

Chapter 1

Modern Machining Process

1.1. Introduction

As a result of the advances in machine tools and cutting tool technology in recent decades, many of the conventional machining processes such as turning, milling and drilling have become cost-effective, flexible and high-throughput manufacturing processes for producing high precision and high quality discrete metal parts for the aerospace, automotive, die and mould manufacturing industries. These processes include: (i) hard part machining of hardened steels (or hard turning) into their near complete shapes, (ii) high-speed end milling at high rotation speeds, or “high-speed milling”, (iii) high-throughput drilling. For example, until recently, high-speed milling was applied to the machining of aluminum alloys for manufacturing complicated parts used in the aircraft industry. In the past decade, with the advance of machine tools and cutting tool technologies, high-speed milling has been used for machining tool steels (usually hardness >30 HRC) for making moulds and dies employed in the production of a wide range of automotive and electronic components, as well as plastic molding parts [SCH 95, DEW 97, FAL 99].

2 Intelligent Machining

In order to remain competitive in a global market environment, manufacturers should enhance the quality of their products and reduce costs while meeting strict customer requirements. Thus, recent research in the machining community has been mainly focused on increasing efficiency by fully utilizing the resources. It has been shown that actual machining times are much shorter than the non-productive times spent on loading/unloading, transferring, etc. the parts. Therefore, if consecutive operations can be performed on a single machine, it would decrease the production time and eliminate accuracy related problems due to re-clamping.

Major advantages of high-speed machining are reported as: high material removal rates, the reduction in lead times, low cutting forces, less work piece distortion and increased precision of the part. However, problems related to the application of high-speed machining differ depending on the work material and desired product geometry. The common disadvantages of high-speed machining are claimed to be: excessive tool wear, the need for special and expensive machine tools with advanced spindles and numerical controllers, fixturing, balancing the tool holder and lastly but most importantly the need for advanced cutting tools.

1.2. High speed cutting

High-speed cutting (HSC) of aluminum alloys has been a successful application of machining for several decades [SCH 82]. In the meantime, the advent of new cutting tools has made possible the machining of hard steels (usually hardness >20 HRC). Previously, the work piece used to be machined near-net shape in the annealed condition, heat treated to desired hardness, then machined to final dimensions and tolerances by grinding. Using advanced cutting tools it is possible to turn and mill steels in their hardened state to the final shape, thereby eliminating further grinding operations and the problems associated with work piece distortion.

Machining of alloy steels in hardened conditions, especially at high cutting speeds, offers several advantages. Those advantages are: reduction of finishing operations, elimination of distortion if the part is finish-machined prior to heat treatment, achievement of high metal removal rates, lower machining costs and improved surface integrity [TÖN 86, KÖN 93]. HSC of hard steels, however, results in high temperatures and stresses at the work piece-tool interface. Consequently, cost-effective application of this

technology requires a fundamental understanding of the relationships between process variables on the one hand and tool life and machined surface integrity on the other hand. Thus, it is necessary to understand how temperatures and stresses developed during HSC influence tool wear and premature tool failure (or chipping) as well as residual stresses on machined surfaces. Therefore, a large number of research studies have appeared in manufacturing research journals over the past decade on the topic of high-speed cutting. In parallel, the demand particularly from the automotive industry for accelerated production during rapid globalization in 1990s pushed high-speed machining to its best.

Experimental data show that when machining hardened steels, work piece material microstructure (not only the hardness) and thermal properties affect the chip flow. It is common to observe higher cutting forces with higher work piece hardness. However, it is also observed that different thermal properties of the tool material may result in lower cutting forces [NG 97, ELB 97]. Therefore, in order to understand the process better and improve the performance of cutting tools, the use of deformation theory and advanced numerical techniques is recommended [STE 97]. Numerical modeling efforts and computational machining have become very popular to understand and further improve advanced applications such as hard turning, high-speed milling and high-throughput drilling.

