CUTTING TOOL EDGE DESIGN

FOR LONGER TOOL LIFE

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By

DIANA BANCIU, B.E.

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AUTHOR: Diana Banciu, B.E. (University of Brasov)

SUPERVISOR: Dr. Stephen Veldhuis

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Abstract

In metal cutting, the effects of edge preparation and tool wear are considered most critical, as they directly determine tool life, surface finish and properties of the subsurface layer.

Proper selection and application of cutting tool edge preparation is one of the basic factors for a successfully manufactured and correctly performing cutting tool. In this regard, the use of cutting tools with honed and chamfered edges is ever increasing.

This thesis develops a procedure to design a subtle feature on the cutting edge of an insert, which mimics as closely as possible the natural wear that occurs in the initial stage of wear and arrive at a geometry that is known to lead to stable wear. In this case the geometry that would naturally occur is established with minimal subsurface damage, thus leading to a longer tool life. Turning test data collected showed that using a 50μm chamfer on the rake face of the insert could minimize tool flank wear. By applying a special coating on this newly created geometry, a significant increase in the stable stage of wear and an overall improvement in performance and productivity have been observed. The analysis of chip morphology showed an improved behavior in the case of chamfered coated inserts.

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1. INTRODUCTION

1.1 Motivation

Tool life is one of the most important economic considerations in metal cutting. In roughing operations, the cutting speeds, feeds and tool geometry are typically chosen to give an economic tool life. Conditions giving a very short tool life will be uneconomical since tool grinding and tool changing, re-grinding or replacement costs will be high. On the other hand, the use of conservative speeds and feeds to give a longer tool life will be uneconomical because of the low production rate. Any tool or work material improvements that increase tool life and productivity will be beneficial.

A major issues associated with tool wear is the degradation in the shape and efficiency of the cutting edge. This directly influences the surface quality and dimensional accuracy of the final product.

The motivation for this work is to improve tool life and improve productivity as well as final part quality. A number of approaches for improving tool life are being used. These include better tool substrate selection, the use of coatings as well as advanced tool geometry designs. Considerable work has gone into tool substrate and coating selection. At this stage there is little guidance for cutter edge design.

1.2 Research Objective

Predicting the change in cutting tool performance as it wears would ultimately allow one to predict tool life, the point at which the cutting tool's performance is no longer satisfactory. In order to achieve this goal the first step was to understand how process mechanics are affected by the comprehensive edge condition – flank wear combined with edge preparation.

The overall objective of this research is to develop a procedure to design a subtle feature on the cutting edge of a cutting tool insert. This feature is designed to mimic the shape of the cutting edge formed during natural wear at point where the tool wear transitions from the initial wear region to the more stable wear region.

The specific tasks were to perform cutting tests, measure the tool wear and study the shape of the cutting edge after different lengths of cut, extract the resulting shape of the cutting edge and model it as a chamfer, produce a new tool with that chamfer and repeat the cutting tests capturing the tool wear. This process for designing the cutting edge is expected to result in a longer tool life.

1.3 Thesis Outline

This thesis is organized as follows:

- Chapter two reviews the literature on aspects regarding tool wear, tool life, coating materials and processes. This chapter introduces the concept of "edge preparation" in metal cutting and surveys the work that has been done regarding the use of various edge designs as a means of improving tool life.

- Chapter three presents the experimental plan and the results obtained for the cutting tests performed with high-speed steel and carbide inserts, with and without coating. A new edge design has been developed and the comparative results of the cutting tests are presented and discussed.
- Chapter four summarizes the conclusions of this research and recommends areas for future work.

2. Literature Review

This chapter presents material related to tool wear and tool life in metal cutting, followed by some considerations on coatings and their importance in enhancing tool performance and process productivity. The concept of "edge preparation" is introduced and a literature review of previous research regarding tool life optimization is presented.

2.1 Tool Wear in Metal Cutting

According to ISO 8688-1 International Standard [1989] tool wear is defined as "the change in shape of the cutting part of a tool from its original shape, resulting from the progressive loss of tool material during cutting". Wear in cutting tools is a regular event, which cannot be avoided and is a function of time.

2.1.1 Types of Tool Wear

There are seven types of tool wear: flank wear, crater wear, chipping, cracking, flaking, plastic deformation and catastrophic failure. Built-up edge is another phenomenon related to tool wear. Figure 2.1 [12] illustrates the main types of wear observed in single point cutting tools.

a.) Flank Wear results in the formation of a wear land on the flank face of the cutter, which is the part of the tool that undergoes the complete effect of the feed. This type of wear exists in all machining operations and is caused mainly by tool abrasion and adhesion. It affects the cutting forces and hence the surface finish and dimensional accuracy of the workpiece. Flank wear can be measured by using the average and maximum wear land size VB and VB_{max}.

Notch wear is a special type of combined flank and rake face wear which may occur on the leading edge or on the trailing edge. Its position is typically associated with the depth of cut. Notch wear that appears on the leading edge is caused by the chip hitting the edge and chipping it. The notch wear on the trailing edge occurs when the hard surface of the job abrades the trailing edge more than the cutting edge. This wear mechanism is a combination of adhesion and oxidation.

b.) Crater Wear occurs on the rake face and weakens the strength of the cutting edge. There are two main underlying causes of crater wear. One is the chip flowing on the rake face of the tool and abrading the tool material. Another is the diffusion of elements from the tool due to the high temperatures typically found in the tool chip interface. Severe crater wear changes the geometry of the edge and usually results in catastrophic failure of the tool due to the degradation in the support of the cutting edge.

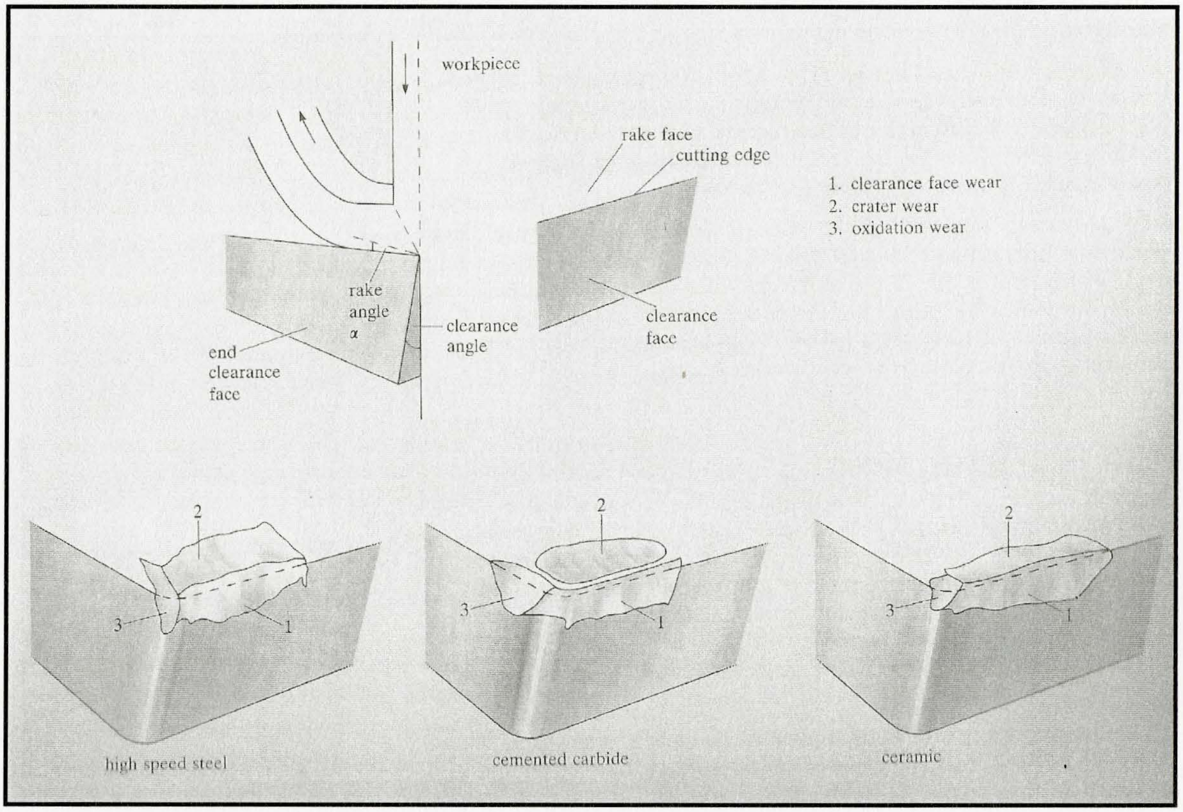


Figure 2.1 Types of wear observed in single point cutting tools [12].

c.) Chipping involves removal of relatively large, discrete particles of tool material and occurs when the cutting edge does not have enough strength to take the cutting loads which may be tensile on the edge.

Built-up edge occurs when portions of the chip adhere to the tool thus changing the cutting edge geometry. This will impact the cutting force and temperatures in the cutting zone. A built-up edge is never completely stable and breaks off periodically. Each time some of the built-up material is removed it may take with it some of the tool edge material.

d.) Cracking can be caused by fatigue wear due to a thermal cyclic load (thermal cracking) or by excessive shocks (mechanical fatigue cracking). Thermal cracks occur usually in interrupted cuts, in operations where insufficient coolant is used, or when the chip cross-sections vary. Mechanical cracks are parallel to the edge and take place when the loads on the tool are varying.

e.) Flaking is defined as a loss of tool fragments in the form of flakes from the tool surfaces. It is mostly observed when coated tool inserts are used, but may also occur with other tool materials.

f.) Plastic deformation takes place as a result of combined high temperatures and high pressures on the cutting edge. The tool material cannot withstand the heat and compressive load caused by the process speeds and feeds and hard workpiece materials, and thus deforms plastically.

g.) Catastrophic failure is the final result of tool wear, meaning the complete removal of the cutting point.

The effectiveness of a metal cutting process (i.e., machinability) is normally evaluated in four aspects: cutting forces, chip controllability, surface quality, as well as tool wear and tool life performance.

Therefore, it is especially important to understand the tool wear behavior for the given combination of the workpiece and tool and then develop the modeling capability to predict the tool life under different cutting conditions. Figure 2.2[57] summarizes various process variables in the tool wear system during finish machining.

The elements affecting the wear of a cutting tool can be classified into four groups:

Workpiece material: its mechanical and thermal properties, microstructure and hardness determine cutting forces and energy for the applied cutting conditions.

Interface conditions: coolants are used to reduce cutting temperatures and tool wear.

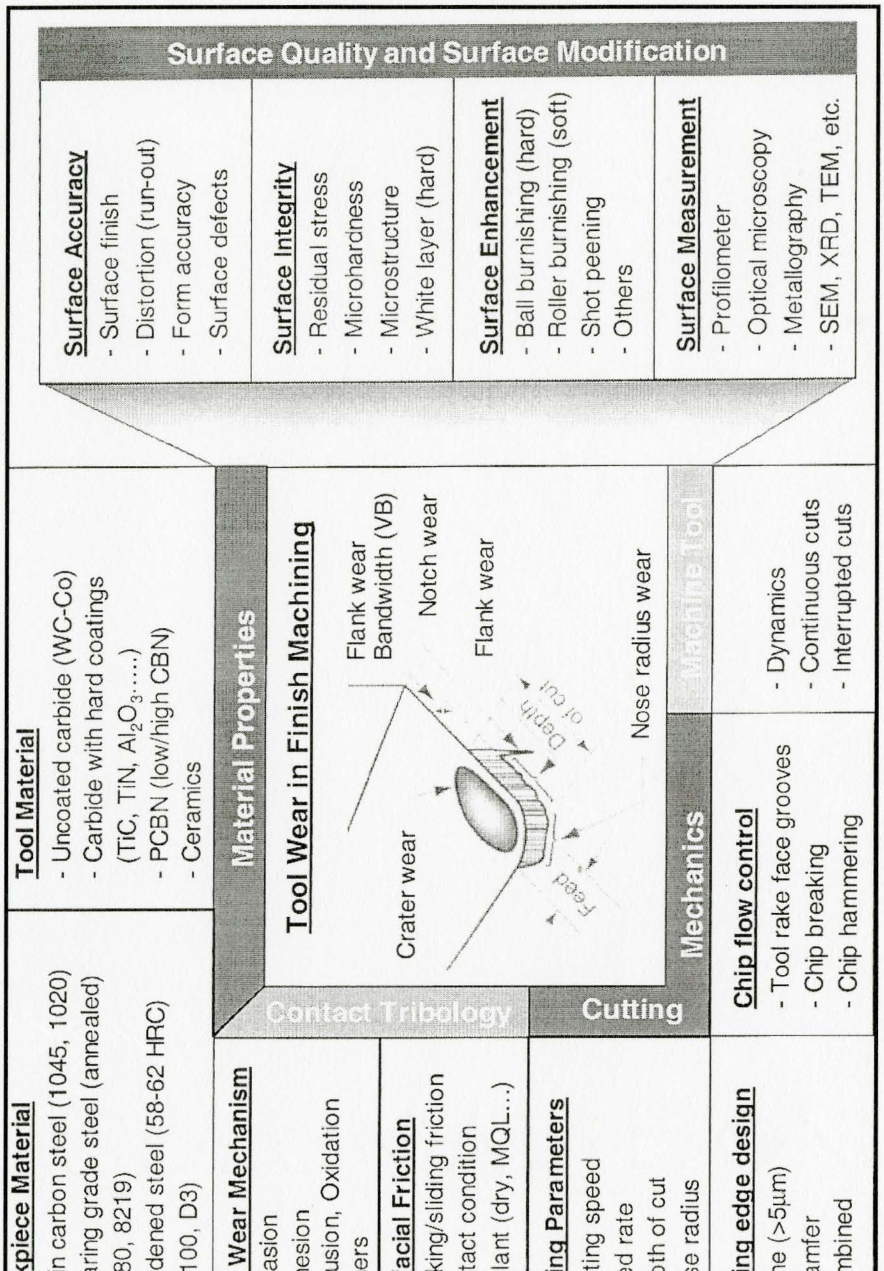


Figure 2.2 Process variables contributing to the tool wear formation and the final properties of the machined surface [57]

Cutting tool: the optimal performance of a cutting tool is determined by the combination of tool parameters such as tool material, coatings and geometric design (edge preparation, rake angle) and cutting conditions (speed, feed rate, depth of cut).

Dynamic characteristics of the machine tool: unstable cutting processes with excessive vibrations (chatter) result in a fluctuating overload on the cutting tool and leads to the premature failure of the cutting edge (chipping).

2.1.2 Tool Wear Phenomena (Mechanisms)

Tool wear is affected by high temperatures, high contact pressure, high relative sliding velocities and the presence of cutting fluid in the tool-chip and tool-workpiece interfaces. The main wear mechanisms identified in the literature are: abrasion, adhesion, diffusion and fatigue (Figure 2.3).

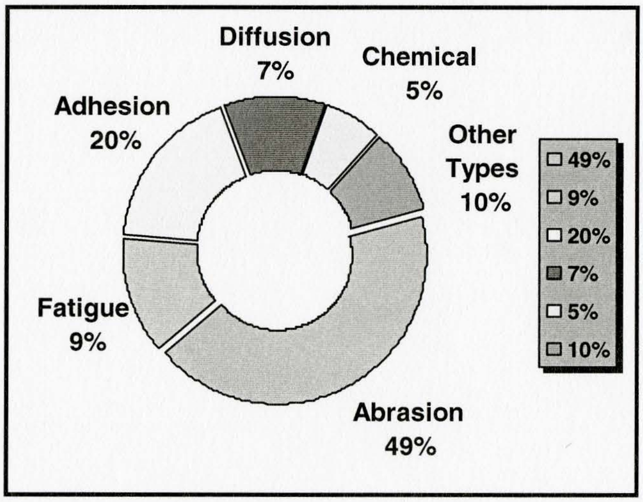


Figure 2.3 Percentages of the types of wear from the total wear [12]

Abrasive wear is mainly caused by the friction between the chip and the active surfaces of the tool. This is a mechanical wear process, and it is the main cause of tool wear at low cutting speeds.

Adhesive wear is caused by the formation of welded junctions between the fresh surface of the chip and the rake face of the tool, and subsequent destruction of these.

Diffusion wear is caused by the transport of electrons due to the thermo-couple formed by the tool-workpiece and influenced by the temperature developed in the cutting process.

Chemical wear is a corrosive wear mechanism due to chemical attack of the surface.

Fatigue wear is often a thermo-mechanical combination. Temperature fluctuations and the loading and unloading of cutting forces can lead to cutting edge cracking and breaking.

Oxidation wear is caused by high temperatures and the presence of air in the cutting zone.

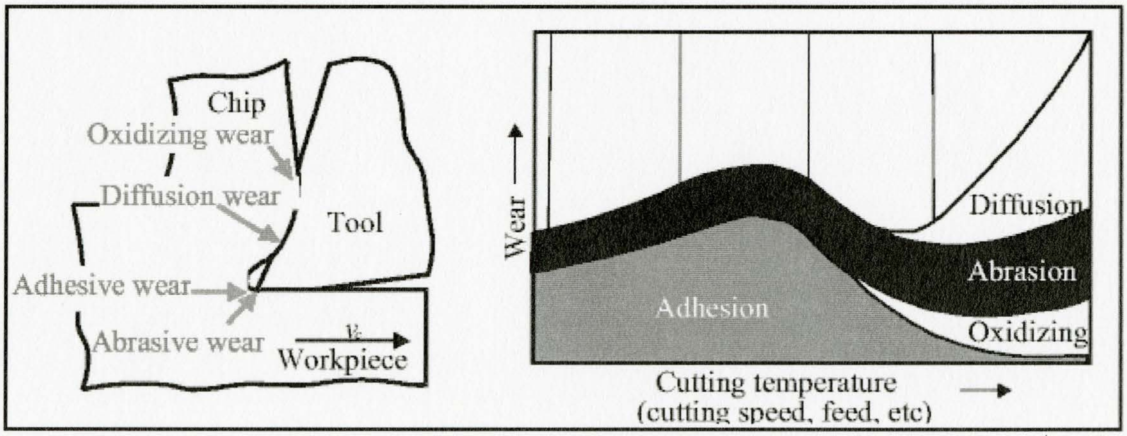


Figure 2.4 Tool wear mechanism [12]

Under different cutting conditions, dominating wear mechanisms are different. As shown in Figure 2.4[12], for a certain combination of cutting tool and workpiece, the dominating wear mechanisms vary with cutting temperature. According to the temperature distribution on the tool face, it is assumed that crater wear is mainly caused by abrasive wear, diffusion wear and oxidation wear. On the other hand, flank wear is mainly dominated by abrasive wear due to the presence of hard secondary phases in the workpiece material.

2.2 Tool Life in Metal Cutting

Tool life is defined as the cutting time required to reach a specific tool life criterion. A tool life criterion is usually defined as a predetermined threshold value of tool wear or the occurrence of a certain phenomenon [13]. It could also be a certain surface quality requirement and the tool is discarded when the surface quality deteriorates to a set point, a Ra number or some other indication of surface or subsurface quality.

Tool wear is typically quantified as follows:

- Crater depth KT (inches or mm);
- Crater ratio K = KT/KM (dimensionless);
- Average flank wear land VB_{av};
- Maximum flank wear land VB_{max}.

As shown in Figure 2.5, the width of the flank wear land at the tool corner (zone C) is designated *VC*. At the opposite end of the active cutting edge (zone N), a groove or wear notch often forms since in this region, the work material tends to be work hardened from the previous processing operation. The width of the wear land at the wear notch is *VN*.

Normally, the criteria recommended by ISO for HSS and carbide tools is catastrophic failure or VB_{av}=0.3mm, or VB_{max} if the flank is irregularly worn, scratched, chipped, or badly grooved in zone B (Figure 2.5).

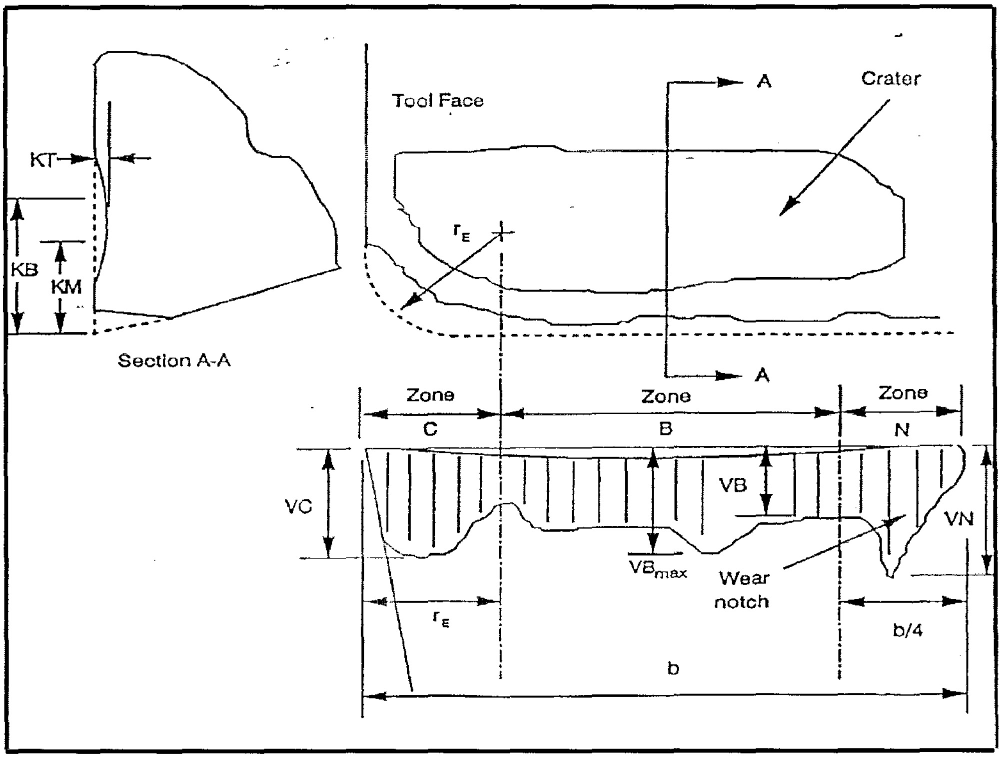


Figure 2.5 Tool life criteria [13]

Table 2.1 Characteristic values for the tool life of different tool materials.

cutting material	measurand			recommended max. values
high speed steel	wear	VB	mm	0.2 to 1.0
	land	VB_{max}	mm	0.35 to 1.0
	crater depth	KT	mm	0.1 to 0.3
cemented carbide	wear	VB	mm	0.3 to 0.5
	land	VB_{max}	mm	0.5 to 0.7
	crater depth	KT	mm	0.1 to 0.2
ceramic	wear land	VB	mm	0.15 to 0.3
	crater depth	KT	mm	0.1

A typical graph of the progress of flank wear land width VB with time is shown in Figure 2.6. The graph can be divided into three regions:

Region I (Initial wear): The sharp cutting edge is quickly broken down, due to micro-cracking, surface oxidation and a carbon loss layer. The high contact pressure on a small contact area causes a high wear rate for the new cutting edge;

Region II (Steady wear): After the initial rounding of the cutting edge, the micro-roughness improves and the wear progresses at a uniform rate;

Region III (Catastrophic wear): Wear progresses at a fast rate. When the wear size increases to a critical value, the surface roughness of the machined surface decreases, cutting force and temperature increase rapidly and the tool loses its cutting ability. In practice, tool regrind should be performed before region III is reached.

