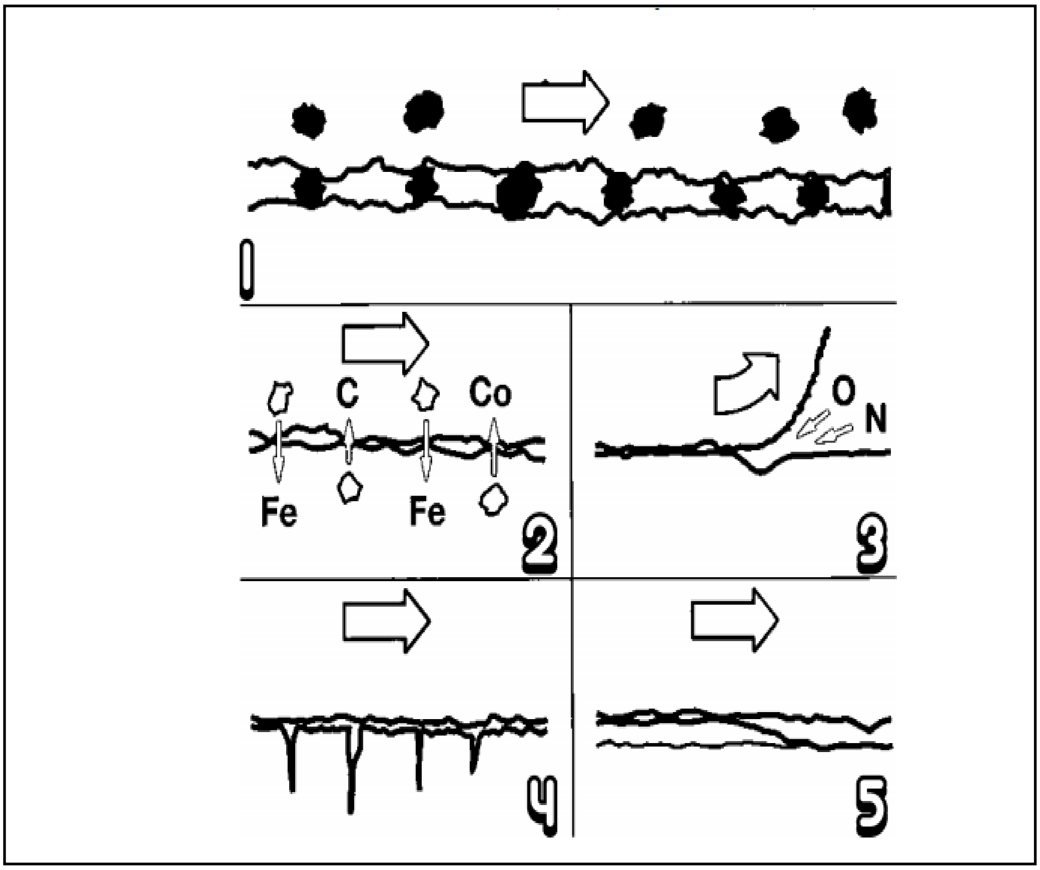


Figure 2.6:Evolution of the flank wear land VB_B as a function of cutting time for different cutting speeds (Abburi & Dixit, 2006).

Abrasion wear occurs when hard particles slide against cutting tool, primarily on the flank surface. The hard particles come from either work material's microstructure, or are broken away from the cutting edge by brittle fracture. Moreover, they can also result from a chemical reaction between the chips and cutting fluids when machining steels or cast irons alloyed with chromium. Abrasive wear reduces the harder the tool is relative to the particles in high temperatures, and generally depends on the machining distance. Adhesive or attrition wear are the most significant types of wear at lower cutting speeds. At high cutting speed, temperature-activated wear mechanisms including diffusion (solution wear), chemical wear (oxidation and corrosion wear), and thermal wear (superficial plastic deformation due to thermal softening effect) occur (Gzersik, 2008).

2.1.4 Tool life

Tool life is important during machining since considerable time is lost whenever a tool is replaced and reset. Tool life is the time a tool will cut satisfactorily and is expressed as the minutes between changes of the cutting tool. The process of wear and failures of cutting tools increases the surface roughness, and the accuracy of workpieces deteriorates.