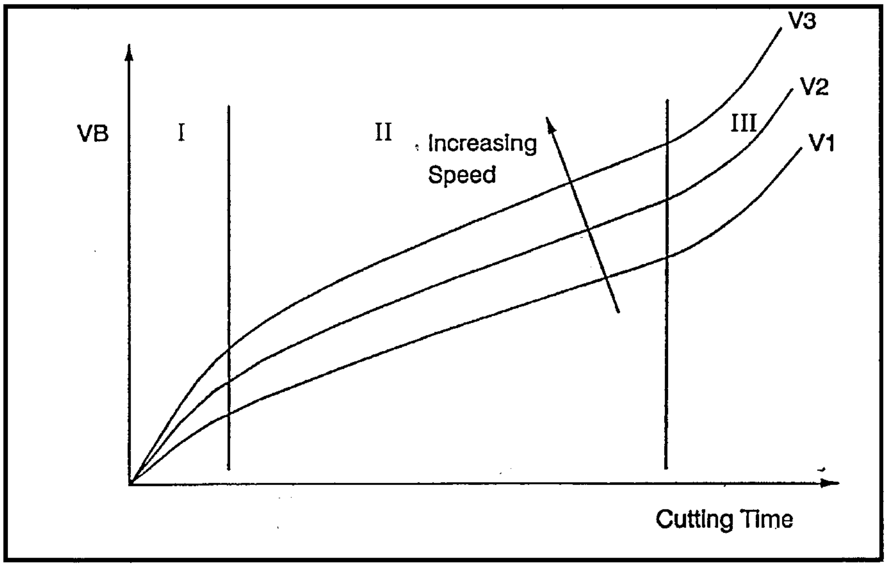


Figure 2.6 Development of flank wear versus time

Tool life is affected by many variables related to the material being used, the machining parameters (cutting speed, feed, depth of cut, tool material, tool form), and the machining conditions (how the tool engages and disengages from the work, condition of the machine etc). Some other conditions are the temperature of the work and tool, the ability of the system to dissipate heat, the chip geometry, the forces required to remove the chip and the feed rate [44].

2.3 Cutting Tool Materials

Tool materials are required to work in environments involving both high temperatures and stresses. Consequently, cutting tool materials must possess such properties as:

- **Hardness,** particularly at elevated temperature,
- **Toughness,** so that sudden loading of the tool as might occur in interrupted cutting operations does not chip or fracture the tool,
- **Chemical inertness** with respect to the workpiece,
- **Wear resistance,** to maximize the lifetime of the tool.

The first three are satisfied by selecting the correct material for a given cutting operation. However, the high temperatures and stresses produced when cutting at high speeds, employed to decrease the cycle time for a given cutting operation, means that wear is inevitable. The limitation to this strategy has long been tool material performance.

2.3.1 High Speed Steels

These are high alloy steels and still remain popular tool materials for specific applications requiring high toughness. High speed steels (HSS) were initially developed in the early 1900s by Mushet, who worked to overcome the problem of the loss of hardness in ordinary steels operating at higher temperatures.

The introduction of high-speed steel permitted the operation of machining processes at twice or three times the speeds allowable with carbon steel, thus doubling the capacities of the world's machine shops.

The term 'high speed steel' was derived from the fact that it is capable of cutting metal at a much higher rate than carbon tool steel and continues to cut and retain its hardness even when the point of the tool is heated to a low red temperature. Tungsten is the major alloying element but it is also combined with molybdenum, vanadium and cobalt in varying amounts. They can be used for machining most materials including wood, plastic, aluminum, brass and steel.

These tools will retain their hardness at temperatures up to 1000° F (588°C). For this reason, depth of cut, cutting speed and feed rates are important. The big advantage of high-speed steel tools is the ease with which they can be sharpened. A standard aluminum oxide grinding wheel can be used. Once shaped and sharpened, they will retain their cutting edge for relatively long periods of time.

There are two basic types of high speed steel: ***T*** type, which contains tungsten and ***M*** type, which contains molybdenum as the main carbide forming element. As seen from Table 1.2 [12] the steels in the T series contain 12-20wt% tungsten with chromium, vanadium and cobalt as the alloying elements whilst those in the M series contain 5-10wt% molybdenum with chromium, vanadium, tungsten and cobalt. The cost of all these steels is directly related to the amount of alloying element present.

Table 2.2 Typical HSS compositions

Type	Alloying elements/wt%					
	C	W	Mo	Cr	V	Co
M2	0.85	6.0	5.0	4.0	2.0	—
M42	1.1	1.5	9.5	4.0	1.2	8.0
T2	0.85	18.0	—	4.0	2.0	—
T15	1.5	12.0	—	4.0	5.0	5.0

High speed steels contain large amounts of carbide-forming elements, which serve not only to furnish wear-resisting carbides but also to promote secondary hardening and thereby to increase resistance to softening at elevated temperatures [32]. In order to achieve these properties, high-speed steels require a special heat treatment. This procedure consists of heating the material to a high temperature of 1175° to 1315°C to obtain a solution with a substantial percentage of the alloy carbides, followed by quenching to room temperature, and then tempering at 535° to 620°C and again cooling to room temperature.

Although high speed steel tools cannot be used at very high cutting speeds, they are relatively cheap and for many applications that require toughness and flexibility, they are still widely used for the manufacture of taps, dies, twist drills, reamers, saw blades and other cutting tools. In recent years, the development of coating technologies for HSS tools has dramatically increased their use for various applications.

2.3.2 Cemented Carbides

The improved performance of high speed steels is due to the introduction of large volume fractions of hard stable carbides. An extension to this approach is to bind carbides together with a metal by powder processing, to produce the materials known as cemented carbides, in which particles of hard carbides are bonded together with metal. Such a tool material would have the hardness given by the carbides and the toughness conferred by the metal binder. This is the basis of cemented carbide tools, which were introduced in the 1930s. The most successful and cost effective binder was found to be cobalt.

Some properties of cemented carbides may be seen in Table 2.3 [12]. Cemented carbide tools can withstand much higher operating temperatures and can thus be used at much higher cutting speeds.

Table 2.3 Properties of carbides

Carbide	Melting temperature T_m/K	Hardness H_V
TiC	3338	3200
NbC	3773	2400
WC	3073	2000

2.4 Coatings

Hardness at high temperatures, toughness and low frictional properties are all important features in the selection of a cutting tool material. If the thermal conductivity of the tool is reasonable, then these characteristics are mainly required on the surfaces in contact both with the workpiece and with the chip that is formed. It is the surface of the cutting tool that sees the most arduous environment such as wear, corrosion and fatigue.

The ability to put the required properties on the surface of a component, just where they are needed, can be very cost effective if cheaper materials can be used for the bulk of the component as a result.

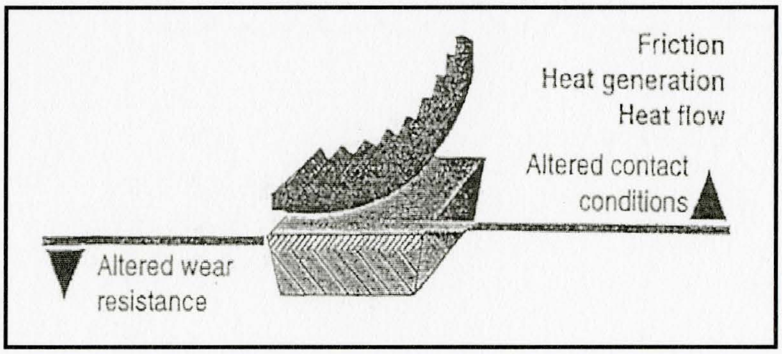
Coating technology is one means of achieving a crucial enhancement in tool performance. There is a large variety of available coating materials, coating structures and coating processes, leading to the development of different coating types such as soft, hard and superhard coatings, with superior properties. However, a careful selection of a suitable coating system is essential. Only coatings which are specifically adapted to the tool and to the application, can achieve optimized results for specific applications [45]. Coating is an important aspect of cutting tool design, just like the geometry and the selection of the cutting material, and thus it should be adapted and optimized for specific applications.

2.4.1 Properties of coatings

Many interactions take place between the coating and substrate materials as well as between the coating process and the coated tool, decisively determining its wear resistance and performance.

The selection of a suitable tool coating requires the identification of the primary wear mechanisms inherent in the specific machining task and is based on the ability of the coating to reduce this wear significantly.

There are two major ways in which a coating may influence tool wear (Figure 2.7 [24]). On one hand, it affects the volume of the bulk tool material by increasing wear resistance. On the other hand, coatings can help to vary contact conditions by altering friction, heat generation and heat flow, thus decreasing the wear rate.



Surface effects:
Abrasion
Adhesion
Tribo-oxidation
Diffusion

Volume effects:
Crack initiation
Scoring
Plastic deformation

Figure 2.7 Influence of coatings on wear mechanisms and contact conditions [24]

There are five wear mechanisms defined in DIN 50320. They may be firstly classified into the three surface effects of abrasion, adhesion and tribo-oxidation. Secondly, the diffusion mechanism, which begins at the tool face, but has also volume effects. Finally, there is the fatigue mechanism, which has a volume effect that leads to the formation of cracks, followed by fracture. Shown in Figure 2.8 [5] are the main features that may affect the wear behavior of coated cutting inserts.

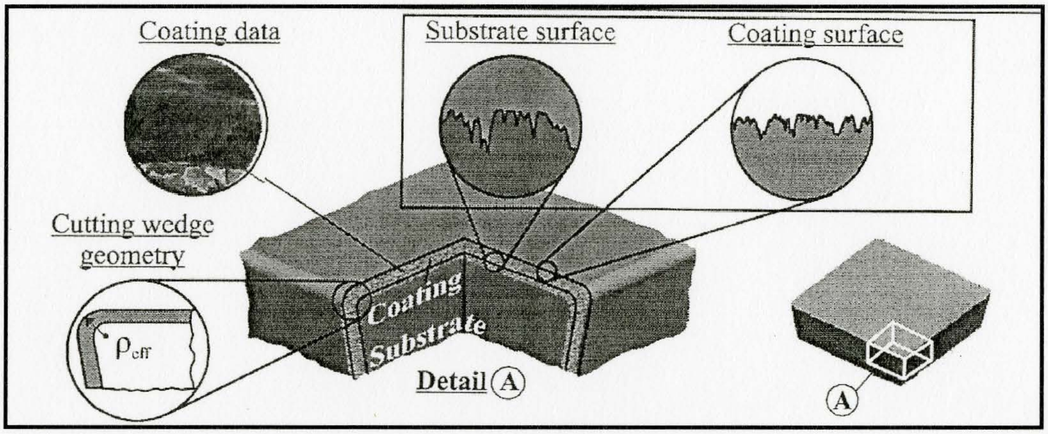


Figure 2.8 Parameters affecting the coated cutting tool performance [5]

Bouzakis et al. [6] studied the fatigue and wear behavior of coated cemented carbides and recommended some measures to improve it, as shown in Figure 2.9.

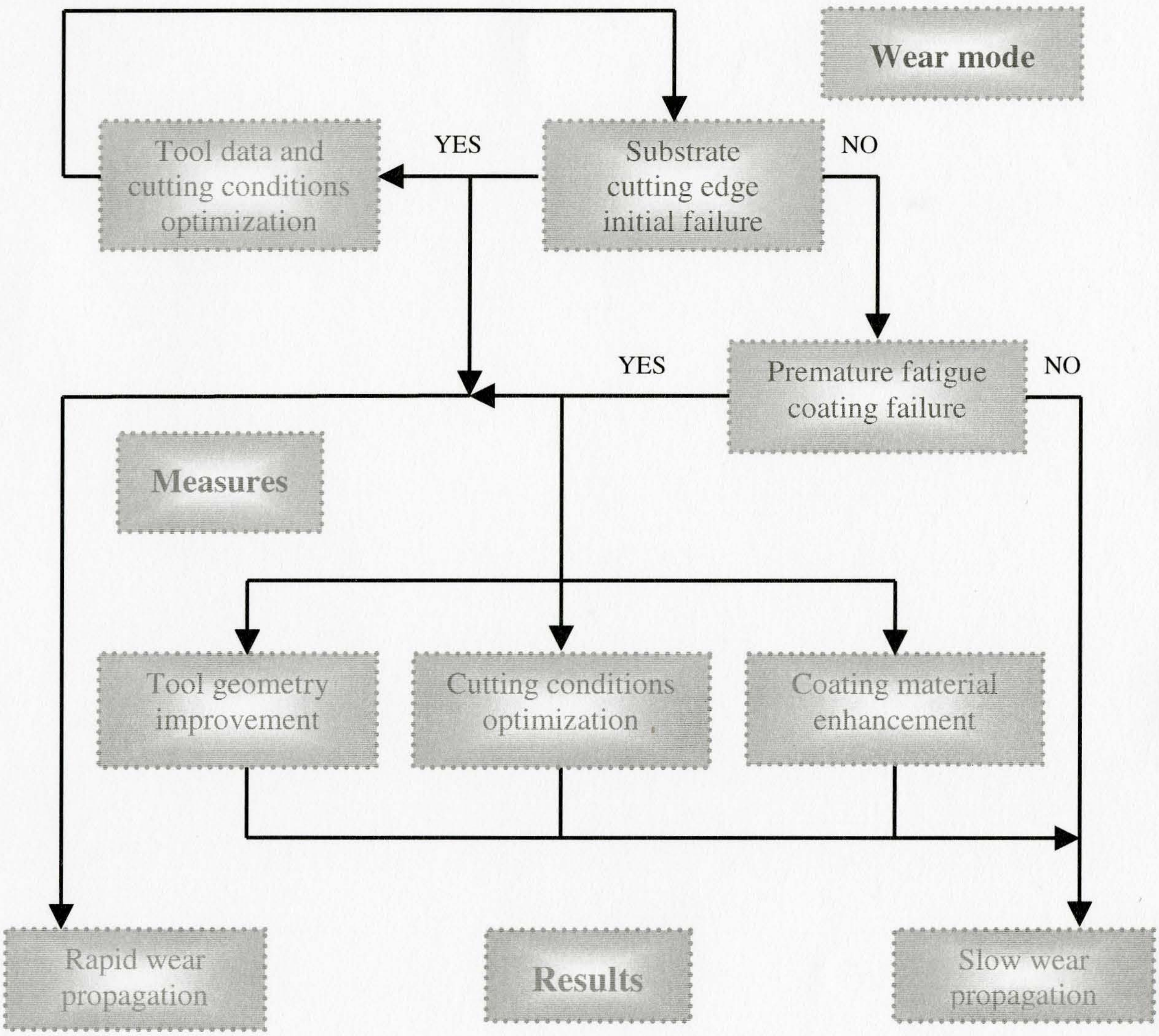


Figure 2.9 Potential tool wear behavior of coated tools [6]

An important factor for effective wear protection is the hardness of the coating, which is strongly dependent on temperature. At temperatures above 500 degrees Celsius the hardness values of many coating materials are no longer comparable to those measured at room temperature. In addition, some coatings are no longer mechanically stable at elevated temperatures and begin to oxidize [45].

Another factor for tool coating performance is the coating thickness. In applications that require resistance against purely abrasive wear a higher coating thickness is deposited. In other applications, where strongly alternating loads are employed, thinner coatings are applied.

Today advanced technologies allow the structure and composition of the coating to be varied so that the properties of the coatings can be significantly changed.

2.4.2 Choice of coating materials

Hard materials suitable for thin films are predominantly but not entirely carbides, nitrides, borides and silicides of the IVth, Vth and VIth groups of the periodic table. Such materials are formed by introducing nitrogen, hydrocarbon, or silicide during the sputtering process.

There are four major groups of hard coating materials on the market. The most popular is the group of **titanium-based** coating materials such as TiN, TiC and Ti(C,N). In order to improve properties like hardness and oxidation resistance, Al or Cr are added to the metallic phase. Such a coating is (Ti, Al)N, which provides very good results.

The final coating on both high speed steel and cemented carbide inserts is titanium nitride (TiN). This is because as well as being hard and having a low dissolution rate in steel, TiN displays a very low coefficient of friction against steel.

In recent years new groups of coatings have been developed. These are **ceramic coatings**, like Al_2O_3, **super-hard coatings**, like CVD-diamond, and the **solid lubricant coatings**, such as amorphous metal-carbon, Me-C:H [24]. In addition, soft lubricant coatings such as pure graphite and Molybdenum Disulfide (MoS_2) may be deposited on top of the hard coatings to reduce friction and wear. The thickness of the coating layers varies from 1-5 μm for a single layer up to 20 μm for multiple layers.

Table 2.4 shows the ranking of major coating properties among a few selected coatings, irrespective of the coating manufacturing process.

Table 2.4 Major material properties for different coatings [Pfouts, 2001]

	Chemical Stability	*Oxidation Resistance*	*Hardness (20 °C)*	*Hot Hardness*
Best	Al_2O_3	Al_2O_3	TiC	Al_2O_3
	TiAlN	TiAlN	TiCN	TiAlN
	TiN	TiN	Al_2O_3	TiN
	TiCN	TiCN	TiAlN	TiCN
Poor	TiC	TiC	TiN	TiC

The Al_2O_3 coating, which can only be made by CVD (Chemical Vapor Deposition), has the best chemical resistance (see Table 2.4.) and hot hardness of all hard coatings, but has poor layer adhesion and thermal shock resistance due to its high brittleness. For this reason, the TiAlN coating deposited by PVD (Physical Vapor Deposition) has been used as a substitute for Al_2O_3 in interrupted cutting applications. This is due to the coatings ability to generate protective tribo films of Al_2O_3 under conditions of high temperature and stress. Another specific property of the Al_2O_3 coating is its decreasing thermal conductivity with increasing temperature, which makes it suitable for high-speed applications, where high temperatures are involved [57].

2.4.3 Coating processes

There are two main coating processes applied on cutting tools: Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD). They can be further differentiated into sub-types, each with its effects on coating structures and on the tribological properties of the coated tools.

Chemical Vapor Deposition (CVD) is a chemical process for depositing thin films of various materials. In a typical CVD process the substrate is exposed to one or more volatile materials, which react and/or decompose on the substrate surface to produce the desired deposit. Frequently, volatile byproducts are also produced, which are removed by gas flow through the reaction chamber.

The CVD process is characterized by the high substrate temperature needed to deposit a coating (about 1100°C). In HSS substrates these high temperatures promote annealing and in cemented carbide substrate materials they affect the toughness and the transverse rupture strength [24].

Some of the forms of CVD that are widely used and frequently referenced in the literature are: CVD processes at atmospheric pressure, CVD processes at sub-atmospheric pressure (Low-pressure CVD), microwave plasma-assisted CVD, plasma enhanced CVD, rapid thermal CVD, ultra-high vacuum CVD and atomic level CVD (the film thickness is controlled by the number of precursor cycles rather than the deposition time as is the case for conventional CVD processes).

The **Physical Vapor Deposition** process is usually performed at 200°C to 500°C. The coating material is evaporated and subsequently condenses on the tool substrate [24]. Further components can be added by using a reactive gas. The evaporation of the coating material can be induced by heating, by an electron beam or by sputtering with a process gas (usually Argon) accelerated to the target.

PVD coatings are in general divided into two sub-divisions, "hard" coatings and "low friction" coatings.

Hard PVD ceramic coatings are used in many applications because of their outstanding wear resistance properties. They have continually developed but can be divided into four distinct generations:

1. single metal nitride PVD coatings (e.g. TiN, CrN, ZrN) are still used for various applications, but their temperature resistance is insufficient for high speed machining;
2. hard PVD ceramic coatings with alloyed elements to improve oxidation resistance and temperature resistance (by introducing Cr, Al or Y into the TiN lattice);
3. hard PVD coatings developed through the deposition of multi-layers and super-lattices (the thin films are formed by alternately depositing two different components to form layered structures);
4. nano-composite coatings that consist of at least two phases: a nano-crystalline phase and an amorphous phase, or two nano-crystalline phases.

Low friction coatings are hard, wear resistant, low friction coatings such as Graphit-iC^{TM}, MoST^{TM} and Dymon-iC^{TM}, developed mainly by the automotive industry.

Coating of high speed steel cutting tools was first performed by PVD processes in such variants as ion plating, arc evaporation and magnetron sputtering. The latter is a powerful and flexible technique which can be used to coat virtually any workpiece with a wide range of materials. Magnetron sputtering is a vacuum coating process and consists of the removal of atomized material from a solid, due to energetic bombardment of its surface layers by ions or neutral particles.

The thermophysical properties of the coatings appear to exert a much greater influence on service properties of high speed steels, which are temperature sensitive substrates, than coating properties such as hardness, abrasive resistance, chemical resistance etc [28].

There are many advantages of using PVD coatings to improve cutting performance:

- PVD is more suitable for coating complex high-speed steel tools which would distort under the high temperatures experienced during exposure to CVD operating temperatures;
- Magnetron sputtered coatings follow the exact surface roughness of the substrate material (smooth coatings are vital for applications such high precision forming);
- PVD coatings are deposited while under concurrent ion bombardment. These energetic ions allow the deposition of dense, hard films by supplying the sputtered neutrals with sufficient energy to find a suitable nucleation site and inducing high compressive stress. PVD coatings with a hardness of 1000-4000HV can be deposited with this technique (approx. 5 times the hardness of high speed steel);

In machining applications substantial reductions in the following wear mechanisms are observed:

- Crater wear (chemical interaction between the tool and the work piece) – PVD offers stable coatings that do not readily react chemically;

- Flank wear (abrasive wear by hard constituents of the work piece) – can be reduced using hard PVD ceramic coatings;

- Built-up edge (welding of the work piece material to the tool tip which may detach along with part of the tip) – low friction coatings reduce heat generation and the formation of solid solutions;

- Depth of cut notching (oxidation of the tool material with some abrasion from the edge of the chip) – some PVD coatings can be deposited to resist oxidation up to 1000°C;

- Thermal cracks (produced by temperature gradients in repeated heating and cooling in interrupted cutting) – low friction coatings that reduce heat generation.

The use of coated cutting tools to machine various materials now represents state-of-the-art technology. More recent process developments are aimed at lessening the negative effects of individual coating techniques by introducing combined or hybrid processes. For example, the coating of hard metals by conventional CVD technology causes a deterioration of the mechanical properties and restricts their technical applicability [48]. By combining PVD and CVD coatings a significant improvement in strength and lifetime was obtained in comparison to conventional CVD coatings.

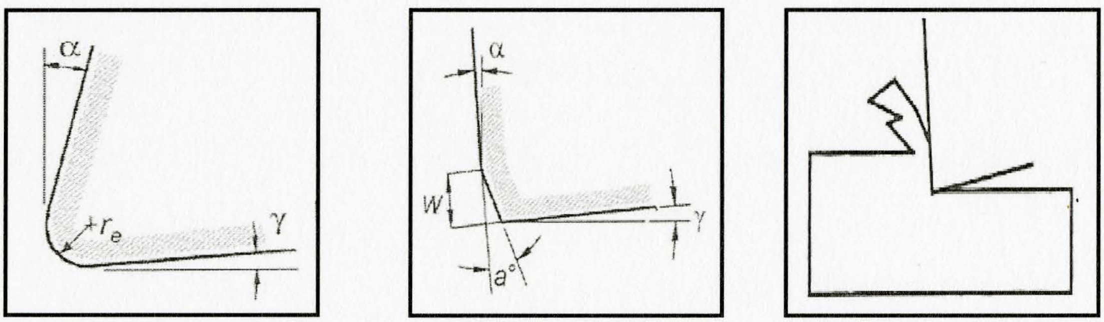
PVD and CVD coatings offer today a powerful alternative to further improve the cutting performance of materials. The flexibility of coating processes, well supported by the superior and controllable properties of modern coatings, is responsible for the almost exclusive application of coated tools world wide [24].

2.5 Cutting Edge Preparation

Due to its large influence, the design of edge preparation has played an important role in the finishing applications of hardened steels and has attracted considerable research, both analytically and experimentally.

Most of the research on the design of a cutting edge relies heavily on trial and error and past experience. Little attention has been given to developing a simple approach to selecting the best cutting edge design. Whereas the present research focuses on the change of cutting edge shape of turning inserts in the initial stage of wear and the use of this geometric information for the design of the cutter edge.

In metal cutting the modification of the tool edge geometry is referred to as "edge preparation". The purposes of edge preparation are to strengthen the cutting edge and prepare a surface for deposition of coatings. The three major types of edge preparation design are hone or round edge, T-land or chamfer edge and up-sharp edge (Figure 2.10).



a. **b.** **c.**

Figure 2.10 Types of cutting edge preparation:

a. honed tool (α - rake angle, γ – relief angle, *re* - edge radius); **b.** chamfered tool (α - rake angle, γ - relief angle, *a* – chamfer angle, *w* – chamfer width); **c.** up-sharp edge.

Some typical cutting edge preparation designs that are used in most commercial cutting inserts are presented in Figure 2.11.

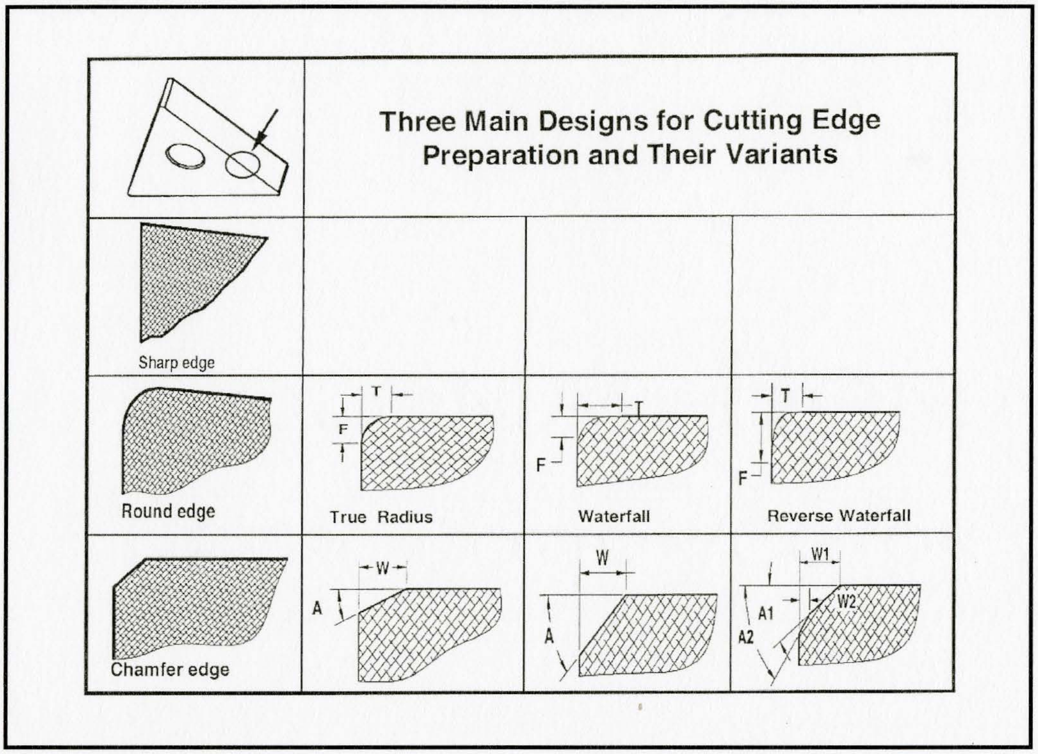


Figure 2.11 Inserts for different types of edge geometry [Kennametal]

2.5.1 Role of Edge Preparation

Previous research related to the effects of the tool cutting edge is primarily related to tool wear. Studies have shown that the wear of the cutting tool represents a change in edge geometry. Furthermore, the tool edge geometry may be optimized in terms of minimum tool wear for the given cutting conditions, as well as tool and workpiece materials.

The design of tool edge geometry influences process parameters such as:

- The shape of the deformation zones;
- Cutting forces;
- Distribution of temperature on the tool face;
- Distribution of stresses on the tool face.

These effects in turn affect the:

- Changes in chip flow,
- Machined surface integrity (e.g. residual stress),
- Tool wear resistance,
- Tool life.

2.5.2 Effects of Edge Preparation on the Shape of the Deformation Zones

The past research of cutting mechanics mainly focused on machining with sharp tools. Merchant [38] and Lee and Shaffer [33] proposed shear plane models which suggested that the chip is formed by a shearing process along a shear plane ahead of the cutting edge, toward a free surface of work material. This zone is typically idealized as a plane OO' (Figure 2.12), called the shear plane. The angle (Φ) the shear plane makes with the cutting velocity (V_1) is called the shear angle.

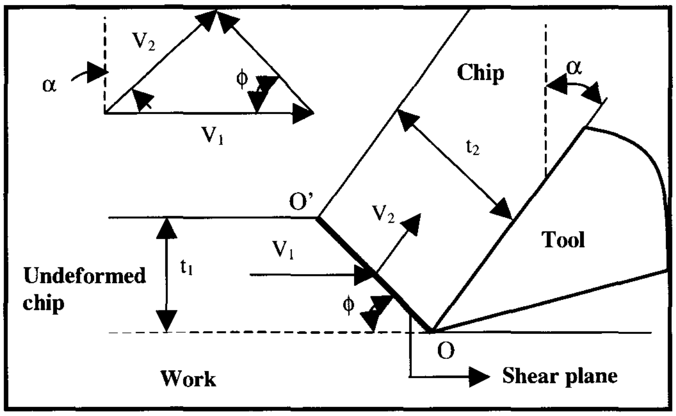


Figure 2.12 Schematic of orthogonal machining and chip formation by large scale plastic shear, geometry of deformation and velocity diagram [38]

Geometric parameters, such as the undeformed chip thickness (t_1), tool rake angle (α) and cutting edge radius, affect the shear deformation. Although their work provided a fundamental understanding of the cutting process, the models didn't take into consideration the effects of strain, strain rate and temperature on the flow stress of the work material.

The 'shear zone' model proposed by Oxley et al.[42] was based on the laws of plasticity and included the effects of strain, strain rate and temperature on the flow stress of the work material. His simplified model consisted of two deformation zones – a primary zone and a secondary zone (Figure 2.13). The work material begins to deform when it enters the primary zone from the lower boundary *CD*, and continues to deform as the streamlines of the material follow in smooth curves until it passes the upper boundary *EF*.

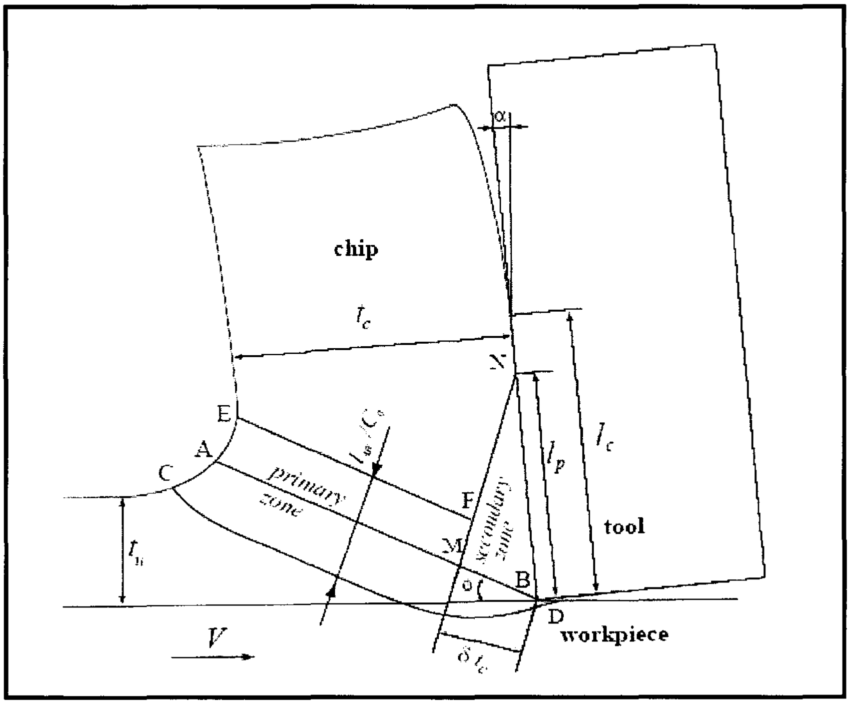


Figure 2.13 Simplified deformation zones in orthogonal cutting [42]

Oxley et al. assumed that the primary zone is a parallel-sided shear zone. The secondary deformation zone is adjacent to the tool-chip interface and is caused by intense contact pressure and frictional force. After exiting from the primary deformation zone, some material experiences further plastic deformation in the secondary zone. Using a - stop method to experimentally determine the flow field, Oxley [42] proposed a slip-line field similar to the one shown in Figure 2.13. The corresponding hodograph indicated that the strain rate in the primary deformation zone increases with cutting speed and has a maximum value at plane *AB*.

In the case of chamfered tools, the main zones of plastic deformation are separated into primary shear, dead metal zone created by the chamfer, and the secondary deformation zone where the chip moves over the regular rake face of the tool. Analyzing the mechanics of machining with chamfered tools, Zhang et al. [58] concluded that the decrease of shear angle due to chamfer is about 2-3 degrees compared to that for cutting with sharp tools under the same cutting conditions.

2.5.3 Effects of Edge Preparation on Cutting Forces

The force acting on the cutting tool may be resolved into three components, as shown in Figure 2.14[43].

The tangential tool force, F_Z, acts in a direction tangent to the revolving work. This force is usually the highest of the three components. The turning power, which is the product of the tangential force and the cutting speed, constitutes approximately 99% of the total power required by the cutting tool.

The longitudinal tool force, F_Y, acts in a direction parallel to the axis of the rotating workpiece. For turning, the longitudinal force is the feed force and averages approximately 40% as high as the tangential force.

The radial tool force, F_X, is normal to the rotating work or is in a direction radial toward the center of the work. For turning operations, the radial component holds the tool to the correct depth of cut. This force is usually the smallest of the three components and averages 50% as large as the longitudinal force. When taking a turning cut, no spindle power is required as a result of the radial tool force since there is no velocity in the radial direction.

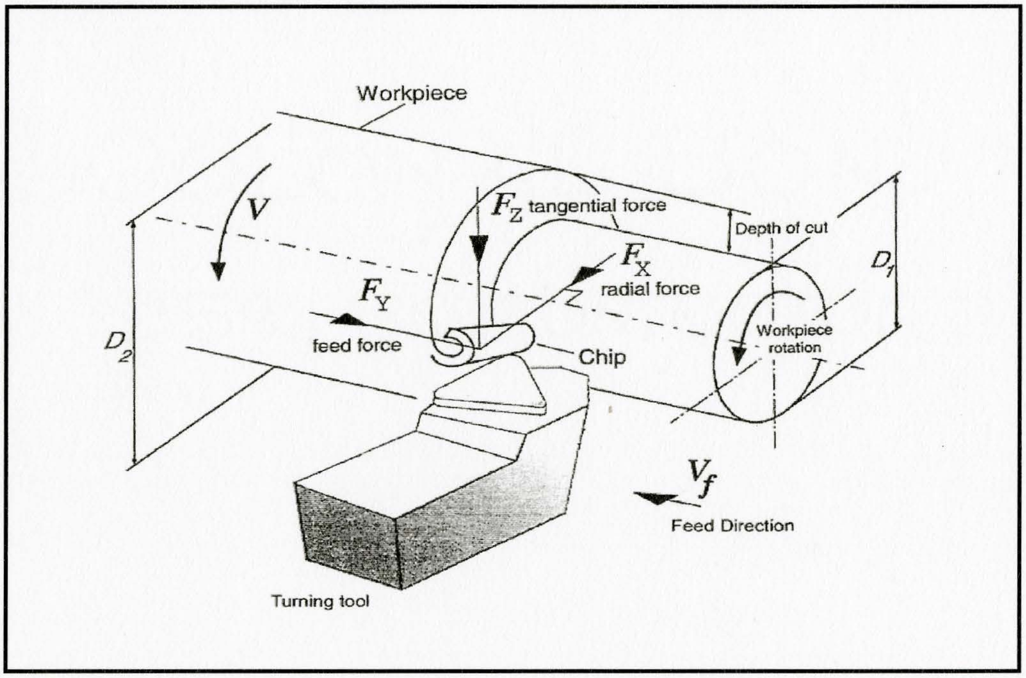


Figure 2.14 Resolution of forces in metal cutting Ozel et al.[43]

Cutting tests have shown that during tool life measurements the values of all components of the cutting force are smaller for coated tools than for uncoated ones.

Simulation results obtained by Yen et al.[56] for a honed edge showed that both cutting and thrust components of the force increase as the edge radius increases. This could be due to the increasing bluntness of the cutting edge, which requires larger forces for material shearing. On the other hand, for chamfer edge tools, simulations have shown that the chamfer has more influence on the feed force than the tangential forces. Generally, an increased chamfer angle appeared to have a stronger effect on the cutting forces when a larger chamfer width was used.

The conclusions drawn by Kim et al. [23] from the study on the effect of tool edge on the cutting process indicated that there is no change in chip thickness, despite the increase of the total edge radius. In other words, the increase in edge radius does not change the shear angle and does not contribute directly to chip formation.

Thiele and Melkote [52] investigated the effects of edge preparation and workpiece hardness on the surface finish and cutting forces in hard turning of AISI 52100 steel. The study has revealed that increasing the edge hone radius tends to increase the average surface roughness, but this effect decreased with an increase in workpiece hardness.

2.5.4 Effects of Edge Preparation on Cutting Temperatures

Yen et al. [56] observed that in the case of hone edge, the magnitude of the maximum tool temperatures near the tool tip was not sensitive to the size of edge radius. In addition, for chamfer edge tools the maximum temperatures on the tool rake face appeared to increase with increasing chamfer width and chamfer angle.

Experimental results obtained by Kim et al. [23] indicate that an increased edge radius causes a change in the temperature distribution of the tool, especially along the tool edge where the maximum temperature appears.

A recent investigation regarding the influence of edge preparation in CBN cutting tools on process parameters and tool performance was conducted by Ozel [41]. Results showed that honed CBN tools resulted in lower cutting forces, but higher rake face temperatures, while chamfered CBN tools resulted in lower temperatures on the rake face.

2.5.5 Effects of Edge Preparation on the Distribution of Stresses

Matsumoto et al. [36], investigated the effect of cutting parameters on residual stress, in the case of precision hard turning, and determined that the tool edge geometry is the dominant factor deciding the residual stress profile. Figure 2.15 [36] shows the residual stress profiles in the machined surface created by a sharp tool and a 0.02mm honed tool.

The honing clearly creates a deeper compressive residual stress. Further attempts to find the effect of the honing size was not successful due to difficulties in getting consistently honed tools.

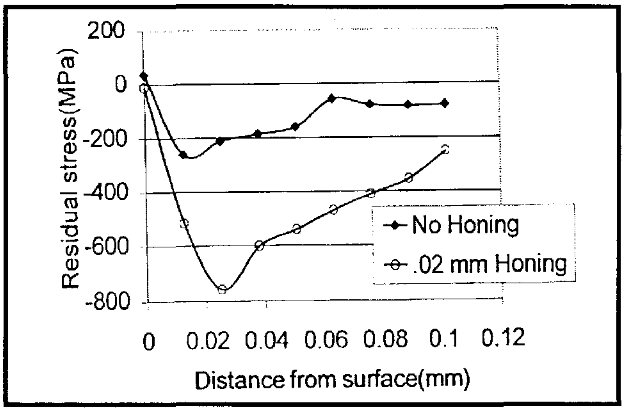


Figure 2.15 Tool edge honing effect on the residual stress profiles in the machined surface [36]

As an alternative to honing, a secondary chamfer of 30 degree and 0.03mm long was added to a major chamfer of 15 degree and 0.12mm long on a tool edge as shown in Figure 2.16 [36].

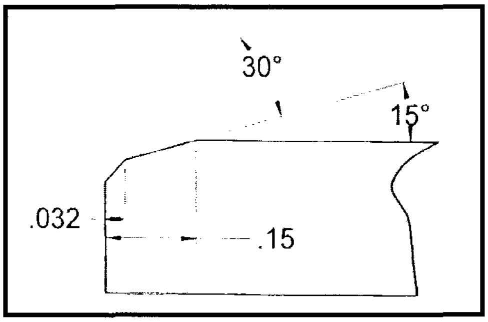


Figure 2.16 Double chamfer geometry (mm)

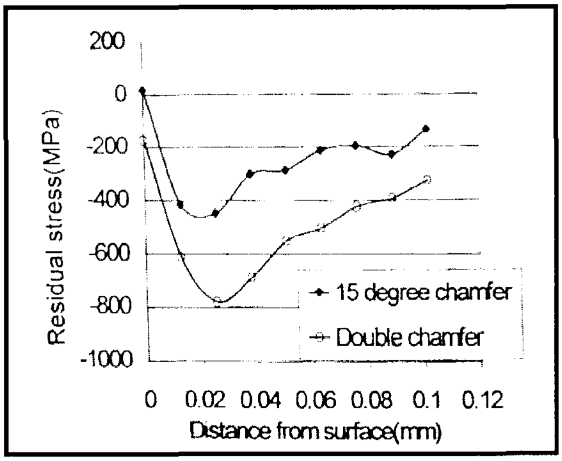


Figure 2.17 Effect of double chamfer on residual stress profiles in the machined surface [36]

The angle of the secondary chamfer to the rake face is 45 degrees. This double chamfer tool was tried again against a sharp tool. Figure 2.17[36] shows the comparison of residual stress profiles. With the double chamfer tool, the compressive residual stress again was larger and deeper than that created by a sharp tool. Either by tool honing or by adding a secondary chamfer, the investigation revealed the dominant effect of tool edge geometry on residual stress magnitude and depth. This study could be extended to better understand the double chamfer size effect.

Simulation results obtained by Shatla et al. [50] showed that the honed tool with an excessive edge radius resulted in a significant increase of the tool stress and shifted the stress concentration close to the flank face. This phenomenon occurred due to the increasing plowing force component in the direction normal to the machined surface.

For chamfered tools, numerical simulations performed by Movahhedy, Altintas and Gadala [39] showed that the effective stress increases as the material moves towards the center of the shear zone due to strain and strain rate hardening, until it reaches a maximum at the center of the shear zone.

2.6 Chip Formation

Chip formation is an essential phenomenon in the cutting process. It is the basis of research on physical phenomena such as cutting forces, cutting temperature, tool wear, chatter, build-up edge, chip curling and chip breakage.

The friction that occurs on the tool face plays an important role in metal cutting because it determines the cutting power, machining quality and tool wear. Due to the extreme conditions in the cutting area, where the normal pressure at tool-chip interface is very high, the mean coefficient of friction generally varies considerably with the change in cutting speed, rake angle etc.

The metal cutting literature reflects many attempts at capturing the effects of edge geometry on the process mechanics. Researchers have investigated the effect of tool edge geometry on the chip removal process and the contribution of edge or “plowing forces” in this process. It was found that the presence of these forces depends on the size of the flank wear and affects the surface integrity and residual stresses in the machined surface. However, the contribution of these forces to chip formation is not significant [39].

2.6.1 Chip formation with chamfered tools

When a chamfer is introduced to the tool edge, the chamfer traps the work material over the chamfered edge and a build-up forms, which acts as if it replaces the missing part of the edge. This dead metal zone becomes the effective cutting edge and temporarily protects the tool surface from wearing under heavy cutting conditions. It is strongly plastically deformed and much harder than either the workpiece or the chip, which leads to a stronger edge and reduces tool wear. However, the drawbacks of cutting with dead metal zone on the chamfered edge are that the forces on the tool change depending on the effective geometry of the cutting edge, and due to the fact that this dead zone varies in size during cutting, dimensional accuracy may be compromised [39].

The chamfered edge acts as the primary rake of the tool, with a limited length and at a relatively large negative rake angle $\propto_1$. As shown in Figure 2.18 [39], the main rake of the tool becomes the second rake at a positive, neutral or slightly negative angle.

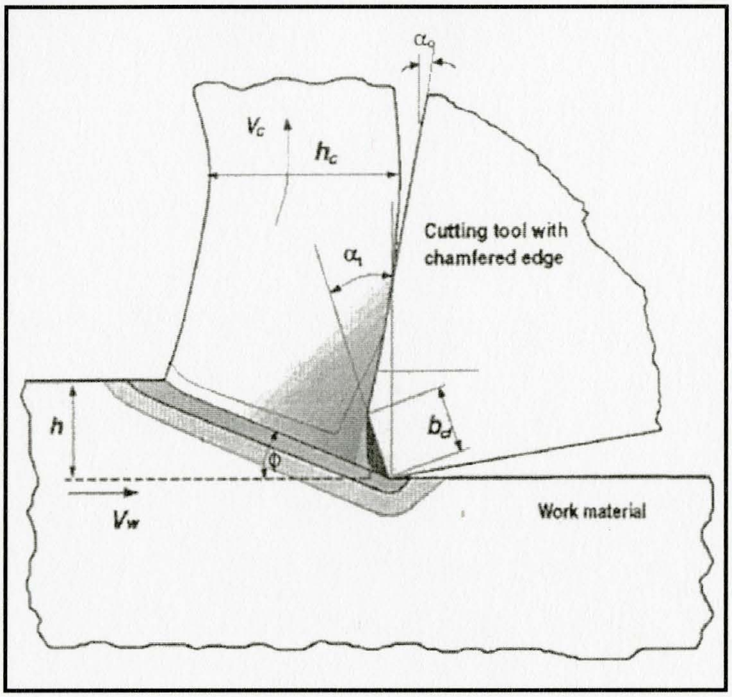


Figure 2.18 Schematic view of cutting process with a chamfered tool [39]

There have been a number of studies on the effect of chamfer on the performance of the cutting tool. Hirao et al. [19] observed that the chip thickness is not affected by the chamfer angle because the dead metal zone effectively replaces the missing nose of the edge, and reported that the chamfer has more influence on the thrust (feed) force than the tangential forces.

The experiments in the case of continuous cutting were conducted for different materials, using a Quick-Stop device. Figure 2.19 applies to 4340 steel and *A, B, C, D* correspond, respectively, to chamfer angles of 0, 22, 41 and 60 degrees, with a chamfer length of 0.4mm.