Tool life is the length of actual machining time beginning at the moment when a tool is used and ending at the moment when the machining operation is stopped because of the poor performance of tool. Different criteria can be used to judge the moment at which the machining operation should be stopped. It is common consider the tool life as over when the tool wear reaches certain stage. The tool life is affected by several variables, the important ones being cutting speed, feed, coolant and radial depth of cut used.

There are two inter-related causes for tool wear that affects life of tool: mechanical abrasion and thermal erosion. Mechanical wear is dominant when low cutting speeds are used or when the work piece possesses high machinability. Thermal wear prevails when high cutting speeds are used with work piece having low machinability. Thermal wear is due to diffusion, oxidation, and the fact that the mechanical properties of the tool change as a result of the high temperature generated during the cutting operation. In practical machining operations, the wear of the face and flank of the cutting tool is not uniform along the active cutting edge; therefore it is necessary to specify the locations and degree of the wear when deciding the amount of wear allowable before regrinding the tool. When the work material and tool shape are chosen for a particular machining operation, the most significant factor affecting the tool life is the cutting speed (Boothroyd & Knight, 2006). Based on Equation 2.1, tool life to be measured as the total length of cut, *L* (the tool failure criteria is attained, VB= 0.3 mm) divided by feed rate, fr.

$$T_L = \frac{LOC}{f_r} \qquad \textbf{(2.1)}$$

Where:

T_L = Tool life (min)

LOC = Length of cut of material removed (mm)

F_r = Feed rate (mm/min)

Increasing material removal rate (MRR) such as higher cutting speed, feed, depth of cut and radial depth of cut to employ higher productivity. Equation 2.2 shows the relation of volume material removal (VMR) to material removal rate (MRR) and tool life (T_L) (Arsecularatne et al., 2006). Furthermore, Equation 2.3 shows the derivation of material removal rate (MRR).

$$VMR = MRR \times T_L \qquad \textbf{(2.2)}$$

Where:

VMR = Volume material removal (mm^3)

MRR = Material removal rate (mm^3/min)

T_L = Tool life (min)

$$\mathrm{MRR} = \mathrm{f_r} \times \mathrm{a_p} \times \mathrm{a_e} \tag{2.3}$$

Where:

MRR	=	Material removal rate (mm^3/min)
f_r	=	feed rate (mm/min)
a_p	=	depth of cut (mm)
a_e	=	radial depth of cut (mm)

2.2 Surface integrity

Surface integrity can be simplistically divided into two parts: first, the external aspects of topography, texture and surface finish and second the internal subsurface aspects of metallurgy, hardness, white layer formation and so on. The concept of surface integrity can be extended to any finishing operations to encompass six different groups of key factors: visual, dimensional, residual stress, tribological, metallurgical and other factors as illustrated in Figure 2.7. It should be noted that all the parameters involved in the hard milling process have a direct influence on the surface integrity of the part. On the other hand, the six groups of key factors presented in the figure are not random, but are rather deterministic outcome of the manufacturing process performed. In consequence, the determination of basic relationships between mechanical, thermal and chemical aspects of a hard milling process is crucial to successful improvement of a finishing process (Grzesik, 2008).

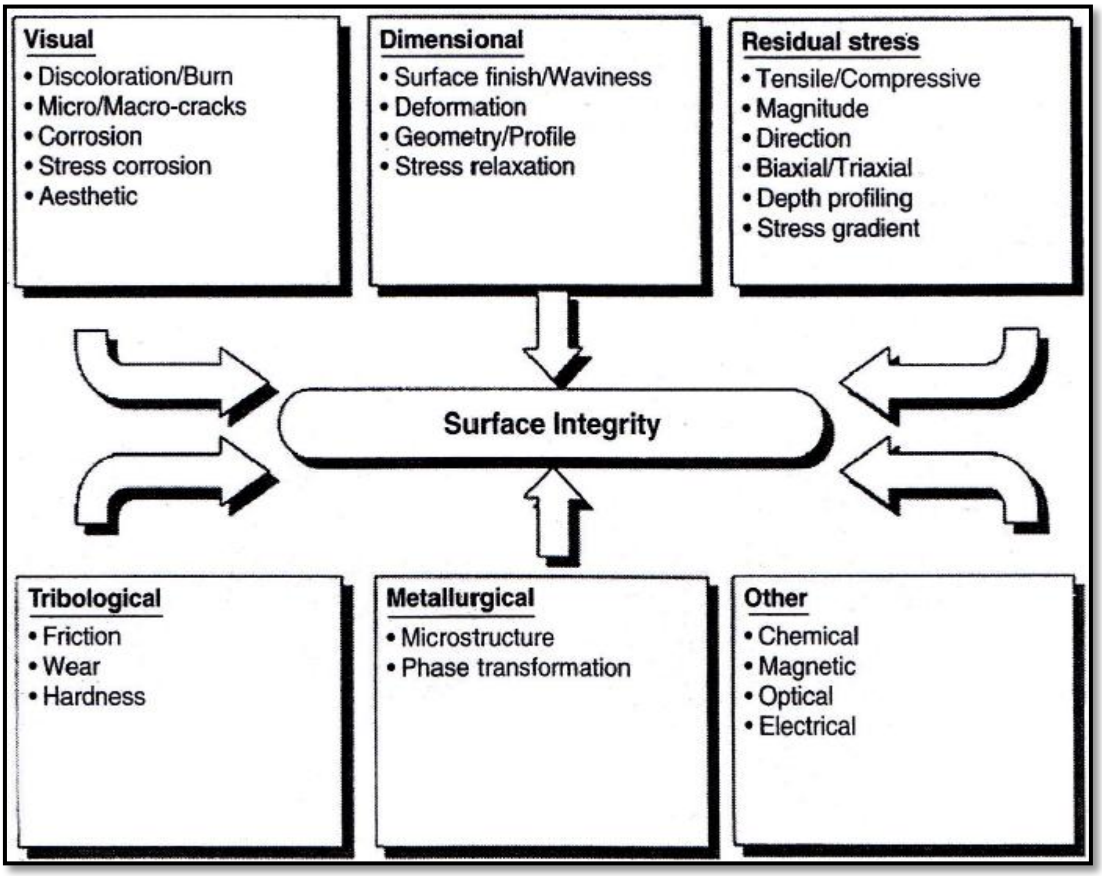


Figure 2.7: The six groups of key factors that define the surface integrity of a finished material (ASM, 1994)

2.2.1 Surface topography

Surface topography is a key factor affecting the function and reliability of a component. The characterization of surface topography has become increasingly important in many fields, such as materials, tribology and machine condition monitoring. Surface topography characterization is very important for a wide range of applications involved with the control of friction, lubrication, and wears (Yuan et al., 2008).

Moreover, engineered component or product must satisfy surface texture requirements (roughness and waviness) and traditionally, surface roughness (mainly arithmetic average, R_a), has been used as one of the principal method to assess quality (Axinte et al., 2002). Therefore, surface roughness has become the most surface topography evaluation in numerous of studies. Surface roughness is referring to high frequency irregularities on the surface caused by the interaction of the material microstructure and the cutting tool action. This relates directly to the manufacturing unit event (the inherent generating mechanisms) and describes the irregularities caused by each feed rate, abrasive grit, particle, or spark. In practice, roughness is never separate with waviness and form, but only superimposed on top of each other. So, these distinctions are therefore qualitative not quantitative. However, roughness results from the manufacturing process rather than machine tool, waviness is attributed to the individual machine and form errors are caused by mutual effects such as insufficient fixturing of the part, straightness errors of the guideways or thermal distortion of both the tool and the workpiece (Grzesik, 2008).