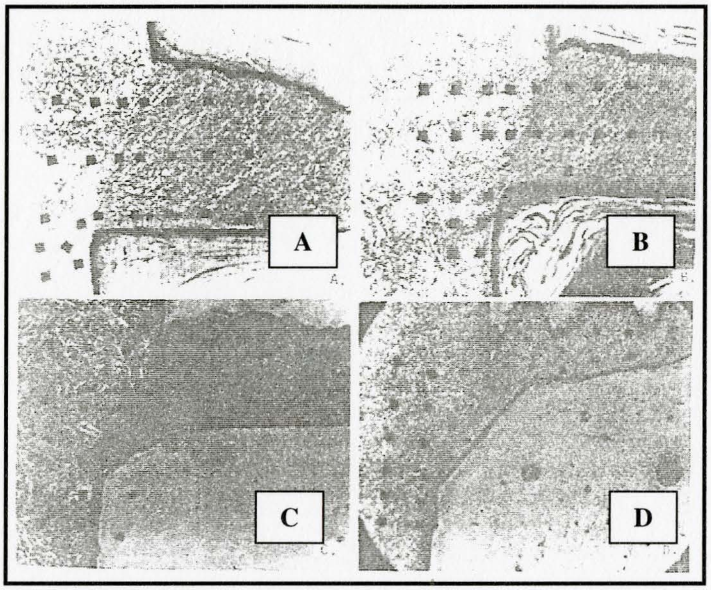


Figure 2.19 Effect of chamfer angle on chip formation for steel 4340 [19]

In cases A, B and C the chip ratios are almost identical and the chip formation process is not significantly affected by the chamfers. The build-up nose almost completely fills the chamfer and similar shear planes are formed in these cases. As seen in Figure 2.10 D, in the case of a 60° chamfer angle the built-up nose does not entirely replace the original tool nose. However, this is an extreme chamfer and therefore the overall chip formation process for chamfered tools can be approximated by a single shear plane model.

The results obtained by Hirao et al. [19] for the forces acting between the workpiece and the tool are summarized in Figure 2.20. These forces were measured for chamfer angles of 22, 41 and 60 degrees and chamfer lengths up to 0.8 mm. The solid lines in the graph connect values of measured tangential cutting forces and the broken lines represent the thrust force components. It can be seen that the chamfers have a small effect on the tangential force, but the thrust force strongly increases with the chamfer angle and its length.

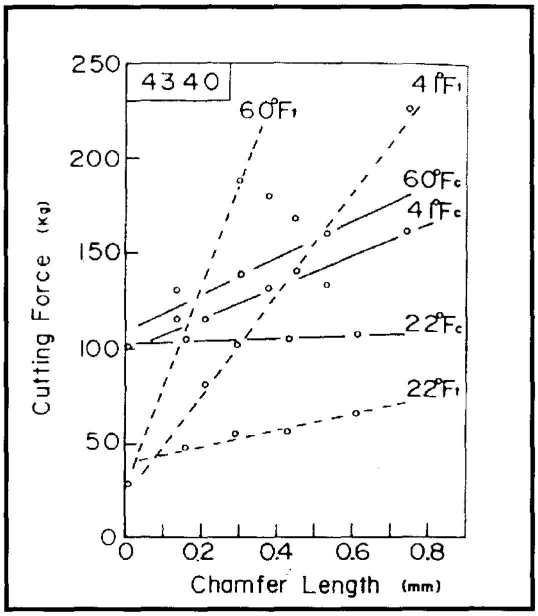


Figure 2.20 Effect of chamfer on tangential and thrust forces [19]

The study conducted by Hirao et al. could be followed by a more in-depth analysis of the stresses and temperatures in chamfered tools, in order to observe the effect on flank wear, chipping and breakage of the tool. These results can then be used to determine the optimum chamfer form and size for various cutting conditions.

Ren and Altintas [46] investigated the influence of chamfer angle and cutting conditions on the cutting forces and temperature. Based on Oxley's slip-line field model (Figure 2.13 [42]), they proposed an analytical cutting model, which divided the three plastic deformation zones into: the primary shear zone, the secondary deformation zone (where the chip moves over the regular rake face), and the chamfered edge zone where the metal is trapped and forms a dead metal zone (Figure 2.21 [46]). In all three zones the material flow stress was identified as a function of strain, strain rate and temperature.

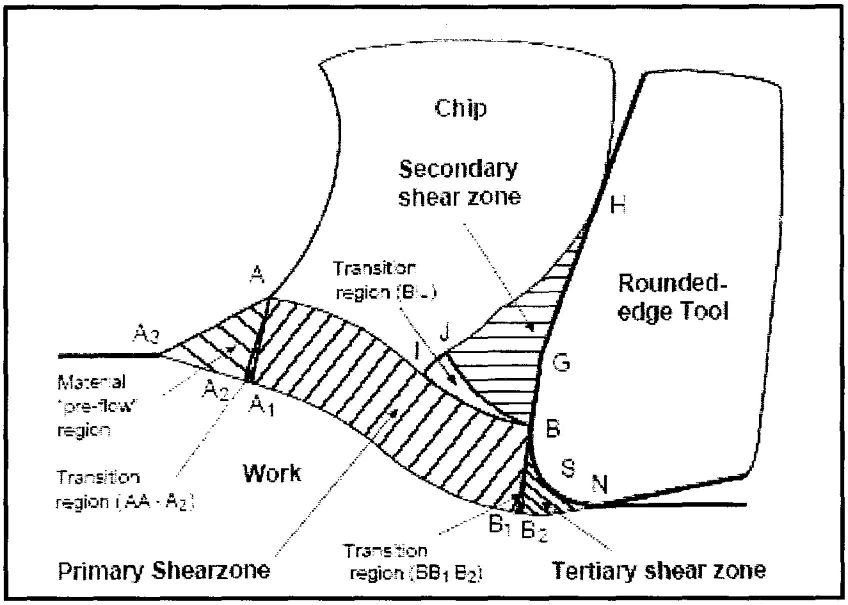


Figure 2.21 Division of the slip-line field into the three major shear zones [46]

By applying the minimum energy principle to total energy, the shear angle in the primary deformation zone was estimated. Cutting forces, friction coefficients and cutting temperatures were determined for different chamfer angles.

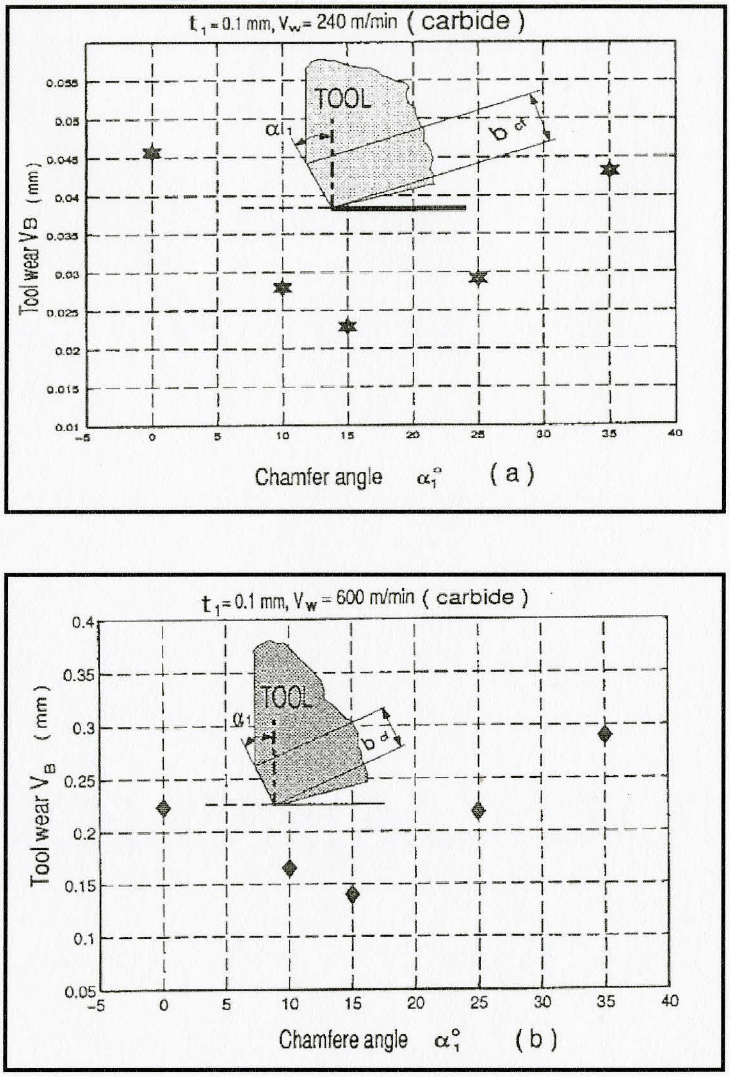


Figure 2.22 Tool wear for ISO S10 carbide: a.) v=240m/min, b.) v=600m/min [46]

As shown in Figure 2.22, when the chamfer angle was varied from 0° (sharp cutting edge) to -35°, the minimum wear was obtained with tools which had -15° chamfer angle.

This means that larger chamfer angles increased the force and friction, and smaller chamfer angles weakened the wedge, causing larger flank wear.

Another aspect observed on these graphs is that for the same volume of material removed, the 240m/min cutting speed gave 6 times lower flank wear than the 600m/min cutting speed, where severe crater wear occurs due to the diffusion of the Cobalt binder into the workpiece material.

Although chamfered edge tools are given increased importance, more attention should be directed to the mechanism of chip formation in cutting with chamfered tools, and the effects of tool edge geometry on cutting variables.

Recently, Movahhedy et al. [39] studied the influence of cutting edge geometry on the chip removal process, through numerical simulation of cutting with sharp and chamfered tools and with carbide and CBN tools. The existence of the dead metal zone represented an important aspect of this study. The authors investigated the velocity of the tool material around the tool edge for different chamfer angles and found that the material in the trapped region has a small velocity, about 10% of the cutting speed.

Although the size of the dead zone might change during cutting, the overall conclusion was that the dead zone on the chamfered edge seems to be much more stable than a built-up edge on a sharp tool.

This study could be extended to include a broader range of tool materials (i.e. high speed steel), cutting conditions and edge geometries, as well as various chamfer lengths and ratios of chamfer size to uncut chip thickness.

2.6.2 Chip formation with honed tools

Applying a honed radius to a cutting edge is being increasingly employed to protect the edge from chipping and enhance tool life. Various studies were conducted in order to better understand the effects of edge-radius tools on cutting performance and to approximate the size of the radius that leads to the associated advantages.

When cutting with a blunt tool, i.e. a tool with a finite cutting edge radius, some material that would typically be expected to form part of the chip may be subducted into the bulk of the workpiece as shown in Figure 2.23 [57] (region marked I), where the arrows indicate the flow of material. This displacement of material is called plowing and the force associated with this is defined as the plowing force. There is no chip formation associated with plowing – only a displacement of material as an indentation. Plowing is also understood to contribute to side (lateral) flow often observed while cutting with blunt tools [52]. Such side flow typically results in burrs.

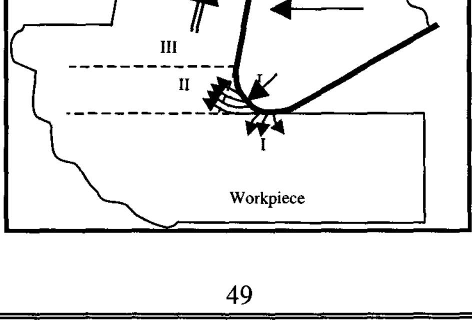


Figure 2.23 Schematic of orthogonal machining with a blunt tool [57]

Plowing is an important contributor to energy dissipation in machining, especially when cutting at undeformed chip thickness values on the same order as the cutting edge radius. In this latter context, plowing gives rise to a 'size effect' in the cutting force.

The explanation most frequently used in the cutting literature is that an increase in edge radius causes an increase in machining forces, which is attributed to a higher proportion being the plowing forces. It was also found that cutting becomes less efficient when the ratio of the uncut chip thickness to edge radius decreases, which leads to higher thermal loads on the cutting edge.

There have been many attempts at modeling the plowing forces, but most of the models developed do not explicitly account for the edge geometry and, hence, are limited in their application.

The force model proposed by Manjunathaiah and Endres [34] proves that the changes in forces that occur with changes in edge radius are not solely attributed to plowing forces. They consider a force balance on the surface *ABC* of the plastic deformation zone (Figure 2.24), assuming that the shear stresses S_1 and S_2 as well as the mean normal stresses P_1 and P_2 are uniformly distributed along *AB* and *BC*.

The results of this analysis indicated that, besides plowing forces, the increase in forces is partly due to an increased chip formation component arising from a smaller shear angle.

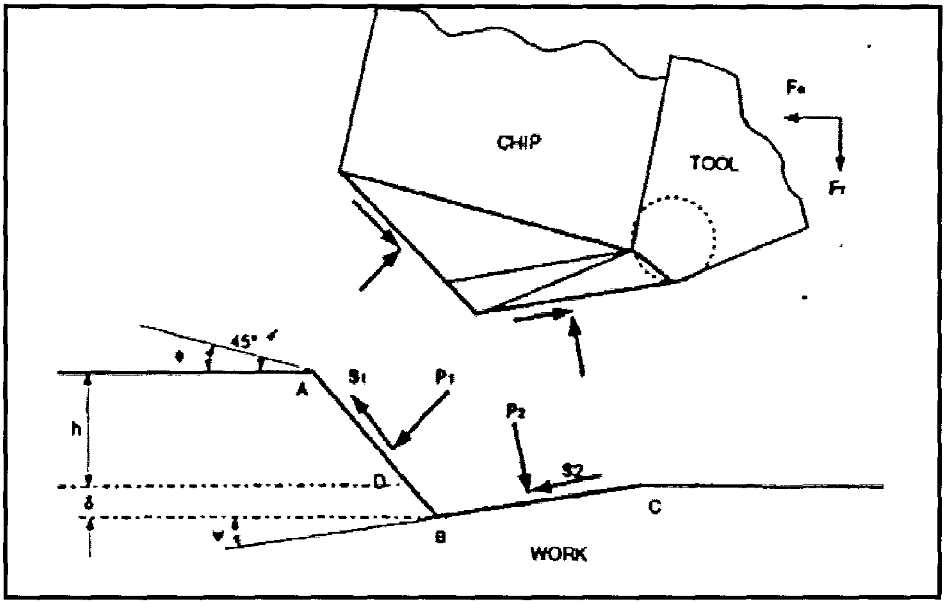


Figure 2.24 Force balance on the lower boundary of the shear zone [34].

The results obtained by Endres et al. [14] show that applying a corner radius improves flank wear relative to that of a sharp tool. The interaction effect between corner radius and edge radius was also observed. This study documented the influence of feed on the lead edge wear and on the corner edge wear.

Figure 2.25[52] presents a schematic of the interaction between the tool and the workpiece for orthogonal cutting. As the cutting edge hone increases, the total machining force increases and the contribution of the plowing component of force, P, increases in magnitude. For large hone tools the plowing effect on the properties of the machined surface becomes especially important.

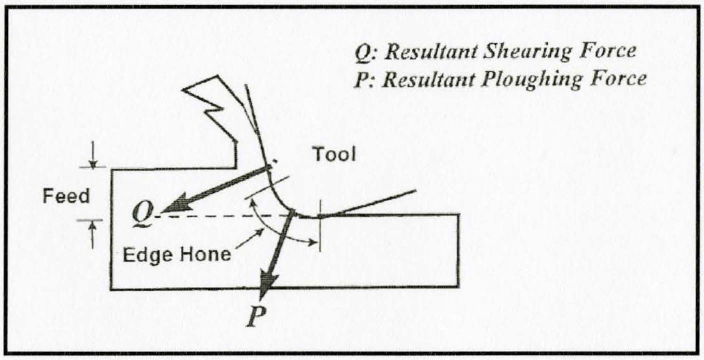


Figure 2.25 Plowing and shearing effects [52].

Manjunathaiah and Endres [34] developed a machining model that explicitly included the effects of edge radius and can be used as the basis for a consistent material behavior model that does not vary with input conditions like rake angle, edge radius and uncut chip thickness. The idealized geometry of their machining model is presented in Figure 2.26[34] and shows a tool of edge radius r_n removing material of uncut chip thickness *h*, measured from the bottom of the tool *C* (same as level D).

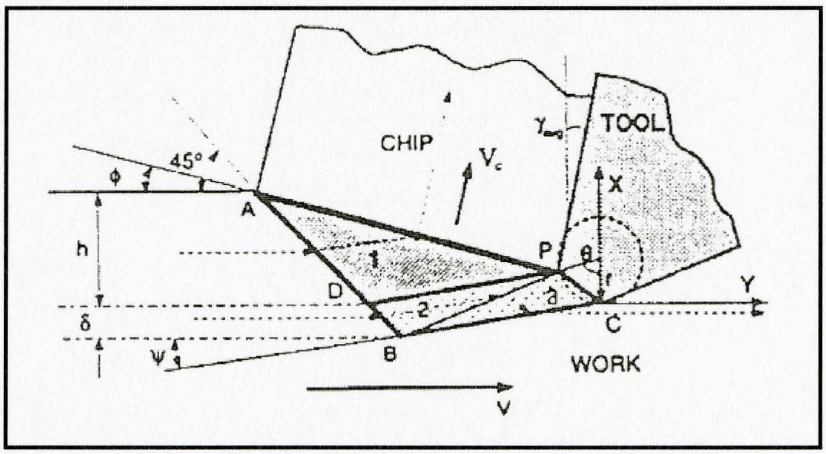


Figure 2.26 Geometric model of the cutting process with an edge radius tool [34]

The material flows at the bottom level of the tool, passes through point *D* and rises up to the chip separation point *P*. The plastic deformation is assumed to occur in the *ABCP* zone instead of a shear plane. In this situation, the material is in a plastic state when it reaches the first line of deformation *AB* and the material that forms the chip exits the plastic zone at *AP*, which is similar to the traditional shear plane. It follows that the work material that represents the machined surface exits the deformation zone at line *BC*.

Yen et al. [56] studied the effects of honed tools on chip formation, cutting forces and process variables. The relationship between the minimum uncut chip thickness (t_{min}) and the size of edge radius (r_e) was observed and a stagnation point of the material flow was identified.

As shown in Figure 2.27[56], the minimum uncut chip thickness is almost equal to the height of the stagnation point, where the separation of the material flow occurs. The upper part represents the chip and the lower part flows under the tool and becomes a part of the machined surface.

It was shown that the plowing forces and their effect of reducing chip load near the nose radius and trailing edge had an important effect on the properties of the machined surface.

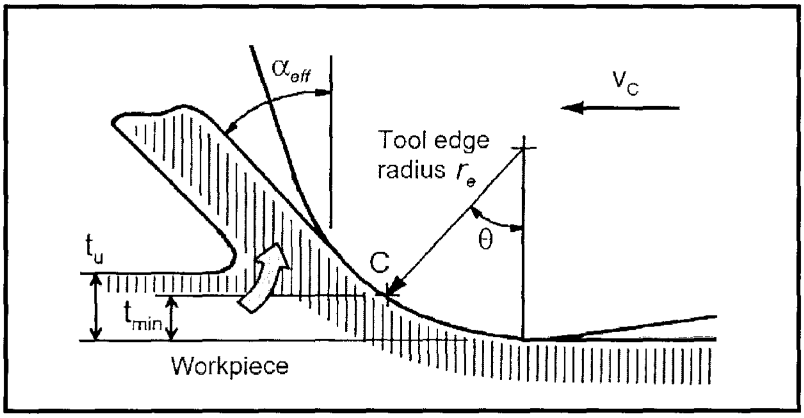


Figure 2.27 Material flow stagnation point *C* and minimum uncut chip thickness (t_{min}) for a large hone tool [56]

The simulation results obtained by Yen et al. in this study enable the estimation of the process variables that are very difficult to measure experimentally. Based on their simulation model the tool edge geometry may be optimized in terms of tool wear for the given cutting conditions and tool and workpiece materials.

2.7 Review of previous work focusing on tool life optimization

The characterization of wear behavior, and thus the optimization of the entire machining system, requires a reliable predictive cutting model to provide insightful information on cutting zone activity. In general, cutting tests are used to correlate the resultant flank wear and crater wear parameters to the cutting conditions, whereas cutting simulations enable the determination of process variables that are not directly measurable or are very difficult to measure.

Merchant [38] identified the most important factors associated with tool wear as being the magnitude of the cutting force, the temperature at the tool-workpiece interface, the surface finish of the workpiece, the dimensional accuracy of the component, the occurrence of vibrations and the noise level. Of all these parameters, cutting forces and the associated power appear to be more generally applicable and closer to accomplishment than temperature and vibrations.

Takeyama and Murata [51] showed that the mechanism of tool wear in turning can be classified into two basic types:

(i) mechanical abrasion, which is directly proportional to the cutting distance and independent of the temperature, and

(ii) a physico-chemical type that is considered to be a rate process closely associated with temperature.

Although the cutting conditions influence which type of wear plays a more important role, the latter is predominant under normal conditions.

A cutting force model was proposed by Chang and Fuh [10] for single-point tools with a chamfered main cutting edge. This model includes the effect of tool wear and introduces a new concept for calculating the variation of the shear plane areas. This variation is caused by the wear effects of the tool edge. The energy method is used in this study to predict a three-dimensional cutting force, when tool wear has occurred. The good correlation between the predicted and the experimental results is very encouraging in extending this model to analyze nose-radius tools.

Kluft et al.[27] analyzed the effect of various cutting parameters on the chip flow direction, indicating that the direction depended not only on the geometry of the tool and the cutting conditions (feed rate, depth of cut), but also on the curvature of the workpiece.

Usui and co-workers [54] used an iterative technique to find the chip flow direction that minimizes the sum of the shear energy and friction energy.

Endres and Kountanya [14] studied the interaction of edge radius (the radius that blends the rake and flank faces) with corner radius (blending the lead and minor edges) and their effects on tool wear and machining forces. The clarification of edge and corner radii is also presented in Figure 2.28[14]. One general conclusion was that wear levels on both the lead and corner edges are most sensitive to corner radius at the lowest feed. On the other hand, as expected, the worn-tool forces were higher than the fresh-tool forces, especially in the thrust direction.

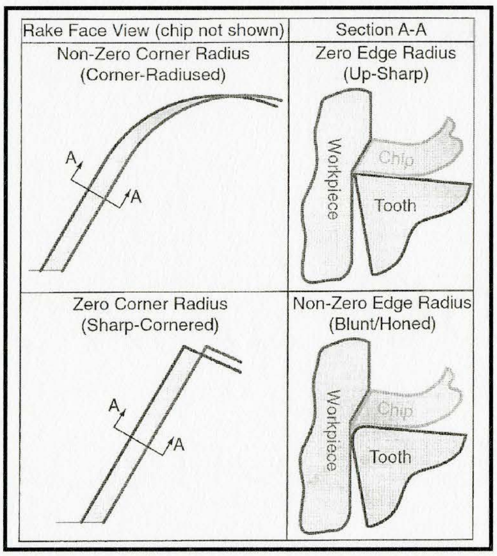


Figure 2.28 Edge radius vs. corner radius [14]

The effect on the performance and efficiency of the cutting process is explained by taking into consideration the variation of the uncut chip thickness, which is mainly driven by feed rate.

As shown in Figure 2.29[14], the uncut chip thickness decreases along the corner radius and approaches zero near the tip of the tool. The hypothesis is that if an edge radius is applied to protect the cutting edge from chipping, the corner radius portion near the tool tip is subjected to a reduced cutting efficiency. An increase in corner radius further reduces the uncut chip thickness, making cutting near the tool tip even less efficient, presumably increasing temperature and tool wear.