2.2.2 Surface metallurgy

During the machining operations, the workpiece material is exposed to thermal, mechanical, and chemical energy that can lead to strain aging and recrystallization of the material produce variety alterations of the subsurface layer illustrated schematically in Figure 2.8. Due to the strain aging process, the material might become harder but less ductile, and recrystallization might cause the material to become less hard but more ductile. These thermal (high temperature and rapid quenching) and mechanical (high stress and strain) effects are the main reasons for the microstructural alterations in the material, as well as phase transformations and plastic deformations (Yang et al., 1999). The primary important changes, strongly influenced by machining operations and their parameters, are: microstructure and hardness profile changes, as well as the introduced residual stresses. The principal causes of surface alterations are as follows:

i. The high temperature or high temperature gradients developed during the machining process.
ii. Plastic deformation and plastically deformed debris.
iii. Chemical reactions and subsequent absorption into the machined surface (Gzesik, 2008)

REFERENCES

Abburi, N.R and Dixit, U.S.(2006). A knowlegde-based system for the prediction of surface roughness in turning process. *Robot Comput-Integr Manuf.* 22:363-372.

Aihua, L., Deng, J., Haibing, C., Yangyang, C. and Jun, Z.(2012). Friction and wear properties of TiN, TiAlN, AlTiN and CrAlN PVD nitride coatings. *International Journal of Refractory Metals and Hard Materials*, 31, pp.82–88.

Alauddin, M., El Baradie, M.A. and Hashmi, M.S.J.(1995). Computer-aided analysis of a surface-roughness model for end milling. *Journal of Materials Processing Technology* 55(2): 123–127.

Altin, A., Nalbant, M. and Taskesen, A.(2007). The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools. *Materials & Design* 28(9): 2518–2522.

Amin, A.K.M.N, Rizal, M.A and Razman, M.(2001). Influence of chatter of VMC arising during end milling operation and cutting conditions on quality of machined surface. *IIUM Engineering Journal*.

Arsecularatne, J.A., Zhang, L.C., Montross, C. and Mathew, P.(2006). On machining of hardened AISI D2 steel with PCBN tools. *Journal of Materials Processing Technology* 171(2): 244–252.

Arunachalam, R.M., Mannan, M.A and Spowage, A.C.(2004). Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools. *International Journal of Machine Tools and Manufacture* 44(14): 1481–1491.

Aslan, E.(2005). Experimental investigation of cutting tool performance in high speed cutting of hardened X210Cr12 cold work tool steel (62 HRC). *Materials & Design.* 26: 21-27.

ASM Handbook. *Surface Engineering Volume 5*, Materials Park: ASM Int. 1994

Attanasio, A., Umbrello, D., Cappellini, C., Rotella, G. and M'Saoubi, R.(2012). Tool wear effects on white and dark layer formation in hard turning of AISI 52100 steel. *Wear* 286-287: 98–107.

Axinte, D.A, and Dewes, R.C.(2002). Surface integrity of hot work tool steel after high speed milling-experimental data and empirical models. *Journal of Materials Processing Technology* 127(3): 325–335 .

Baumann, G., Fecht, H.J. and Liebelt, S.(1996). Formation of white-etching layers on rail treads. *Wear*. 191: 133–140.

Boothroyd, G. and Knight W.A.(2006). *Fundamentals of Machining and Machine Tools*. Third Edition. Taylor & Francis.

Camuşcu, N. and Aslan, E.(2005). A comparative study on cutting tool performance in end milling of AISI D3 tool steel. *Journal of Materials Processing Technology* 170(1-2): 121–126.

Che-Haron, C.H., and Jawaid, A.(2005). The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V. *Journal of Materials Processing Technology* 166(2): 188–192.

Chen, L., Yong, D., Xiang, X., Chang, K and Ming J.W.(2011). *Int . Journal of Refractory Metals and Hard Materials Improved properties of Ti-Al-N coating by multilayer structure.RMHM* 29(6): 681–685.

Chen, M., Jing, L. and Li, X.(2007). The Surface Integrity in Machining Hardened Steel Skd11 for Die and Mold. *Machining Science and Technology* 11(1): 99–116.

Davim, J.P.and Astakhov, V.P.*Machining*, London: Springer. 2008.

Davim, J.P. *Machining of Hard Materials*, London: Springer. 2010a.

Davim, J.P. *Surface Integrity of Machining*, London: Springer.2010b.

Daymi, A, Boujelbene, M.., Amara, B., Bayraktar,E. and Katundi, D.(2011). Surface integrity in high speed end milling of titanium alloy Ti-6Al-4V. *Materials Science and Technology* 27(1): 387–394.