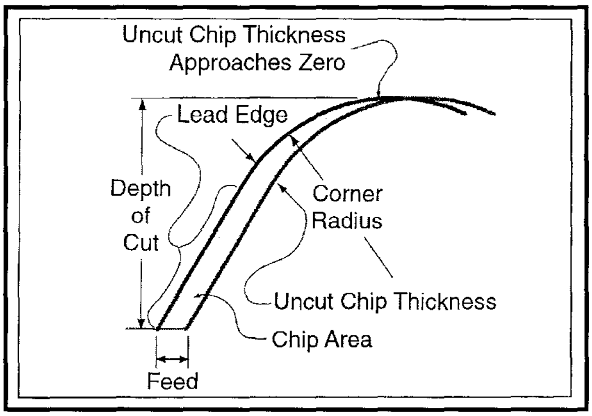


Figure 2.29 Tooth geometry and uncut chip thickness variation for corner-radiused tools [14]

Knowing that sharp-cornered tools often exhibit an increase in wear that is concentrated near the sharp corner, the authors proved in this research that an increase in corner radius can serve to spread the overall thermal load across a greater region, providing a better heat conduction path to the bulk of the tooth, lowering the temperature along the cutting edge and reducing wear.

The physical interpretations of these effects could be extended to include the role of the depth of cut and its correlation with the corner radius.

The importance of edge radius in the cutting process was closely investigated by Schimmel et al. [47], who showed that the machining force components were sensitive to changes in edge radius. The conclusion was that an accurate prediction of force magnitude and direction, for honed tools, may likely require consideration of hone variation around the corner and along the leading edge.

Considering the fact that the hone radius of commercial cutting inserts varies along the edge (presumably due to the geometry of the brush honing process), the development of a cutting model that reflects the effects of the edge radius on the cutting process is particularly beneficial.

Previous efforts oriented towards a better understanding of surface generation mechanisms have shown that differences in the nominal values of edge geometry will result in differences in the surface roughness and machining forces. In this regard, the results obtained by Thiele and Melkote [52] with CBN tools, showed that the feed rate is the dominant parameter associated with surface roughness and the edge geometry provides a secondary contribution. These are important observations, because empirical models of surface roughness, which ignore the effects of edge geometry, diverge from measured values at low feeds where the edge geometry is most significant.

Overall, the effect of edge hone on the surface roughness seemed to decrease with the increase in workpiece hardness. The study also showed that the cutting edge geometry has a significant effect on the axial and radial cutting force components (or the equivalent thrust force). The detailed experimental results obtained by Thiele and Melkote create the basis for further work focusing on the effect of cutting edge geometry on additional factors (such as residual stresses), aiming to optimize tool performance and machining processes.

The most effective approach used for the optimization of tool life and surface finish in high speed machining of hardened tool steels is by predicting stress and temperature distributions using finite element (FE) based numerical simulation of chip formation. Based on these models the optimum tool geometry and cutting conditions can be identified.

This technique was used by Ozel [41] in the investigation of temperatures and stresses developed on CBN cutting tools with different edge preparations, at different cutting speeds and feeds.

FEM cutting simulations were also performed by Yen et al. [56], who analyzed the effect of various edge geometries (hone edge and chamfer edge) on process variables that are very difficult to measure by experiment, such as contact stresses on the rake face and flank face of the tool, cutting temperatures at the tool-chip and tool-workpiece interfaces, chip temperature and sliding velocities between the chip and the tool.

Based on the results obtained by this simulation model the edge geometry may be optimized in order to achieve minimum tool wear, for a given set of cutting conditions and tool and workpiece materials.

The new orthogonal process model developed by Manjunathaiah and Enders [34] includes the effects of edge hone, without resorting to the finite element method or rigorous slip line analysis. The authors relied mainly on several observations and experimental results from the metal cutting literature. Based on their model, valuable insight is obtained in terms of shear strain and strain rate distribution, and other material behavior models can be developed.

In the case of ultra-precision machining, where the depth of cut is much less than $1\mu m$ or even to the order of nanometers, the tool edge radius plays an essential role in the chip formation process and is reported to be an important cause of the 'size effect'.

In the work of Kim et al. [23], numerical and experimental analyses, performed for different edge radii, confirm that a major cause of the 'size effect' is the tool edge radius and show the effects on cutting forces, strain rate and temperature distribution.

The analytical model proposed by Ren and Altintas [46] is intended to enable the selection of optimal chamfer angles and cutting speeds which result in minimum tool wear and relatively lower cutting forces and temperatures. This model was experimentally verified by high-speed orthogonal cutting tests using carbide and CBN cutting tools, but to date no results have been reported for HSS tools.

Movahhedy et al. [39] developed a finite element model that can be used to optimize the cutting edge shape, chip load and cutting speed which lead to lower residual stresses on the finish surface and maximum temperature gradients on the tool. The experimental verification, however, was performed on a limited range of cutting conditions and edge geometries, leaving room to extend this study for varying chamfer length, ratio of chamfer size to uncut chip thickness, cutting parameters and materials.

For uncoated carbide tools, Schmidt et al. [49] suggested a FEA-based model to predict the evolution of tool wear in orthogonal cutting conditions. Although the results proved to be in good agreement with the experimental measurements to some extent, the capability of the model applied to different edge geometries seems to be limited.

For the optimization of cutting operations in mass production environments the objective functions and constraints are normally proposed for 'steady state' conditions, where a cutting tool is used for machining the same workpiece material, at the same cutting conditions, until the tool reaches the end of its useful life.

In small batch production environments, such conditions are rarely encountered and such assumptions are not realistic [1]. In this case it is assumed that a cutting tool is used to cut a variety of workpiece materials, under a wide range of cutting process parameters, so that a wider range of cutting tools can be used for a range of materials.

In the work of Axinte and Gindy [1] a new strategy for turning process optimization is proposed for batch production environments. This optimization strategy attempts to maximize material removal rate by taking into account surface roughness, system stability and cutting tool failure as its technical constraints. One of the novel aspects of this work is that it enables a more complete tool failure avoidance strategy to be developed, taking into account tool wear progression under a variety of conditions. 'Tool wear history' is included in the formulation of process constraints and represents the additive nature of tool flank wear, resulting from machining different materials under various cutting conditions.

Based on the knowledge of the accumulated tool wear, the remaining cutting time up to a specified level of tool flank wear is then evaluated. A comparison of the available cutting time with the required cutting time necessary to machine a batch of components, is used as the basis of a strategy for adjusting process parameters and maximize material removal rate, while avoiding premature tool failure.

In their analysis, Axinte and Gindy used the term '*hyperspace i*' to designate the set of cutting conditions at a certain stage *i* of a cutting process. In each hyperspace a cutting tool accumulates a certain amount of tool wear and flank wear is assumed to be additive throughout all hyperspaces. A cutting tool reaches the end of its useful life after progressing through a finite number of hyperspaces.

Figure 2.30 [1] shows two theoretical plots of tool wear versus cutting time in succeeding hyperspaces, when the influence of workpiece material and cutting parameters are not taken into account.

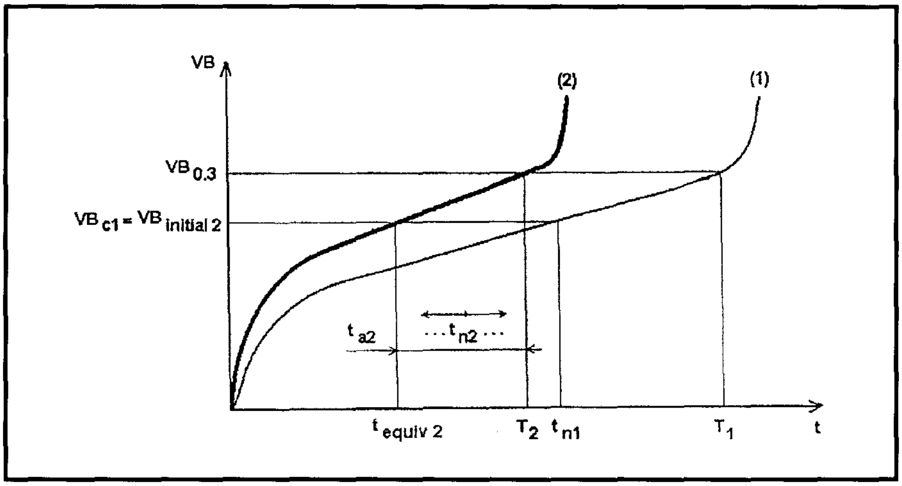


Figure 2.30 Examples of tool wear vs. cutting time in two different hyperspaces, when the influence of workpiece material and cutting parameters are not taken into account [1].

The concept of recording the evolution of tool wear under different cutting conditions and the methodology of transferring cumulative amounts of wear between hyperspaces was termed as 'tool wear history'.

The strategy proposed by Axinte and Gindy proved to maximize material removal rate, fulfilling technical restrictions (such as surface roughness, vibration and tool failure), by selecting the appropriate cutting parameters for each batch of components. A step further could be to extend this procedure to include different combinations of tool-workpiece materials and cutting edge geometries.

Current research suggests that coatings are a critical component of modern tool manufacturing, meaning that a good coating will extend tool life. Experiments conducted by Dr. Johann Rechberger of the Swiss tool manufacturer Fraisa, indicated a complex interdependence between the geometry, including substrate material, and the coating [45]. In these experiments two different geometries for HSS inserts were tested in turning operations. Geometry *A*: rake angle = 6°, clearance angle = 5° and geometry *B*: rake angle = 5°, clearance angle = 6°. The cutting tests were repeated for geometries *A* and *B* coated with TiN.

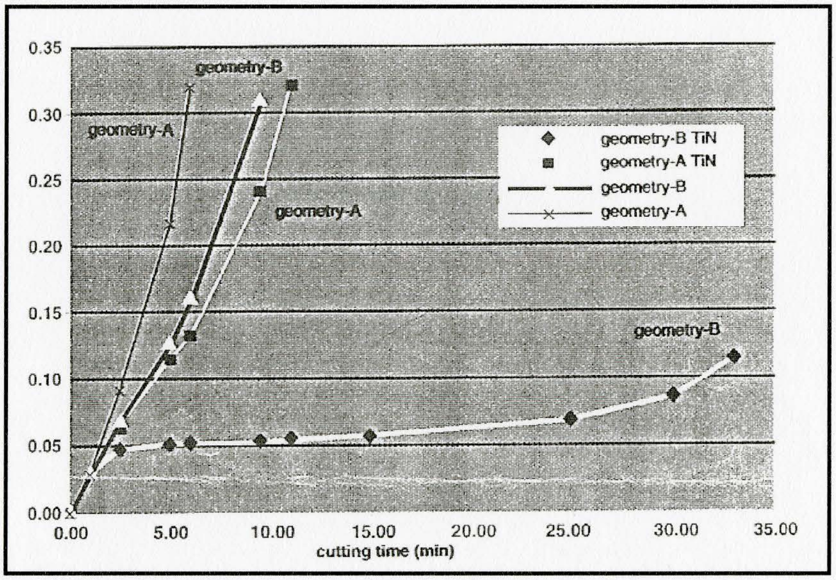


Figure 2.31 Influence of cutting tool geometry on the wear of HSS tools for turning [45].

As shown in Figure 2.31 [45], no considerable advantage can be observed with tool geometry *A* and a TiN coating in terms of tool life improvement. By changing the tool's orthogonal rake and clearance angles with only one degree (geometry *B*), tool life can be significantly increased.

Besides cutting tool geometry, tool life enhancement can be obtained based on an extensive investigation of tool failure mechanisms. Bouzakis et al. [7] studied the wear mechanisms of PVD coated cemented carbide tools in turning, at various cutting speeds.

Their experimental and analytical results show that the cutting speeds have a significant impact especially on chip compression ratio and stress distribution on the tool rake face. The evolution of the flank wear is shown in Figure 2.32[7]. At lower cutting speeds, the coating failure was initiated by the intense loads, close to the coating static load limit at the beginning of cutting. This caused a loss of adhesion between the coating and the tool and then chipping.

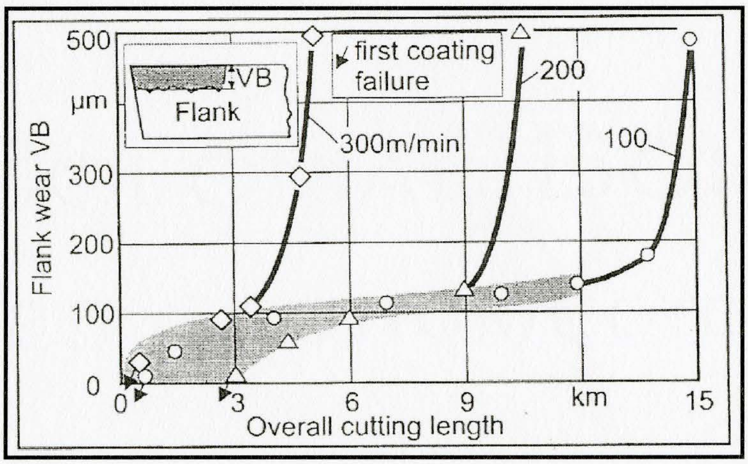


Figure 2.32 Flank wear vs. accumulated cutting length in turning at various speeds [7].

At higher cutting speeds, an improvement of coating adhesion was observed, increasing the coating service life. A further increase in cutting speed revealed the dominant influence of abrasive phenomena and loss of adhesion for the coating.

Klocke et al. [26] studied the effect of advanced coatings, such as multilayer hard thin films or composite hard/soft coatings, on the contact conditions and wear mechanisms during machining of different materials. It was found that the most significant factor is the influence of coating thickness on the progress of wear in terms of the available wear volume and the thermal relief of the substrate material. Experiments indicated that coatings reduced adhesion mainly in the lower range of cutting speeds and for abrasion the most suitable coatings were the TiAl-based or films containing Al_2O_3.

Some research directions suggested by the authors are to study the possibilities to change the contact conditions in order to reduce adhesion and improve the resistance of the substrate-coating combination against adhesive wear. This could be realized by using friction reducing coatings, or work materials with lubricating functions.

The influence of the coating structure on the behavior of the tribo-contact between the tool and the chip was experimentally studied by Grzesik and Nieslony [18], for different coating materials. The results were presented from the mechanical and thermal point of view. The mechanical aspect included the variations of the specific cutting pressure and mechanical loading equivalent and the thermal aspect was discussed in terms of thermal conductivity of coating and workpiece materials.

For milling operations, Bouzakis et al. [3] studied the wear behavior of PVD coated cemented carbides for various cutting edge radii (Figure 2.33[5]). The results indicated that the cutting performance of PVD coated tools can be increased through size optimization and appropriate manufacturing procedure of the edge roundness.

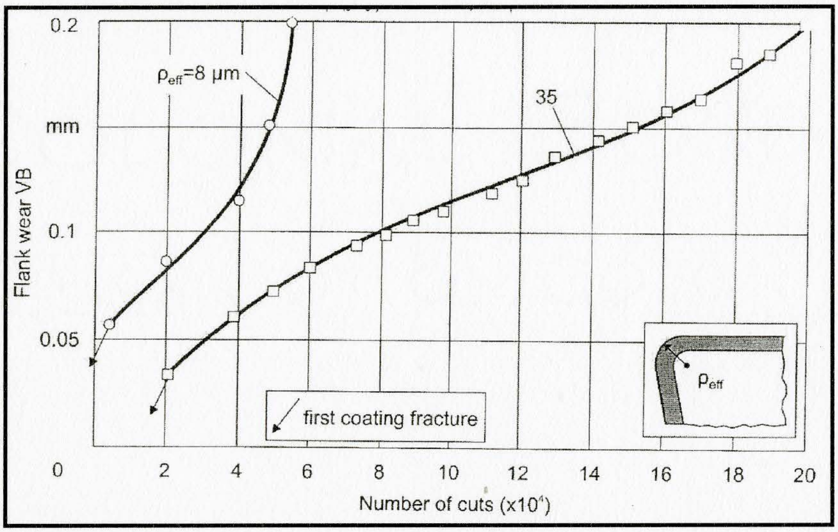


Figure 2.33 Flank wear versus number of cuts for 2 different radii, 8 μm and 35 μm [5].

The most recent developments are in the field of superhard nanocomposite coatings. J. Musil [40] reviewed the evolution of hard coatings from a titanium nitride film through superlattice coatings to nanocomposite coatings and discussed the correlation between the hardness and structure of these coatings.

Zhang et al. [59] studied the advances in the design concepts and preparation methods of superhard nanocomposite coatings, with emphasis on magnetron sputtering. In this research it was shown that superhard nanocomposite thin films can be obtained through an optimal design of the microstructure, which confers high hardness and high toughness to the material. Although these coatings are at the beginning of their development, they are already finding a wide range of applications.

G. Fox-Rabinovich et al. [15] investigated the wear behavior of cutting tools with 'duplex' coatings as well as the change in chemical composition and microstructure at the tool/workpiece interface. The research shows that for non-stable or surface damaging friction conditions, much of the hard coating is destroyed during the running-in stage of wear, which leads to a significant decrease in the wear resistance of the coatings.

To protect the surface of the hard coating, the authors suggest a top layer with high anti-frictional properties. The idea is to localize most of the external interaction into a thin surface layer, at the maximum dissipation of energy generated during friction. The application of the anti-frictional layer is intended to prevent the intensive surface damage of TiN coating and to promote a stable compound formation at the surface during the running-in stage of wear. As a result, the stable stage of wear starts with lower surface damage, corresponding to an increased tool life.

Several oxides, such as WO_3, V_2O_5 and TiO_2 exhibit good tribological properties at elevated temperatures and can be deposited by PVD methods.

A very effective commercial coating of this type (which was also used in the cutting experiments of the present research), is the multi-layered TiAlN/WC-C hard lubricant coating developed by Balzers, which presents the advantage of a very low initial wear rate during the running-in stage of wear.

Further improvement of tool life can be achieved by applying an additional sublayer to the 'duplex' coating at the surface of the tool substrate. This process is called 'triplex' coating and combines the desired protective and anti-frictional properties at the surface and good adhesion at the coating-substrate interface. These coatings are formed by a diffusion saturation process with nitrogen (ion-nitriding), followed by the application of a (Ti, Cr)N hard PVD coating. Fox-Rabinovich et al. [16] studied the wear behavior of HSS cutting tools with a 'duplex' coating that is additionally improved by ion mixing. The coating included an additional ion mixed layer applied to the previously nitrided surface of HSS prior to the deposition of a hard PVD coating. A significant increase (3-4 times) in tool life was observed, due to the increase of the stable stage of wear.

This review was intended to give an account of the technological developments in tool life optimization that have been commercially implemented in modern metal-cutting tools. There is a trend toward new geometries to meet the requirements of speed, feed, and depth of cut in removing metal faster, cleaner and more manageably.

Coating developments have extended the range and performance of high-speed steels and solid-carbide tooling. Other materials such as polycrystalline diamond and cubic boron nitride are finding application in difficult machining operations.

At the same time, carbide indexable inserts continue to show their versatility and ability to combine machining operations in one tool, while high-speed steels are used for applications requiring long life at relatively high operating temperatures, such as for heavy cuts or high-speed machining and under conditions which benefit from the toughness of material.

3. Experimental Results and Discussion

Experimental plan

The goal of this research is to develop a technique for establishing the best edge preparation for a specific application which results in a long tool life and higher productivity and quality. Tool life improvement by means of adapting the tool edge geometry to mimic the shape of the "natural wear" is the method being proposed. The steps followed to obtain this goal were to:

- perform cutting tests
- measure tool wear
- extract shape of cutting edge that corresponds to the shape of natural wear
- model this shape as a chamfer
- produce a new tool with the chamfer
- repeat cutting tests with the new tool to confirm tool life improvement

3.1 Cutting tests

A series of orthogonal turning tests were performed on a Boehringer (VDF 180 CM) turning centre (Figure 3.1). The work-piece material, cutting tools and cutting conditions are presented in Table 3.1. For the cutting tests using inserts that were not coated, a coolant was used.

Table 3.1 Cutting parameters

<table>
<tr><td>Cutting tools</td><td>Workpiece material/hardness</td><td>Speed, m/min</td><td>Feed, mm/rev</td><td>Depth of cut, mm</td></tr>
<tr><td>HSS insert</td><td>4340 steel/
HRC 50</td><td>35</td><td>0.11</td><td>0.5</td></tr>
<tr><td>Cemented carbides with TiAlN coating</td><td>1040 steel/
HB 220
4340 steel/
HRC 50</td><td>450

182</td><td rowspan="2">0.11</td><td rowspan="2">0.5</td></tr>
<tr><td>HSS with multi-layer WC/C-TiAlN coatings</td><td>4340 steel/
HRC 40</td><td>150</td></tr>
</table>

These cutting conditions were experimentally determined to minimize build-up edge and avoid chipping.

The tetragonal indexable cutting inserts were made of HSS T15 and Sandvik H1P WC-TiC grade of carbide, especially designed for high-speed machining applications. The chemical composition of the cemented carbides is the following: WC-85.5; TiC-7.5; TaC-1.0; Co-6.0 wt. %. TiAlN coatings were deposited on the rake and flank surfaces of HSS and cemented carbide substrates.

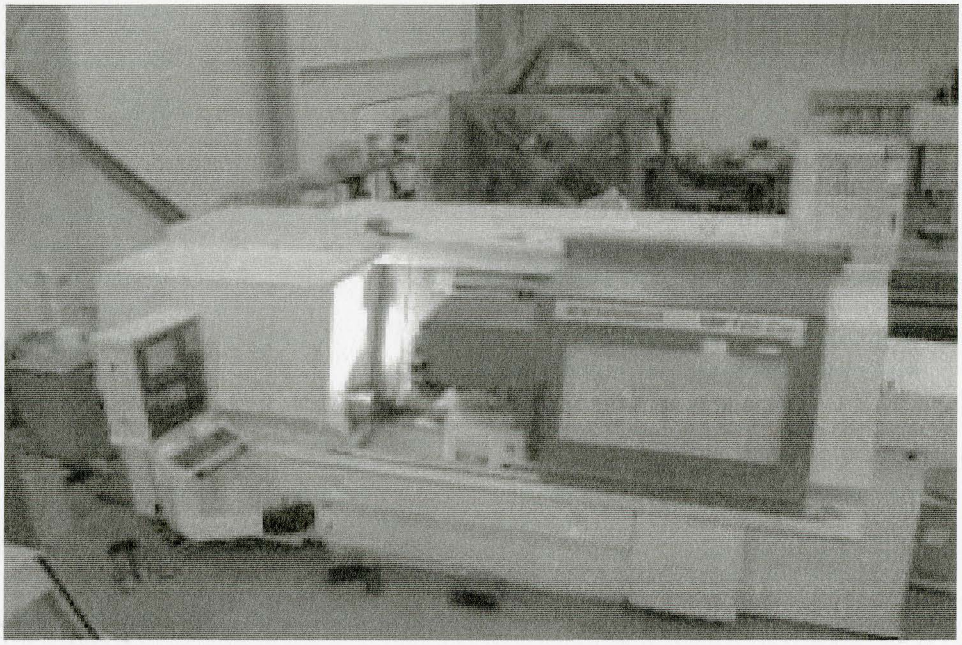


Figure 3.1 Boehringer VDF 180CM

3.2 Tool wear measurements

Four types of edge geometries were tested for uncoated HSS and cemented carbide inserts (Figure 3.2). Geometry **I** had a chamfer on the rake face of 0.1-0.15 mm wide, at an angle of 10°, geometry **II** had a facet on the flank face of 0.1mm, geometry **III** had a rounded edge of radius 0.1-0.15 mm. An up-sharp edge (lead angle = 15°, clearance angle = 11°) was also used for comparison.

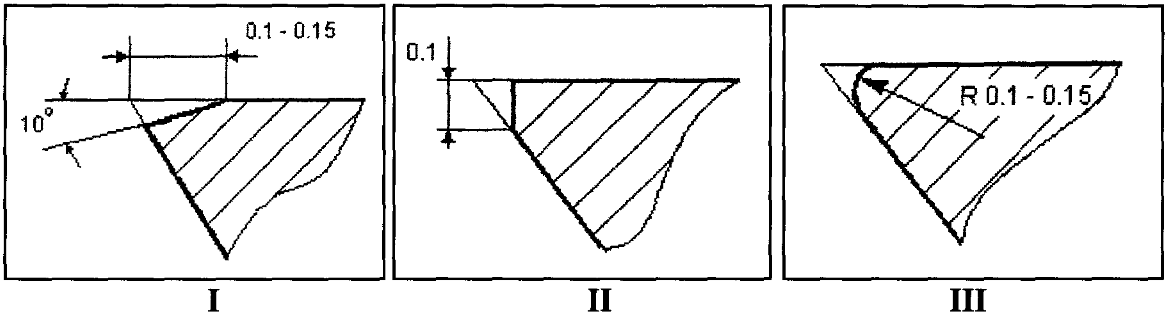


Figure 3.2: Types of facets investigated: **I** chamfer on rake face;
II chamfer on flank face; **III** cutting edge rounding. The length of land is 50 μm

Flank wear was measured after each pass with a *Nikon SMZ 1000* electronic microscope and chips were collected at different lengths of cut, corresponding to the running-in and stable stages of wear.

3.2.1 Cutting tests with cemented carbide inserts

The data obtained for the tool wear from the cutting tests with cemented carbides with TiAlN coating (Balzers X-treme) are presented in Figure 3.3. The inserts without a chamfer as well as the inserts with the chamfer on the flank face (II) and the rounded facet (III) exhibited linear curves of wear. This indicated that the wear rate was high. On the other hand, the chamfer on the rake face (I) significantly improved tool life, due to the stabilization of the wear rate after a length of cut of about 400-500 m. There are two main reasons for this behavior. The first is attributed to the geometry of the cutting edge, which contributes to the distribution of forces and residual stresses. Secondly, the tribofilms that are formed and their effects on cutting temperature and tool wear.

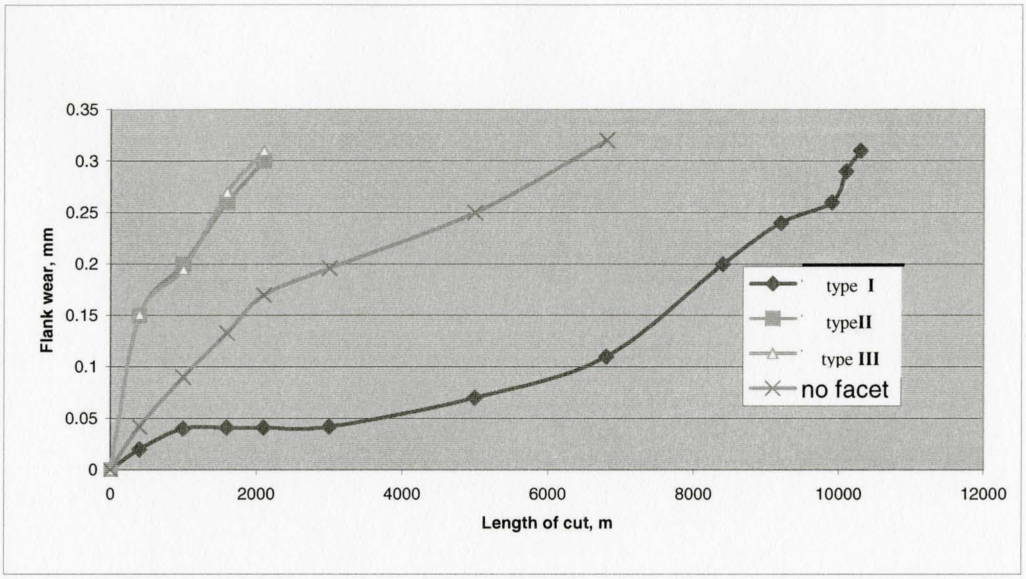


Figure 3.3 Flank wear vs. length of cut for the three types of edges of cemented carbide inserts with TiAlN coating. (v = 450 m/min; feed =0.11 mm/rev; depth of cut= 0.5 mm)

This phenomenon can be explained based on the SEM investigations of the cutting edge morphology vs. length of cut. The images presented in Figure 3.4 show regions of plastic lowering. Under conditions of high-speed machining the cutting edge change in shape takes place, in other words 'plastic lowering' is observed due to high temperatures (around 1000°C) generated during cutting at the tool/workpiece interface.

The fabrication of a chamfer on the rake face strengthens the cutting wedge, which prevents plastic lowering and thus leads to wear rate stabilization. The length of the chamfer is also important. Experimental results have shown that an increase in length from 50 microns to 150 microns led to an improvement of tool life by 65%. This can be explained by the fact that the chamfer of 0.05mm is smaller than the uncut chip thickness

(0.11 mm) and leads to plowing, whereas the chamfer of 0.15mm is greater than 0.11mm and enables better cutting conditions.

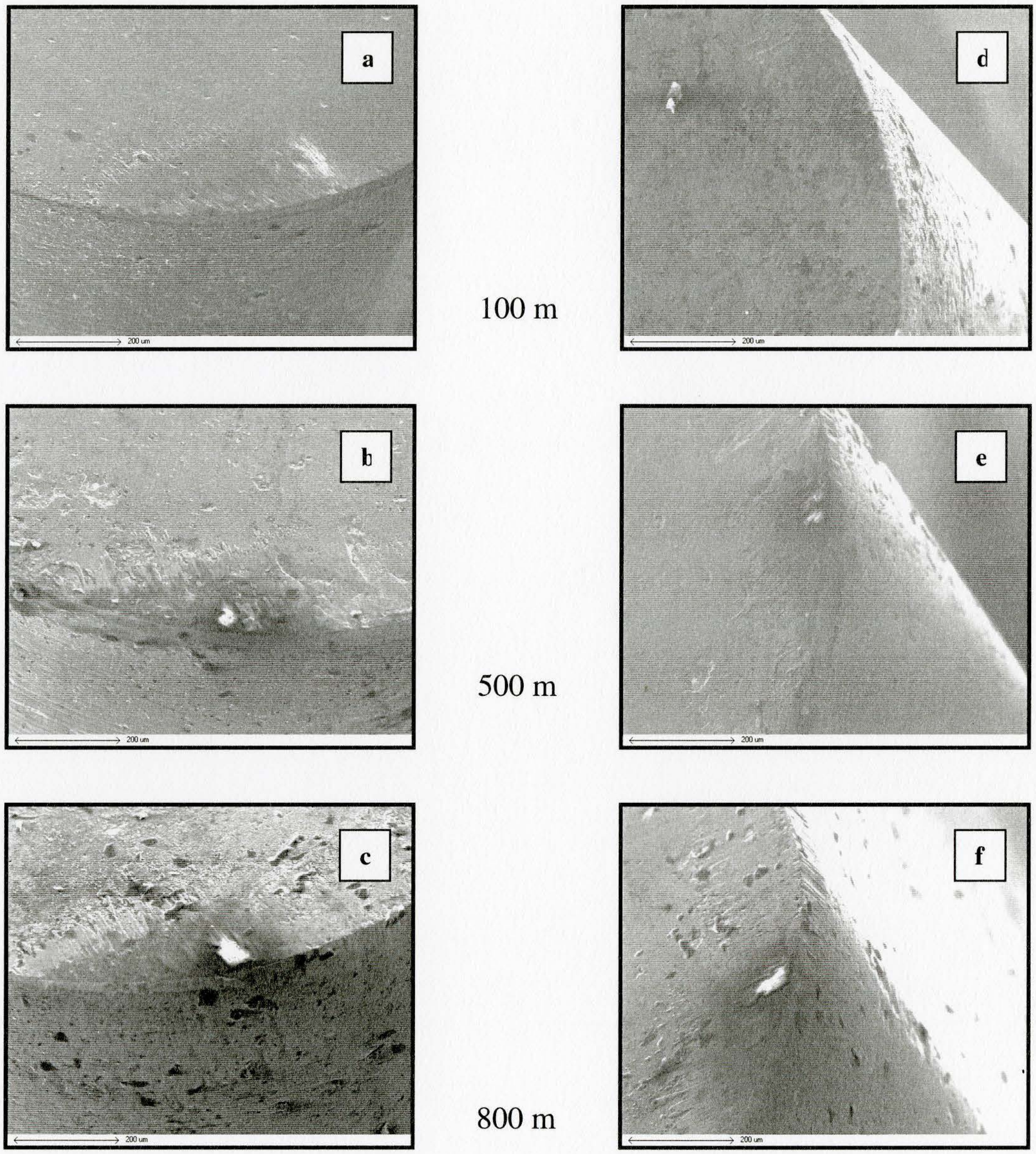


Figure 3.4: SEM images of the cemented carbides inserts with Balzers X-treme TiAlN coating. Plain view of the rake face (a-c) and side view of the cutting edge (d-f). The rake face morphology changes vs. length of cut.

3.2.2 Cutting tests with high speed steel inserts

The cutting tests revealed that the design of the turning inserts had a significant effect on wear behavior, during machining with HSS tools at low and moderate speeds. Comparative studies were conducted between the sharp tool and the chamfered tools regarding flank wear and tool life. The longest tool wear was obtained with geometry **I**, as shown in Figure 3.5.

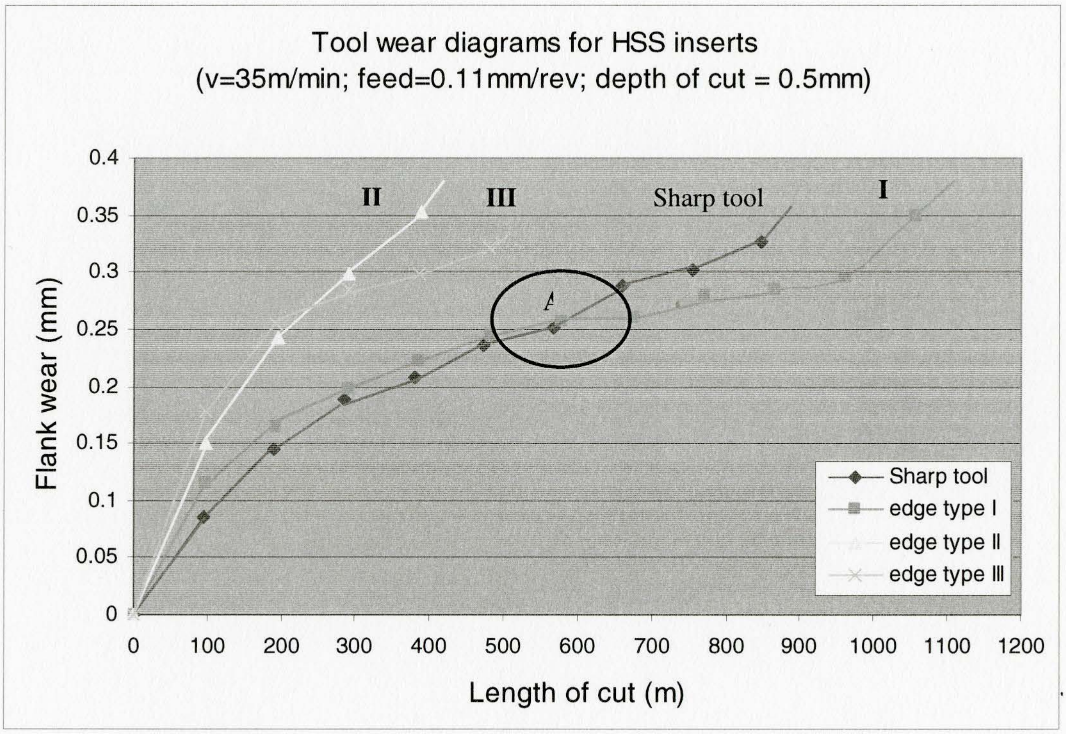


Figure 3.5 Tool wear diagrams for the various cutting edge types:
sharp tool; type **I** – chamfer on the rake face of 0.1-0.15 mm wide, at an angle of 10°; type **II** – chamfer on the flank face of 0.1mm; **III** - rounded edge of radius 0.1-0.15 mm.

This improvement in durability shows that the chamfer on the rake face of the tool strengthens the cutting edge and reduces surface damage. The intersection between the wear curves of the sharp edge and chamfered edge **I** (point A in Figure 3.5) indicates that the chamfered tool takes on the same geometry as the sharp tool, but the damage done reaching this geometry is less, so the stable stage of wear is longer.

3.2.3 Cutting tests with coated high speed steel inserts

In order to avoid the formation of a built-up edge and investigate the change in edge geometry during cutting, the HSS inserts were coated with Balzers Hardlube multilayered coatings (outer layer-WC/C coating; sublayer TiAlN coating). The results obtained for the flank wear are shown in Figure 3.6.

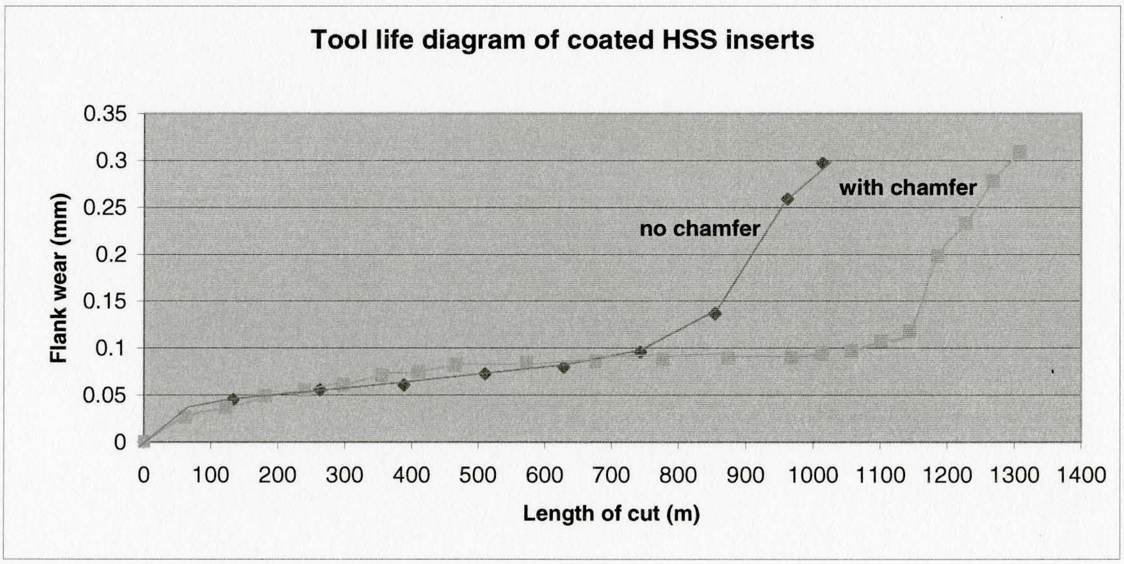


Figure 3.6 Tool life diagrams for coated HSS inserts (cutting speed=150m/min, feed=0.11mm/rev, depth of cut=0.5mm)

The change in the rake face morphology can be observed in Figure 3.7, for the two edge geometries (sharp and chamfered), at different lengths of cut.

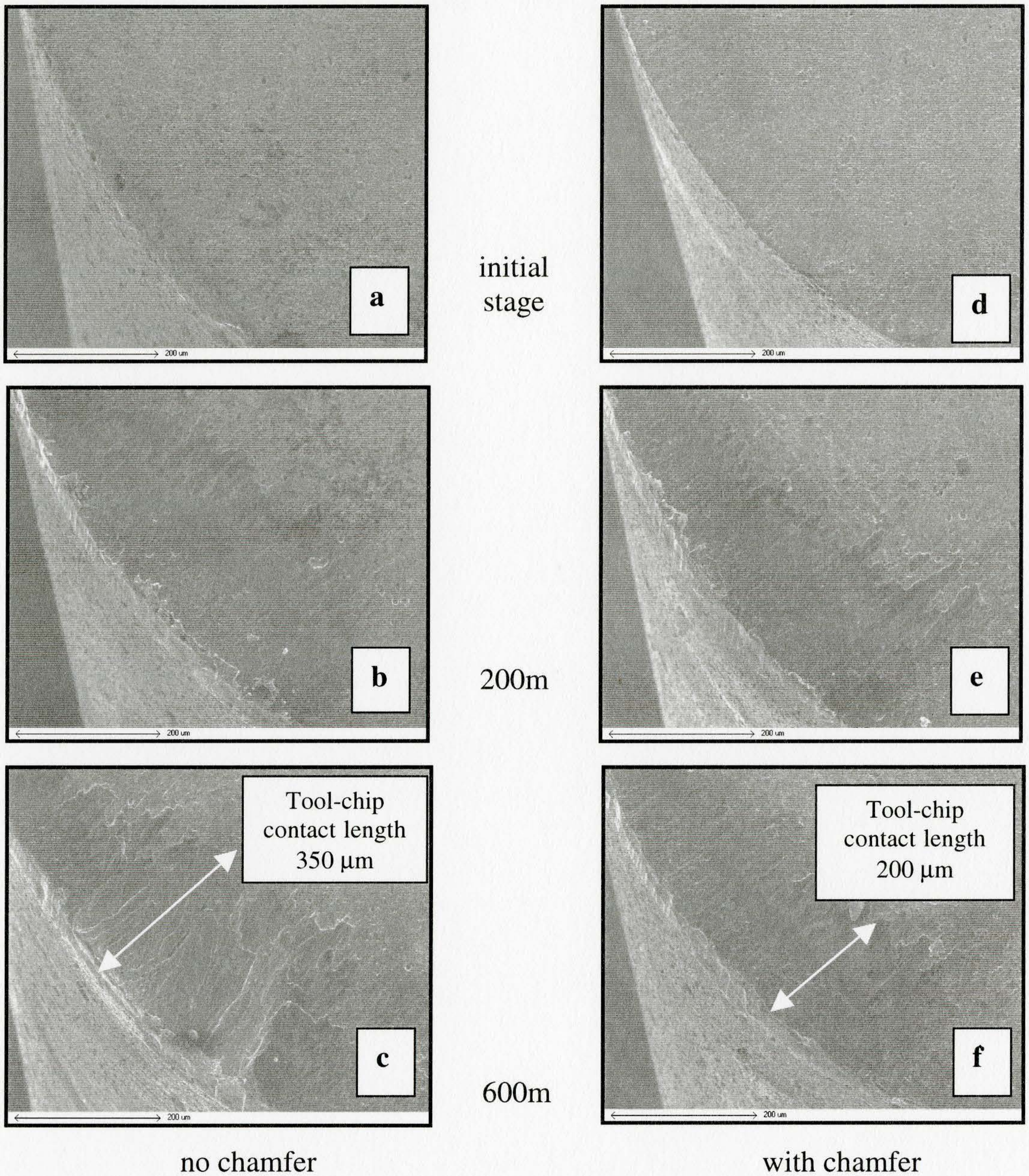
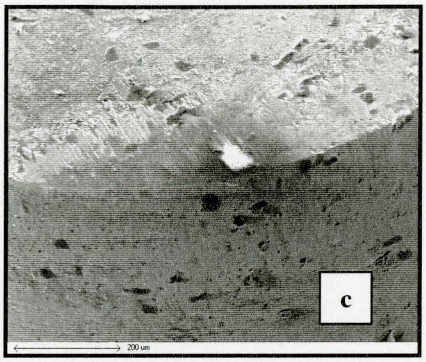


Figure 3.7: SEM images of HSS inserts with WC/C+TiAlN multi-layered coatings a-c) no chamfer; d-f) with edge type **I**; (a, d) initial stage; (b, e) – length of cut, 200m; (e, f) – length of cut, 500 m.

The most intensive tool surface damage during cutting takes place in the zone close to the cutting edge, which undergoes plastic deformation or chipping at the very beginning of the wear process. Based on the data obtained we can assume that the type of cutting tool failure strongly depends on the cutting conditions. Under high-speed machining conditions the cutting edge of cemented carbide tools undergoes plastic deformation, or a so called 'plastic lowering' (Figure 3.4, c), while the HSS cutting tools operating under low and moderate cutting speed conditions, where an abrasive wear mode dominates and deep surface damage of the cutting edge is exhibited (Figure 3.7, c).

The processes of plastic deformation and fracture switch the 'tool/workpiece' tribosystem to the strongly non-equilibrium conditions. The processes considered are very far from their equilibrium state and the mimicking of the wear pattern is practically impossible. The process of wear should be transformed to a quasi-stable mode through a modification of the cutting edge design (Figure 3.8), by modeling the shape of the resulting cutting edge. Since the process of wear is transformed to a quasi-stable mode there is an improved ability to mimic the edge shape that corresponds to the point of transformation from the running-in to the post running-in stage of wear.



(Figure 3.4, c)

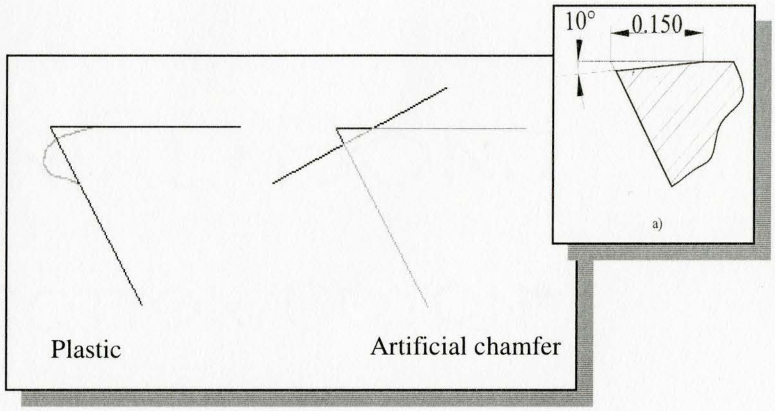


Figure 3.8 Prevention of cutting edge plastic deformation due to the rake face chamfering.

The areas around the cutting edge of the HSS inserts coated with multi-layered WC/C + TiAlN coatings, have been closely investigated (Figures 3.9 – 3.11).

Detailed SEM and EDS investigations of the area close to the cutting edge show that at the very beginning an intensive wear of the lubricating outer WC/C layer is taking place as a result of seizure with the workpiece material (Figure 3.9). As soon as the lubricating layer is gone, an intensive build-up forms on the cutting edge (Figure 3.10). This extremely unstable attrition wear mode results in rapid chipping of the cutting edge (Figure 3.11). EDS spectra presented in Figure 3.11 show the involvement of the substrate HSS material in the process of surface damage.