Derflinger, V., Brändle,H. and Zimmermann,H.(1999). New hard/lubricant coating for dry machining. *Surface and Coatings Technology* 113(3): 286–292.

El-Bestawi, M.A, El-Wardany, T.I , Yan, D and Tan, M.(1993). Performance of Whisker-Reinforced Ceramic Tools in Milling Nickel-Based Superalloy. *CIRP Annals - Manufacturing Technology* 42(1): 99–102.

El-Wardany, T.I., Kishawy, H.A. and Elbestawi, M.A.(2000). Surface Integrity of Die Material in High Speed Hard Machining, Part 1: Micrographical Analysis. *Transactions of the ASME*: 122.

Ezugwu, E.O, Bonney,J. and Yamane, Y.(2003). An overview of the machinability of aeroengine alloys. *Journal of Materials Processing Technology* 134(2): 233–253.

Ezugwu, E.O. and Tang, S.H. (1995). Surface abuse when machining cast iron (G-17) and nickel-base superalloy (Inconel 718) with ceramic tools. *Journal of Materials Processing Technology*. 55: 63–69.

Enzugwu, E.O., Wang, Z.M. & Okeke, C.I. (1999). Tool life and surface integrity when machining Inconel 718 with PVD- and CVD-coated tools. *Tribology transactions*. 42(2): 353-360

Fox-Rabinovich, G.S., Yamomoto,K., Veldhuis,S.C., Kovalev, A.I, and Dosbaeva, G.K.(2005). Tribological adaptability of TiAlCrN PVD coatings under high performance dry machining conditions. *Surface and Coatings Technology* 200(5-6): 1804–1813.

Ghani, J.A., Choudhury, I.A. and Masjuki, H.H.(2004). Wear mechanism of TiN coated carbide and uncoated cermets tools at high cutting speed applications. *Journal of Materials Processing Technology* 153-154: 1067–1073.

Ginting, A., and Nouari, M.(2009). Surface integrity of dry machined titanium alloys. *International Journal of Machine Tools and Manufacture* 49(3-4): 325–332.

Griffiths, B.(2001). Surface Integrity and Functional Performance. *Manufacturing Surface Technology*. London: Penton Press.

Grzesik, W.(2008). Influence of tool wear on surface roughness in hard turning using differently shaped ceramic tools. *Wear* 265(3-4): 327–335.

Grzesik,W.(2008). *Advanced Machining Processes of Metallic Materials: Theory, Modelling and Applications.* First edition, Oxford, UK: Elsevier.

Gopalsamy, B.M., Mondal, B., Ghosh, S., Arntz, K. and Klocke, F.(2010). Experimental investigation while hard machining of DIEVAR tool steel (50 HRC). *Int J Adv Manuf Technol.* 51(9-12): 853-869.

Gopalsamy, B.M., Mondal, B., Ghosh, S., Arntz, K. and Klocke, F.(2009). Investigations on hard machining of Impax Hi Hard tool steel. *Int J Material*. 2:145-165.

Guo, Y.B. and Janowski, G.M.(2004). Microstructural characterization of white layers formed during hard turning and grinding. *Transactions of NAMRI/SME*. Vol 32.

Guerville, L. and Vigneau, J.(2004). Influence of machining conditions on residual stresses, in: D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquerre, V. Zerrouki, J. Vigneau (Eds.). A review of developments towards dry and high speed machining of Inconel 718 alloy. *International Journal of Machine Tools and Manufacture.*44: 439–456.

Habeeb, H.H., Abou-El-Hossein, K.A, Mohammad, B. and Kadirgama, K.(2008). Effect of tool holder geometry and cutting condition when milling nickel-based alloy 242. *Journal of Materials Processing Technology* 201(1-3): 483–485.

Haron, C.H., Ginting, A. and Arshad, H.(2007). Performance of alloyed uncoated and CVD-coated carbide tools in dry milling of titanium alloy Ti-6242S. *Journal of Materials Processing Technology*, 185(1-3), pp.77–82.

Holmberg, K., Matthews, A. and Ronkainen, H.(1998). Coatings tribology—contact mechanisms and surface design. *Tribology International*, 31(1-3), pp.107–120.

Huang, D.H., Hsun Hsu, C., Yen-Chun, L., Chi-Lung, C., Ko-Wei, W. and Wei-Yu H.(2007). Thermal stability behaviors of Cr(N,O)/CrN double-layered coatings by TGA/DTA analysis. *Surface and Coatings Technology* 201(15): 6681–6685.

Hughes, J.I., Sharman, A.R.C. and Ridgway, K.(2004). Workpiece surface integrity and tool life issues when turning Inconel 718 nickel based superalloy. *Machining. Science Technology* 8 (3)399-414.

Iqbal, A., Ning, H., Khan, I., Liang, L. and Dar, N.U.(2008). Modeling the effects of cutting parameters in MQL-employed finish hard-milling process using D-optimal method. *Journal of Materials Processing Technology*. 199: 379–390.

Jaharah, A.G, Choudhury, I.A, Masjuki, H.H and Che Hassan, C.H.(2009). Surface Integrity of AISI H13 tool steel in end milling process. *Journal of Mechanical and Materials Engineering*., 4(1), pp.88–92.

Jasni, N.A.H., Lajis, M.A. and Kamdani, K.(2012). Tool Wear Performance of TiAlN/AlCrN Multilayer Coated Carbide Tool in Machining of AISI D2 Hardened Steel. *Advanced Materials Research* 488-489: 462–467.

Jawahir, I.S., Brinksmeier,E., M'Saoubi, R., Aspinwall, D.K., Outeiro, J.C., Meyer, D., Umbrello,D. and Jayal, A.D.(2011). Surface integrity in material removal processes: Recent advances. *CIRP Annals - Manufacturing Technology* 60(2): 603–626.

Jawaid, A., Sharif, S. and Koksal, S.(2000). Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy. *Journal of Materials Processing Technology* 99(1-3): 266–274.

Jeong, Y.K., Kang, M.C., Kwon, S.H., Kim, K.H., Kim, H.G. and Kim, J.S.(2009). Tool life of nanocomposite Ti–Al–Si–N coated end-mill by hybrid coating system in high speed machining of hardened AISI D2 steel. *Current Applied Physics* 9(1): S141–S144.

Kang, M.C., Kim, K.H., Shin, S.H, Jang, S.H., Park, J.H. and Kim, C.(2008). Effect of the minimum quantity lubrication in high-speed end-milling of AISI D2 cold-worked die steel (62 HRC) by coated carbide tools. *Surface and Coatings Technology* 202(22-23): 5621–5624.

Kadirgama, K., Abou-El-Hossein, K.A., Noor, M.M., Sharma, K.V. and Mohammad, B.(2011). Tool life and wear mechanism when machining Hastelloy C-22HS. *Wear*. 270: 258-268.

Kim, S.W., Lee, D.W., Kang, M.C. and Kim, J.S.(2001). Evaluation of machinability by cutting environments in high-speed milling of difficult-to-cut materials. *Journal of Materials Processing Technology*. 111: 256-260.

Kishawy, H.A, and Elbestawi, M.A.(2000). Surface Integrity of Die Material in High Speed Hard Machining , Part 1 : Micrographical Analysis." 122(November): 2–13.

Konig, W., Klinger, M., and Link, R. (1984). Machining Hard Materials with Geometrically Defined Cutting Edges. Field of Applications and Limitations, " *Annals of the CIRP*, Vol.(39) pp.(61-64).

Koshy, P., Dewes,R.C. and Aspinwall, D.K.(2002). High speed end milling of hardened AISI D2 tool steel (~58 HRC). *Journal of Materials Processing Technology* 127(2): 266–273.

Kovalev, A.I., Wainstein, D.L.,Rashkovskiy, A.Y, Fox-Rabinovich, G.S., Yamamoto, K., Veldhuis,S., Aguirre,M. and Beake, B.D.(2009). Impact of Al and Cr alloying in TiN-based PVD coatings on cutting performance during machining of hard to cut materials. *Vacuum* 84(1): 184–187.