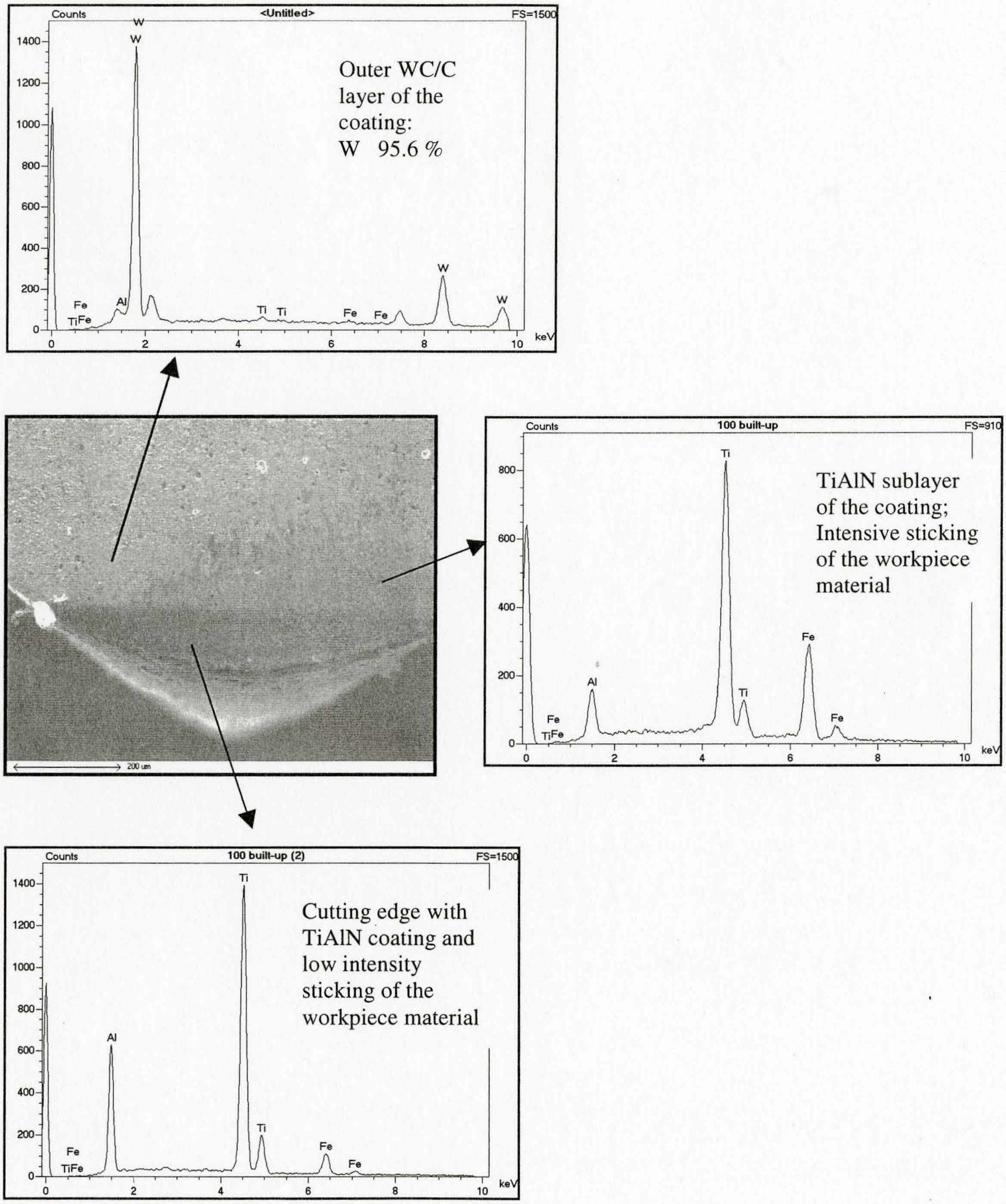


Figure 3.9 SEM images with EDS spectra of the rake face morphology of a HSS insert with Balzers multi-layered WC/C+TiAlN coating, after a length of cut of 100m.

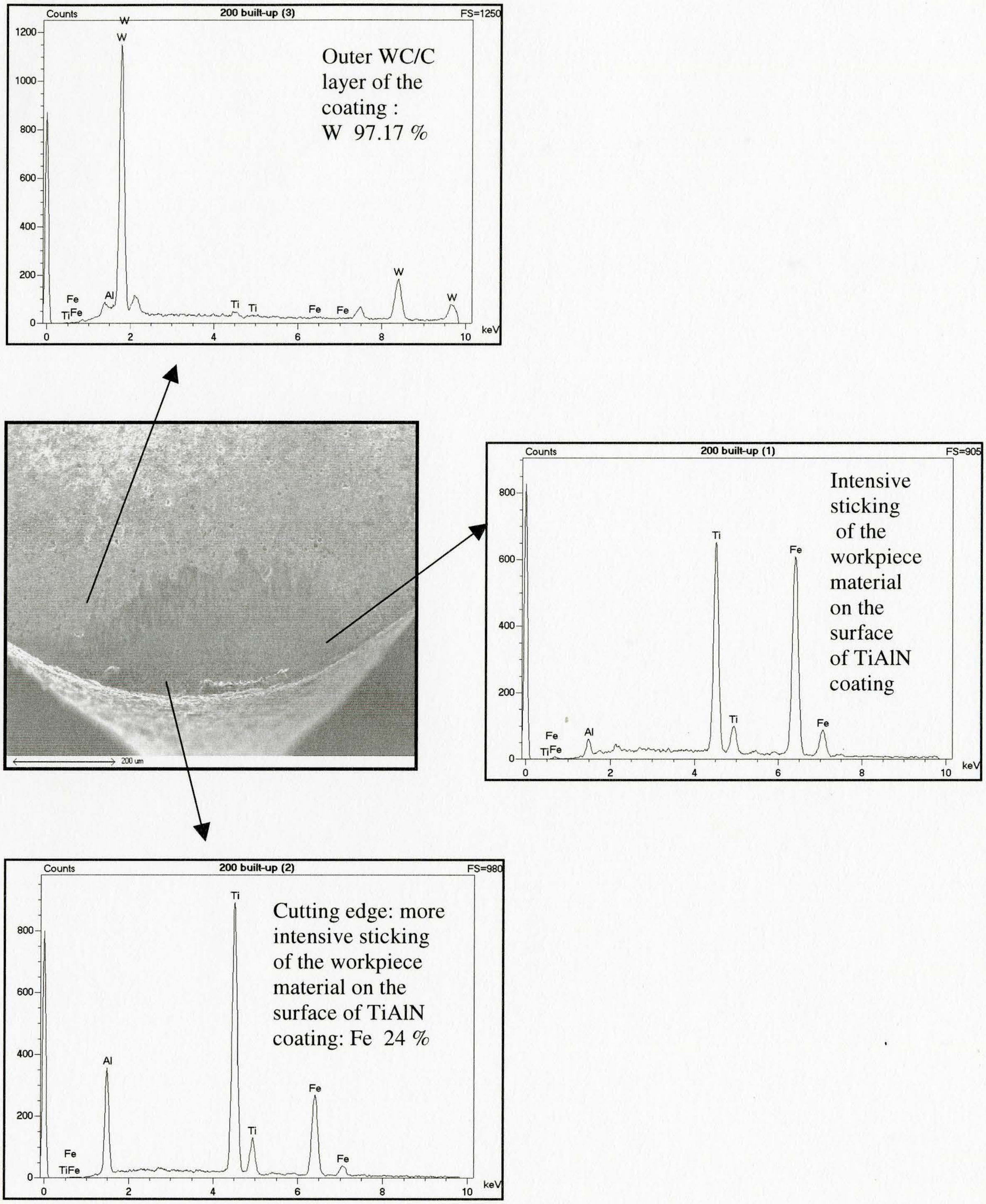


Figure 3.10 SEM images with EDS spectra of the rake face morphology of a HSS insert with Balzers WC/C+TiAlN multi-layered coating, after a length of cut of 200m.

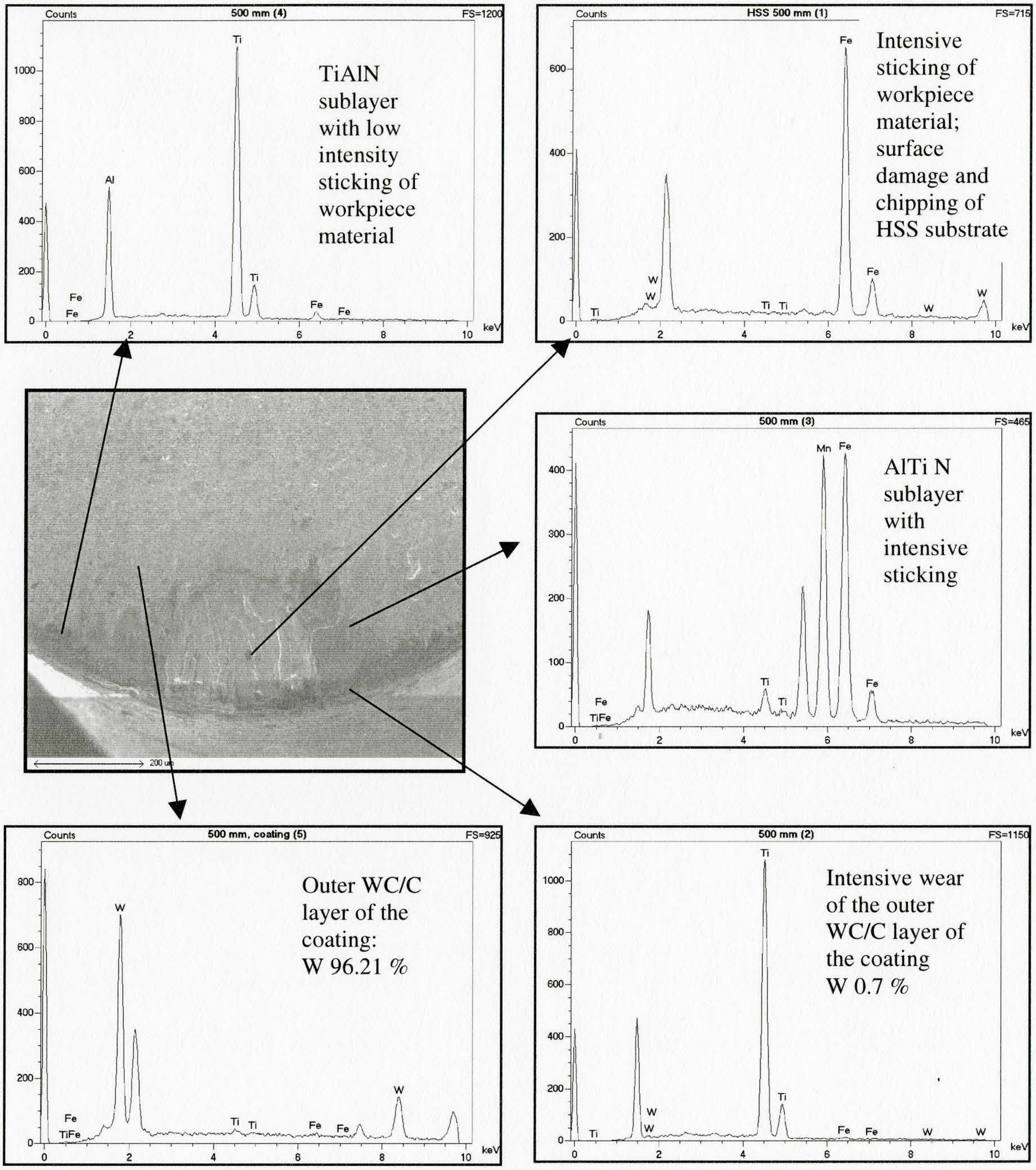


Figure 3.11 SEM images with EDS spectra of the rake face morphology of a HSS insert with Balzers WC/C+TiAlN multi-layered coating, after a length of cut of 500m.

3.2.4 Analysis of chip morphology

The chamfer fabrication leads to significant changes in the shape of the chips (Figure 3.12) produced during machining. The chips formed using the cutting inserts without a chamfer exhibit significant curling (Figure 3.12, a). In contrast, the chips that are formed when using cutting inserts with a chamfer on the rake face have almost no curl at all (Figure 3.12, c).

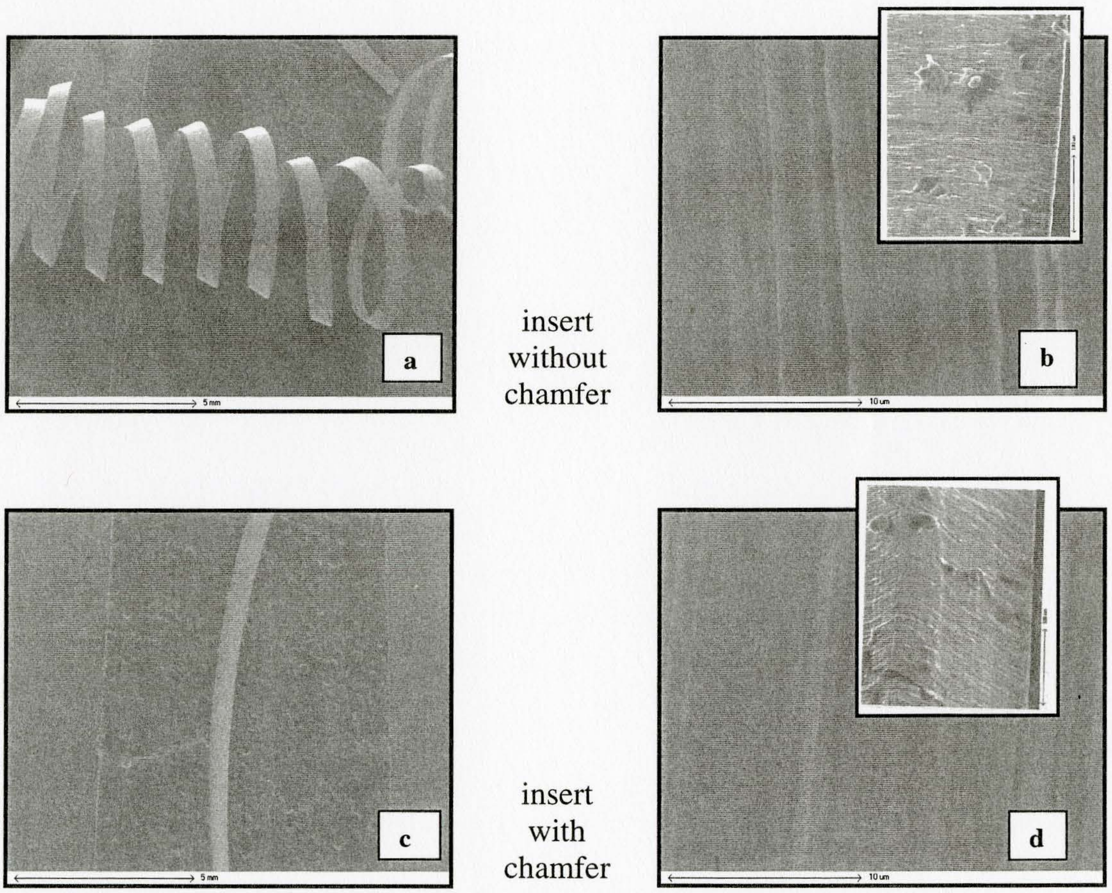


Figure 3.12 Types of chips for HSS turning cutters with multi-layered WC/C-TiAlN coatings. Length of cut 96 m.

In addition to this, comparing the images b) and d) in Figure 3.12, it appears that the chip is smoother when cutting with a tool chamfered on the rake face.

It is known that chips consist of a few typical zones. There is a zone of dynamic re-crystallization at the chip/tool contact area (Zone 1) and an extended deformation zone (Zone 2), that is far away from the interface. More heat flux goes into the chips causing more intensive re-crystallization to occur. This is exhibited in the grain coarsening of the chips within the contact zone (Figure 3.13 c). Figures 3.13, b-c show the dynamic re-crystallization of the chip contact zone for the inserts with chamfers on the rake face. Figures 3.13, e-f present similar images for the tools without chamfer. We can see that more intensive re-crystallization of the contact zone is taking place for chamfered inserts, because the thickness of this zone (Zone 1) is significantly wider and the grains are coarser.

When chips slide along the rake face of the turning insert, the curved flow lines are formed due to friction. More intensive metal flow results in intensive deformation within the extended deformation zone (Zone 1). Due to the higher intensity of deformation, Zone 2 is thinner (Figure 3.13, a and d). On the other hand, the tool-chip contact length, that can be measured directly using Figure 3.7, c-f is higher for the tools without the chamfer. This means that in-situ frictional characteristics chips are supposed to be better as well as the curling of the chips should be more intensive for the cutting tools with chamfers.

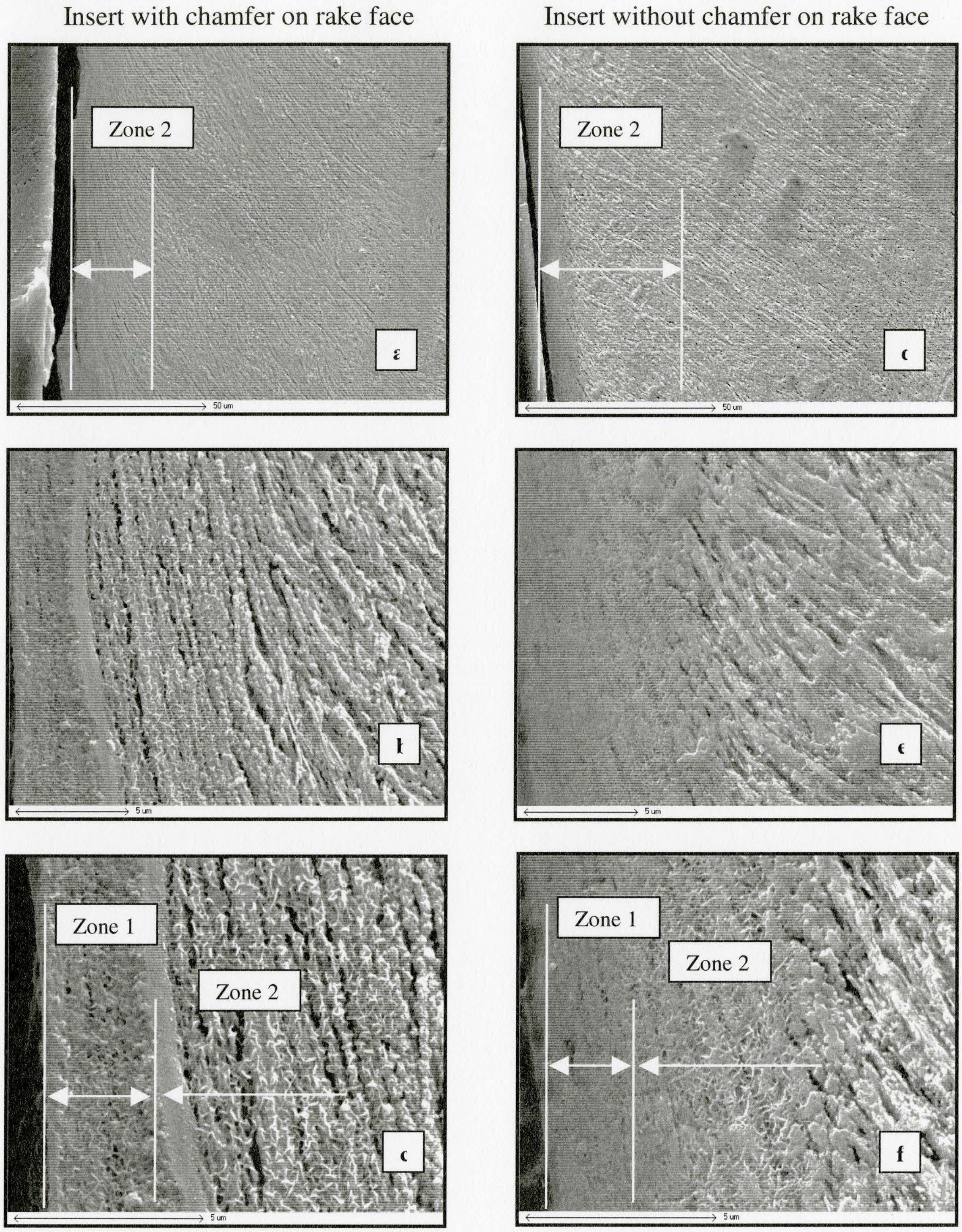


Figure 3.13 SEM images of the chips cross-sections for HSS inserts with multi-layered WC/C - TiAlN coatings. Length of cut 96 m; Zone 1- contact zone of the dynamic re-crystallization; Zone 2-extended deformation zone.

However, due to intensive heat flux into the chip (thicker zone of dynamic re-crystallization and coarser grain sizes, Figure 3.13), chips are forming without curling. The cause of this beneficial heat redistribution is the formation of protective tribo-films. These protective films have less time to form, due to the chipping that occurred when the inserts without the chamfer were used (Figure 3.7, c).

When inserts with chamfers were used, a more gradual wear process was observed, that resulted in wear rate stabilization, as shown by the high concentration of Al on the insert in the tool-chip contact area.

3.3 Extracting the shape of 'natural' wear

As mentioned earlier in this chapter, the process of adaptation is taking place during the running–in stage of tool wear. This is a very complex process related to the geometrical, chemical, structural and other transformations within the friction zone.

The "geometrical adaptation" refers to the geometrical changes of the cutting wedge that take place during cutting. This process results in the formation of a quasi-stable shape of the cutting edge, as well as stabilization of the wear rate. The shape of the cutting edge that corresponds to this point of transformation, from non-equilibrium (running in) to the quasi-equilibrium (stable) stage of wear and corresponding cutting wedge geometry, is the so-called shape of 'natural' wear.

Using a chamfered cutting tool we can create quasi-stable wear conditions and eventually observe an evolution of the cutting edge shape vs. the length of cut. Intensive wear takes place on both faces of the inserts (Figure 3.14) and eventually the hard coating is intensively wearing on the rake surface. The area of wear is wider due to the lower stress concentration, when compared to the tools without the chamfers (Figure 3.14, b-c). From the images presented in Figure 3.14, e-f, the 'natural' wear shape can be determined.

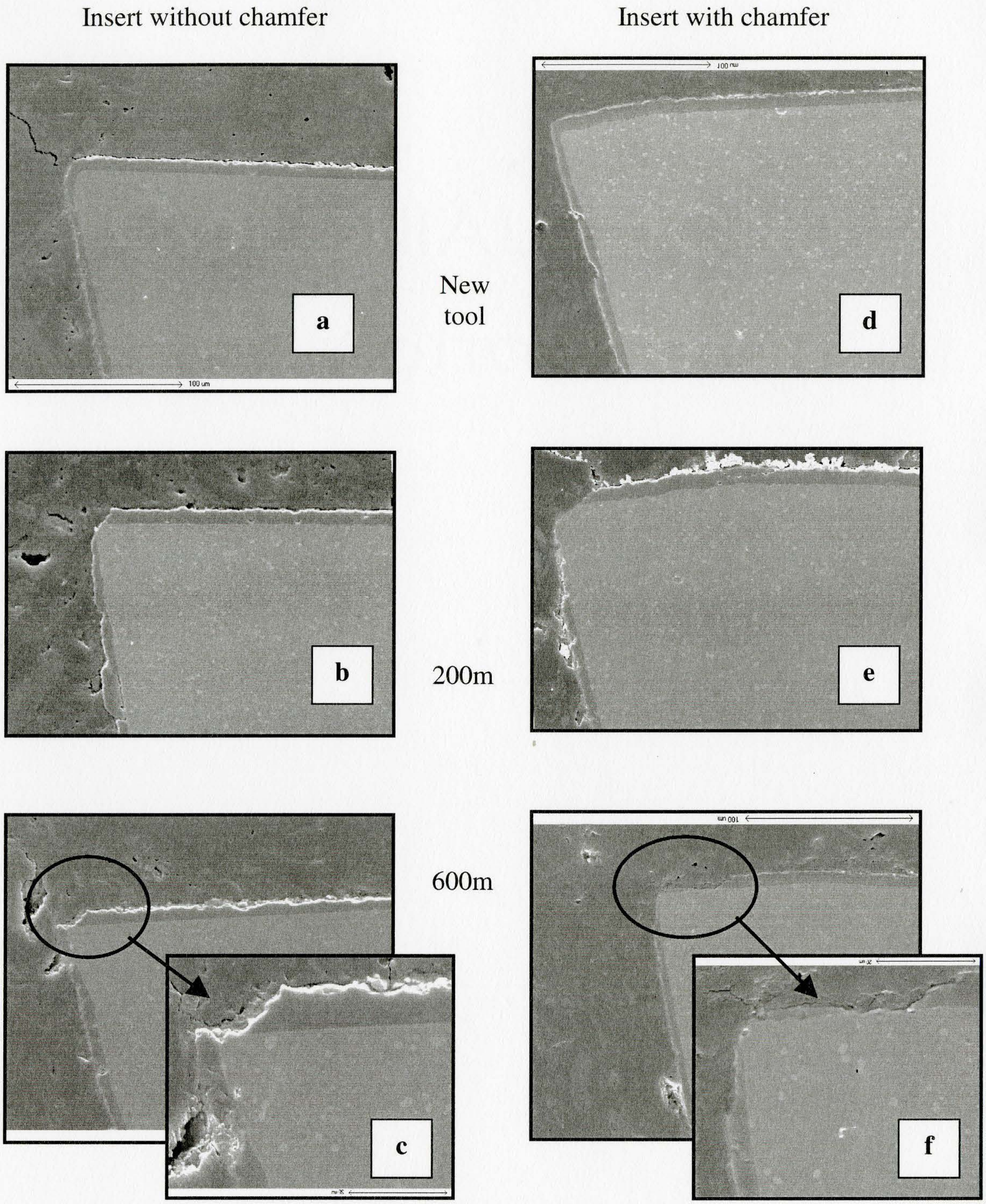


Figure 3.14 SEM images of cross-sections of coated HSS inserts with and without chamfer, for different lengths of cut.

3.4 Modeling the shape of 'natural' wear as a chamfer

The results of the modelling of the worn cutting edge at the transition from the running in to the stable wear stage were used to justify the design of the adaptive cutting tools. Based on the cross-sections shown in Figure 3.15 and the calculations performed, the chamfered cutting tools have been used with negative rake angles 5-10^0 and various types of chamfers of 150 microns (Figure 3.15, a-j) and 350 microns (Figure 3.15, k). The chamfered rake face design was compared to the variety of different cutting edge designs.

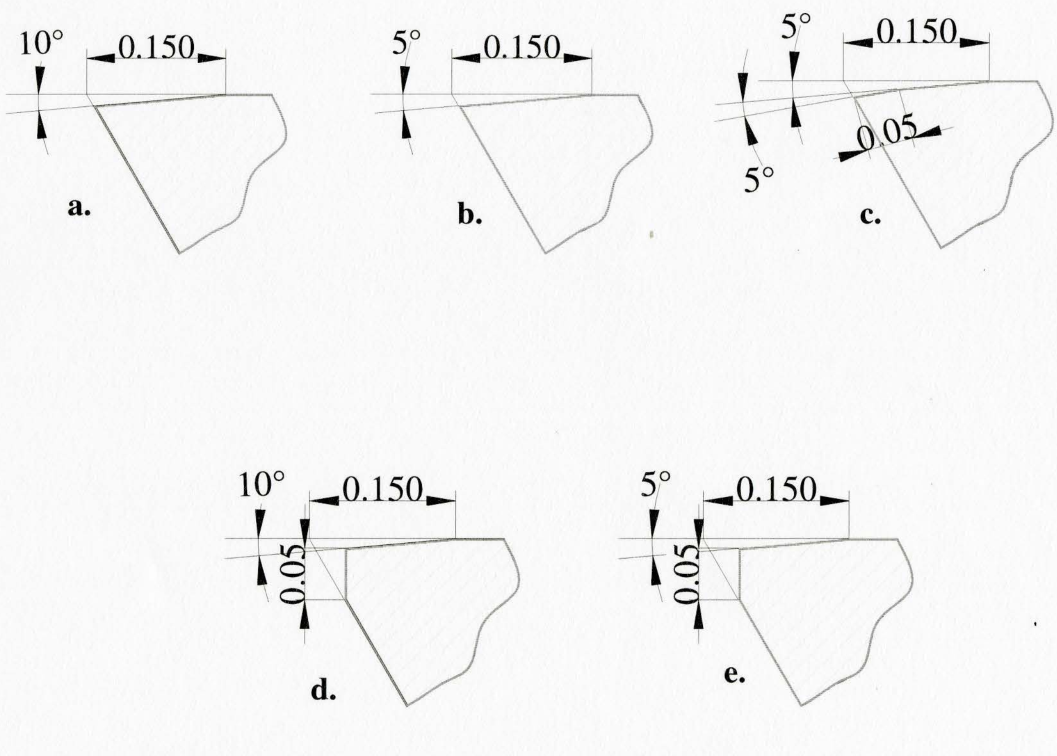


Figure 3.15 Chamfer designs that mimic 'natural' wear

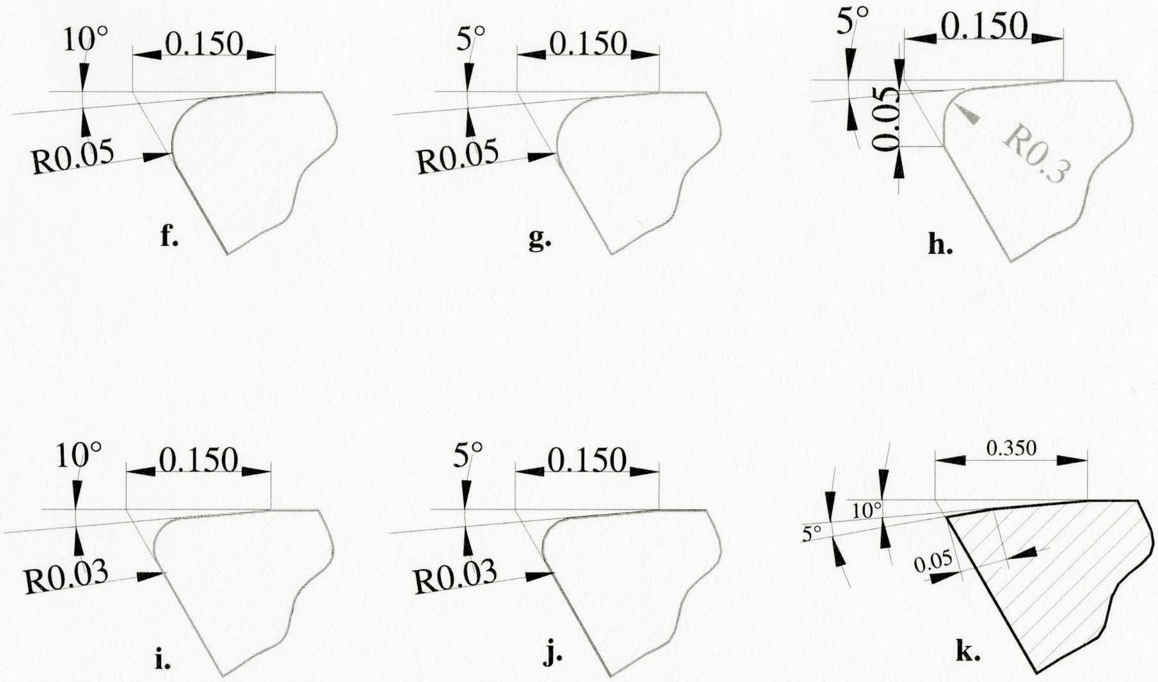


Figure 3.15 (continued) Chamfer designs that mimic 'natural' wear

3.5 Cutting tests with the new chamfered tools that mimic natural tool wear

Due to the difference in failure mechanisms for the HSS cutters under moderate cutting speed conditions and cemented carbide cutters under high-speed conditions, the impact of the cutting edge design on their adaptability is considered separately for the two types of cutting tools.

3.5.1 High Speed Steel Tools

The HSS inserts were manufactured in Great Britain and coated with Balzers Hardlube multi-layer coating.

The cutting tests performed showed that the double chamfered rake surface (Figure 3.15, c) resulted in a significant tool life improvement (Figure 3.16). This shape corresponds to the shape of 'natural' wear of the cutting edge at the specific point of transformation, from running-in to the post running-in stage when the wear rate drops significantly (Figure 3.16). This chamfer obviously strengthens the cutting edge and prevents deep surface damage (Figure 3.16, d-f). This leads to wear rate stabilization and improves the overall wear behavior and chip formation during cutting.

The size of the chamfered zone is the other important parameter. An increase in the total length of the double chamfered zone from 150 up to 350 microns results in critical tool life improvement due to the relationship with the value of the uncut chip thickness.

We can assume that the wear rate stabilization of the double chamfered tools is also associated with the microstructure of the tribo-films that are formed. Low wear intensity could indicate the formation of more stable tribo-films. Thus the geometrical adaptability could affect the structural adaptability. Further research is needed to confirm this hypothesis.

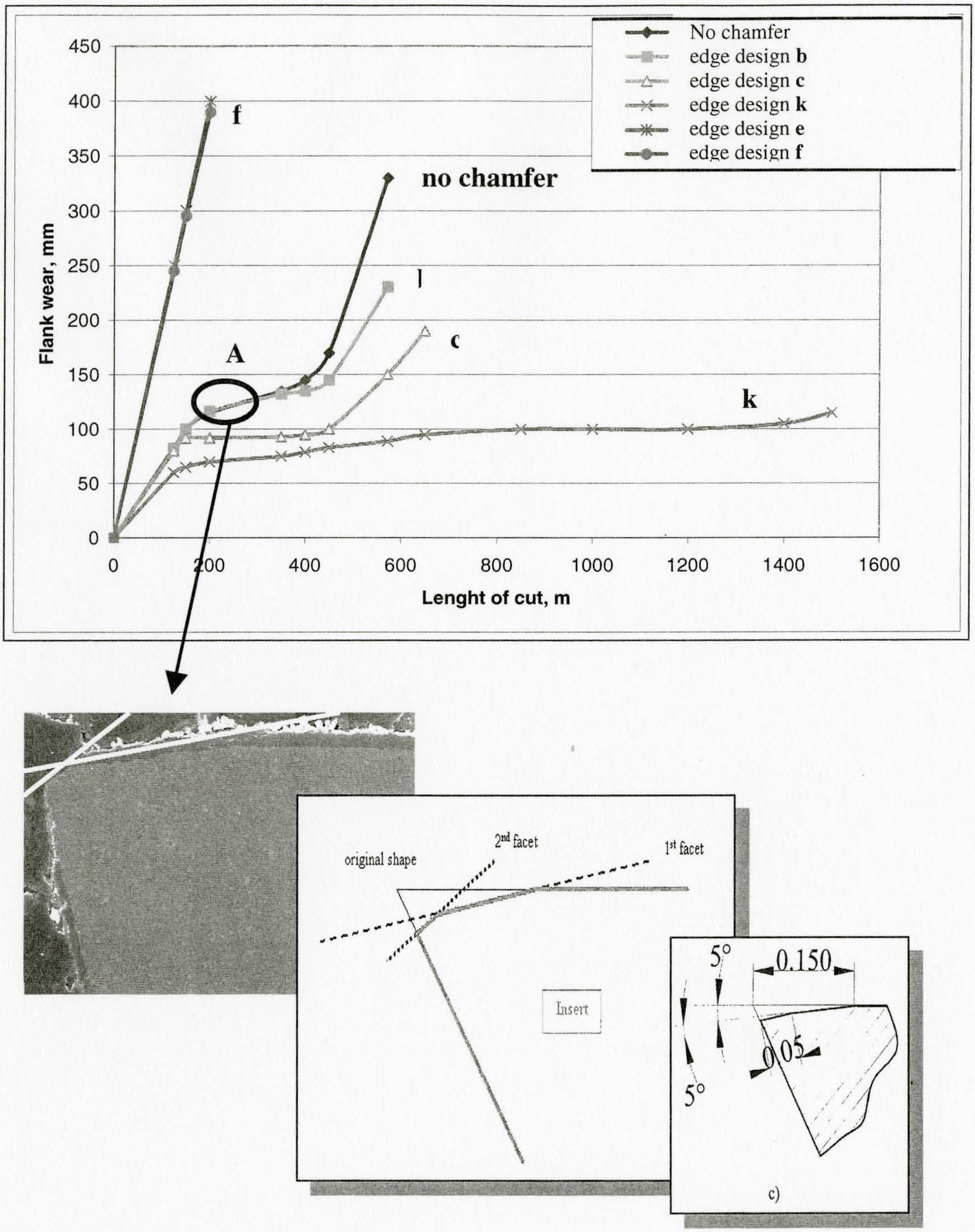


Figure 3.16: Flank wear vs. length of cut for HSS turning inserts with WC/C+TiAlN multi-layered coating, for different designs of cutting edge. Workpiece material: steel 4340 (HRC 40); cutting speed = 100 m/min; feed = 0.11 mm/rev; depth of cut = 0.5 mm.

3.5.2 Cemented Carbide Tools

The evolution of surface morphology for cemented carbide inserts was presented earlier in Figure 3.4 and Figure 3.8. Tool life has been studied under two significantly different cutting conditions: high-speed machining of annealed 1040 steel (HB 220), and turning of 4340 steel (HRC 50).

Under high speed cutting conditions, thermal processes are dominating, but stresses at the work-piece/tool interface are moderate due to the fact that the annealed workpiece material has been machined. The second type of cutting conditions is the machining of hardened steel (HRC 50) under moderate cutting speed (Figure 3.17). In this case the stresses generated at the work-piece/tool interface play a decisive role.

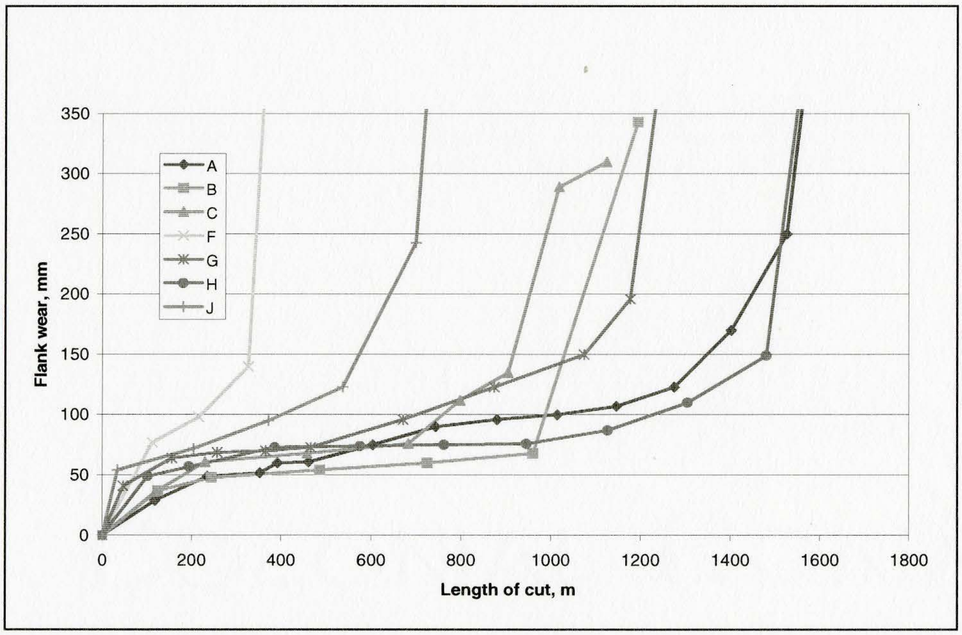


Figure 3.17: Flank wear vs. length of cut of cemented carbide turning inserts with mono-layered TiAlN coating, for different designs of cutting edge. Workpiece material: 4340steel (HRC50); cutting speed=182 m/min; feed =0.11mm/rev; depth of cut =0.5 mm.

During machining of hardened 4340 steel, when stress related processes dominate, the most efficient design of the cutting edge is similar (Figure 3.17). Chamfering of the rake surface stabilizes the wear rate at a lower level and significantly widens the stable stage of wear. Slightly better wear behavior of the chamfered rake surface with the cutting edge rounding could be explained by intensive stress concentration of the cutting edge during machining of hardened steel.

The rake face chamfering of cemented carbide inserts results in a better load bearing capacity of the cutting edge and improves stress and temperature distribution at the tool surface. This probably prevents intensive plastic lowering of the cutting wedge during friction, which results in better wear rate stabilization under high speed machining conditions. The data presented shows that all the other types of cutting edge designs exhibit linear wear curves, which means that the wear rate is high. On the other hand, the rake face chamfering improves tool life due to a low level of wear rate stabilization, after a short period of time (Figure 3.17).

The length of the chamfers is also important. Table 3.2 presents the impact of the chamfer lengths on the tool life of coated cemented carbide turning inserts.

Table 3.2 Relative tool life of the cemented carbides with TiAlN coating vs. length of chamfers on the rake face.

Length, microns	Relative tool life
30	0.9
50	1.0
100	1.04
150	1.1

It can be noted that the length of the chamfer has a lower impact on the tool life of chamfered cemented carbide tools than in the case of HSS tools. This could be explained by the more stable wear mode of the cemented carbide cutters, as compared to the more stochastic surface damage of HSS cutters under attrition wear conditions.

The optimal design of the cutting edge strongly depends on the cutting operation and the design of the cutting edge. For turning operations the best tool life corresponded with the inserts that have a chamfered rake surface.

3.6 Discussion of results

The fabrication of a chamfer on the rake face proved to strengthen the cutting wedge, which resulted in the prevention of its plastic lowering and stabilization of the wear rate. Experimental results of cutting with carbide tools have shown that an increase in the facet length from 50 μm to 150 μm led to a significant tool life improvement.

In the case of HSS turning inserts the length of the chamfer on the rake face had an even more beneficial effect on tool life, due to reduced surface damage during the running-in stage as well as wear rate stabilization. Cutting tests revealed that the design of the cutting edge of HSS tools had a significant influence on wear behavior, especially at low and moderate speeds.

The chamfer on the rake face of the HSS tool produced the longest tool life. This was due to the fact that the chamfer strengthened the cutting edge and reduced the surface damage.

The fabrication of a chamfer on the cutting edge had a significant influence on the shape of the chips. When cutting inserts without a chamfer were used, the resulting chips were found to curl. In contrast, the chips formed when cutting with inserts with a chamfer on the rake face, had almost no curl at all and the chips were smoother.

These experimental observations indicated that the chamfer affected not only the surface damage intensity of the tool, but also the metal flow and heat redistribution at the tool/workpiece interface.

In the chip/tool contact area, more heat flux goes into the chips causing an intensive re-crystallization, which resulted in the coarsening of the chips' grain structure. More intensive re-crystallization of the contact zone took place for the inserts with a chamfer, because the thickness of the contact zone was significantly wider and the grains coarser. Due to the intensive heat flux into the chip (thicker zone of dynamic re-crystallization and coarser grain sizes), chips were formed without curling. The cause of this beneficial heat redistribution was the formation of protective tribo-films that have less time to form, due to the chipping that occurred when the inserts without chamfer were used.

Since HSS cutting tools usually operate under conditions of intensive adhesion wear, seizure associated with build-up occurred at the workpiece-cutting tool interface. Therefore, the HSS tools were coated with a multi-layered WC/C +TiAlN coating.

The most intensive tool surface damage during cutting with HSS tools with multi-layered coatings was observed in the zone close to the cutting edge, which undergoes plastic deformation or chipping at the very beginning of the wear process. SEM and EDS investigations of the area close to the cutting edge showed that at the very beginning of cutting an intensive wear of the outer lubricating WC/C layer took place as a result of seizure with the workpiece material.

Wear on the rake face was initiated by the formation of superficial cracks in the coating, parallel to the cutting edge. Adhesion of work material at the cracks then led to attrition of the TiAlN layer, and damage progressed by propagation of the cracks and further attrition. Superimposed on this process was a continuous contribution of abrasive wear (microabrasion), which is particularly strong at the flank face. The reduction in the wear rate caused by coatings is ascribed primarily to a more favorable contact geometry. This effect persists even after coating breakthrough, in that the remaining coating at the tool edge keeps the built-up edge small, producing thin chips which flow rapidly over the tool surface. The resultant strong heating of the contact area in the breakthrough zone leads to the formation of a flow layer in which a large part of the shear deformation of the chip is concentrated. The flow layer acts as a high temperature lubricating film, prolonging the protection of the substrate even after partial removal of the coating. Uncoated tools do not form a flow layer in the crater area.

3.7 Proposed methodology for designing a cutting tool edge

The steps for designing a cutting tool edge can be summarized as follows:

- find the set of cutting conditions that results in an optimal cutting process, with no build-up or chipping, for the chosen work-piece and tool;

- perform cutting tests, measure flank wear and draw tool life diagrams in order to create the baseline for the following measurements;
- take images of the cross sections of the tool edge after a length of cut that corresponds to the transition point between the running-in (intensive and unstable wear stage) and the stable stage of wear (with critically lower wear intensity), which represents the shape of the 'natural' wear. This 'natural' shape of wear corresponds to wear rate stabilization and could be used for further mimicking.
- Geometrically model this shape as a facet;
- produce a tool with the type of facet that was modeled as the shape of 'natural' wear;
- apply coating in order to return the tool to its original as tested condition.

4. Conclusions and Recommendations for Future Research

This research explored the possibility of developing a procedure to design a subtle feature on the cutting edge of high speed steel and carbide inserts. The design of the edge is based on closely mimicking the natural wear that occurs in the initial stage of running-in.

The "geometrical adaptation" resulted in the formation of a quasi-stable shape of the cutting edge that corresponded to the point of transformation from non-equilibrium (running in) to the quasi-equilibrium (stable) stage of wear.

Using a chamfered cutting tool we could create quasi-stable wear conditions and eventually observe an evolution of the cutting edge shape vs. length of cut. A chamfered facet on the rake face of the tool strengthens the cutting edge and reduces surface damage, which results in the stabilization of the wear rate and improvement in durability. When inserts with chamfer were used, a more gradual wear process was observed, that resulted in wear rate stabilization, due to the formation of protective tribo-films.

The data obtained shows that the type of cutting tool failure strongly depends on the cutting conditions. Under high-speed machining conditions the cutting edge of cemented carbide tools undergoes plastic deformation, while the HSS cutting tools operating under low and moderate cutting speed conditions, when attrition wear mode dominates, results in significant surface damage of the cutting edge.

The application of coatings influenced the chip formation process at the cutting edge. Chip flow velocity, chip thickness and chip curvature were changed by the tribological and thermo-physical properties of the coating. The advantage offered by coatings usually becomes apparent at high cutting speeds and heavier cutting loads which induce higher temperatures.

Research contributions:

- advancement in the understanding of the effect of cutting edge geometry (edge preparation) on tool wear behavior for both uncoated and coated HSS and cemented carbide tools;
- development of a methodology for designing cutting tool edges.

Recommendations for future research:

- investigate these trends using more tool types and workpiece materials;
- include a broader range of tool materials, cutting conditions and edge geometries, as well as various chamfer lengths and ratios of chamfer size to uncut chip thickness;
- further work focusing on the effect of cutting edge geometry on residual stresses and to better understand the double chamfer size effect on residual stress magnitude and depth;
- an in-depth study of chip formation in cutting with chamfered tools, and the effects of tool edge geometry on cutting variables;

- investigate the effect of the geometrical adaptability on the structural adaptability, based on the assumption that the wear rate stabilization of the double chamfered tools is also associated with the microstructure of tribo-films formed;
- develop a cutting model that reflects the effects of the edge radius on the cutting process in the case of honed tools, considering the fact that the hone radius of commercial cutting inserts varies along the edge;
- apply this work to milling operations.

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