Krain, H.R., Sharman, A.R.C and Ridgway, K.(2007). Optimisation of tool life and productivity when end milling Inconel 718TM. *Journal of Materials Processing Technology* 189(1-3): 153–161.

Lajis, M.A, Nurul Amin, A.K.M, Mustafizul Karim, A.N and Hafiz, A.M.K.(2009). Preheating in End Milling of AISI D2 Hardened Steel with coated Carbide Inserts. *Journal of Advanced Material Research*. 83-86: pp 56-66.

Lajis, M.A, and Turnad, L.G.(2008). Prediction of Tool Life in End Milling of Hardened Steel AISI D2. *Journal of Scientific Research*.21(4): 592–602.

Lajis, M.A., Nurul Amin, A.K.M. and Mustafizul Karim, A.N.(2012). Surface Integrity in Hot Machining of AISI D2 Hardened Steel. *Advanced Materials Research* 500: 44–50.

Li, A., Jun, Z., Hanbing, L., Zhiqiang, P. and Zeming, W.(2011). Progressive tool failure in high-speed dry milling of Ti-6Al-4V alloy with coated carbide tools. *International Journal of Advanced Manufacturing Technology* 58(5-8): 465–478.

Liu, Z.Q., Ai,X., Zhang, H., Wang, Z.T. and Wan, Y.(2002). Wear patterns and mechanisms of cutting tools in high-speed face milling. *Journal of Materials Processing Technology* 129(1-3): 222–226.

Liew, W.Y.H.(2010). Low-speed milling of stainless steel with TiAlN single-layer and TiAlN/AlCrN nano-multilayer coated carbide tools under different lubrication conditions. *Wear* 269(7-8): 617–631.

Mo, J.L. and Zhu, M.H.(2009). Tribological oxidation behaviour of PVD hard coatings. *Tribology International*, 42(11-12), pp.1758–1764.

Modern Metal Cutting, A practical Handbook, Sandvik Coromant.

Okada, M., Akira, H., Ryutaro, T.and Takashi, U.(2011). Cutting performance of PVD-coated carbide and CBN tools in hardmilling.” *International Journal of Machine Tools and Manufacture* 51(2): 127–132.

Poomari, A. (2012). Study on Tool Life of Coated , Cryogenically Treated and Coated and Plain Cermet Cutting Tools While Machining Steel. *Journal of Scientific Research*. 85(3): 394–407.

Prengel, H.G., Jindal, P.C., Wendt, K.H., Santhanam, A.T and Hegde, P.L.(2001). A new class of high performance PVD coatings for carbide cutting tools. *Elsevier Surface and Coatings Technology*.

Pawade, R.S., S.Joshi, S., Brahmankar, P.K. and Rahman, M.(2007). An investigation of cutting forces and surface damage in high-speed turning of Inconel 718. 193: 139–146.

Prengel, H.G., Santhanamb, A.T, Penichb, R.M., Jindalb, P.C. and Wendt, K.H. (1997). Advanced PVD-TiAlN coatings on carbide and cermet cutting tools. *Elsevier Surface and Coatings Technology*.95: 597–602.

Prengel, H.G., Jindal, P.C., Wendt, K.H., Santhanam, A.T., Hegde, P.L. and Penich, R.M.(2001). A new class of high performance PVD coatings for carbide cutting tools. *Elsevier Surface and Coatings Technology*.139: 25–34.

Qin, F., Chou, Y.K., Nolen, D., Thompson, R.G.(2009). Coating thickness effects on diamond coated cutting tools. *Surface and Coatings Technology*, 204(6-7), pp.1056–1060.

Rababa, Khalid, S. and Ahmad, A.(2012). The Effect of Austenite Temperature on the Microstructure , Mechanical Behavior , Hardness , and Impact Toughness of AISI D2 Tool Steel. *International Journal of Engineering Research and Application*.2(3): 2890–2896.

Rahim, E.A, and Sasahara, H. (2011). A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. *Tribology International* 44(3): 309–317.

Rigney, D.A. and Glaeser, W.A. (1978). The significance of near surface microstructure in the wear process, *Wear*, 46: 241–250.

Sahin, Y. (2009). Comparison of tool life between ceramic and cubic boron nitride (CBN) cutting tools when machining hardened steels. *Journal of Materials Processing Technology*, 209(7), pp.3478–3489.

Sandvik Coromant CoroMill 390 catalogue at www.thomasskinner.com.

Sharif, S., and Rahim, E.A. (2007). Performance of coated- and uncoated-carbide tools when drilling titanium alloy—Ti–6Al4V. *Journal of Materials Processing Technology* 185(1-3): 72–76.

Shaw, M.C. *Metal Cutting Principles.* Clarendon Press,Oxford University Press,1984,p.324.

Sun, J. and Guo, Y.B. (2009). A comprehensive experimental study on surface integrity by end milling Ti–6Al–4V. *Journal of Materials Processing Technology* 209(8): 4036–4042.

Siller, H.R., Vila, C., Rodríguez, C.A. and Abellán, J.B. (2009). Study of face milling of hardened AISI D3 steel with a special design of carbide tools. *Int J Adv Manuf Technol*. 40:12–25.

Soković, M., Kopač, J., Dobrzański, L.A and Adamiak, M.(2004). Wear of PVD-coated solid carbide end mills in dry high-speed cutting. *Journal of Materials Processing Technology* 157-158: 422–426.

Saedon, J.B., Soo, S.L., Aspinwall, D.K., Barnacle, A. and Saad, N.H. (2012). Prediction and Optimization of Tool Life in Micromilling AISI D2 (~62 HRC) Hardened Steel. *Procedia Engineering* 41(Iris): 1674–1683.

Soković, M. (2007). Quality management in development of hard coatings on cutting tools. *Journal of Achievements in Materials and Manufacturing Engineering.* 24(1): 421–429.

Tonshoff, K., Karpuschewski, B., Mohlfeld, A., Leyendecker, T., Erkens, G. and Wenke, R. (1998). Performance of oxygen-rich TiALON coatings in dry cutting applications. *Elsevier Surface and Coatings Technology*. 109: 535–542.

Trent, E.M. and Wright, P.K. (2000). *Metal Cutting*. Fourth Edition. Newton: Butterworth-Heinemann.

Tuffy, K., Byrne, G. and Dowling, D .(2000). Determination of the optimum TiN coating thickness on WC inserts for machining carbon steels. *Journal of Materials Processing Technology.* 156: 1861–1866.

Torrance, A.A. and Cameron, A. (1974). Surface transformations in scraffing. *Wear*. 28: 299–311.

Uddeholm tool steels, publications “Steels for Cold Work Tooling”.

Ulutan, Durul, and Tugrul Ozel. (2011). Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools and Manufacture* 51(3): 250–280.

Umbrello, D., and Filice, L. (2009). Improving surface integrity in orthogonal machining of hardened AISI 52100 steel by modeling white and dark layers formation. *CIRP Annals - Manufacturing Technology* 58(1): 73–76.

Veprek, S. and Veprek-heijman, M.J.G.(2008). Industrial applications of superhard nanocomposite coatings. *Surface & Coatings Technology* , 202, pp.5063–5073

Vivancos, J., Luis, C.J., Costa, L. and Ortíz, J.A.(2004). Optimal machining parameters selection in high speed milling of hardened steels for injection moulds. *Journal of Materials Processing Technology* 155-156: 1505–1512.

Warren, A.W. and Guo Y.B.(2006). On the clarification of surface hardening by hard turning and grinding. Trans.NAMRI/Sme 34,309-316.

Yahya, Z. (2005). High-speed end-milling of AISI 304 stainless steels using new geometrically developed carbide inserts. *Journal of Materials Processing Technology* 163: 596–602.

Yang, X. and Liu, C.R. (1999). Machining titanium and its alloys. *Machining Science and Technology*. 3(1): 107–139.

Yuan, C.Q., Peng, Z., Yan, X.P. and Zhou, X.C. (2008).Surface roughness evolutions in sliding wear process. *Wear*.265: 341–348.

Zhang, B., Shen, W., Liu, Y., Tang, X. and Wang, Y. (1997). Microstructures of surface white layer and internal white adiabatic shear band. *Wear*. 211: 164–168.