1.3. Hard turning

The advent of cutting tool and machine tool technologies has made it possible to circumvent the traditional machining route for hardened steels (Figure 1.1). Previously, the work piece was machined to a near-net shape in the annealed condition, heat treated to the desired hardness, then machined to the final dimensions and tolerances by grinding. Using polycrystalline cubic boron nitride (PcBN) cutting tools it is possible to turn and mill steels in their hardened state to the final shape, thereby eliminating further grinding operations and the problems associated with work piece distortion. Therefore hard part machining (HPM) is often defined as machining of a material with a hardness higher than 45 HRC [DEW 97].



Figure 1.1. *Hard turning: cylindrical turning of hardened steel parts*

Turning of hardened steels into finished parts by eliminating intermediate machining and reducing grinding processes has been a cost-effective method for manufacturing high quality automotive components [BYR 03].

From a productivity viewpoint, HPM is reported to offer substantially higher metal removal rates than grinding, leading to a reduction in machining times [BUD 80]. Moreover, set-up and tool changing times are reduced. In contrast, HPM demands a minimum DOC (depth-of-cut), whereas in grinding an infinitesimal DOC can be removed by sparking out. Batch size is another relevant aspect in that, with large batches typically comprising 1,000 parts and more, grinding is generally the most suitable process. With small part numbers, however, HPM seems to be the best option. An economic analysis comparing grinding with OD (outside diameter) turning, chamfering and fine boring of hardened steels using PcBN tools indicate that the tooling cost per work piece for single point cutting is slightly higher than for grinding. However, when considering other matching costs, including capital investment, floor space and electrical power consumption, the cost for single point cutting operations is lower.

HPM offers the opportunity of eliminating the grinding process, which is usually applied after turning in order to obtain a good surface finish. If this can be achieved, benefits such as reduced machining costs and increased material removal rates can be obtained. Recent advances in cutting tool technology and the introduction of high quality lathes into the market have made hard turning a viable technology. The ability of manufacturing

complex geometries in one machine and still obtaining a comparable surface finish as in grinding has made hard turning a favorable choice. Besides, since no or a minimal quantity of cutting fluid is used in hard turning, it is also beneficial from an ecological point of view.

However, a general approach to HPM is unrealistic and each application needs to be evaluated individually. Factors to be considered include: work piece type and condition, component design requirements including batch size, the machinery available and its condition, together with tooling and labor costs, etc. Tönshoff *et al.* [TÖN 86] outlined these factors and discussed the advantages of HPM in comparison to grinding in a comprehensive paper on the requirements of tools and machines when cutting hard materials. König *et al.* [KÖN 93] also compared turning vs. grinding under the aspect of surface integrity and attainable accuracy. Although, hard turning is a more flexible, more environmentally friendly and higher throughput alternative to grinding, process reliability and surface quality is still considered behind grinding processes due to issues related to geometrically defined cutting tools [KLO 05]. Figure 1.2 illustrates a comparison of capability profiles for hard cutting (turning) and grinding processes. Whilst dimensional and surface quality is superior with grinding over hard turning, process economics as well as flexibility were found to be less favorable.

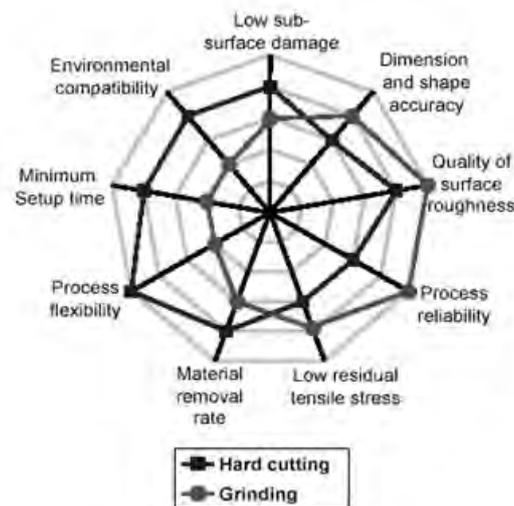


Figure 1.2. Comparison of capability profiles for hard turning and grinding processes [KLO 05a]

In hard turning, since hardened parts are machined, cutting tools are subjected to high stresses and temperatures and thus tool wear is an important issue. Different from the conventional turning, the thrust force, F_t , (Figure 1.3) component is the greatest in hard turning. This is due to the high hardness of the steel material and blunt shape of the cutting tool edges for added strength.

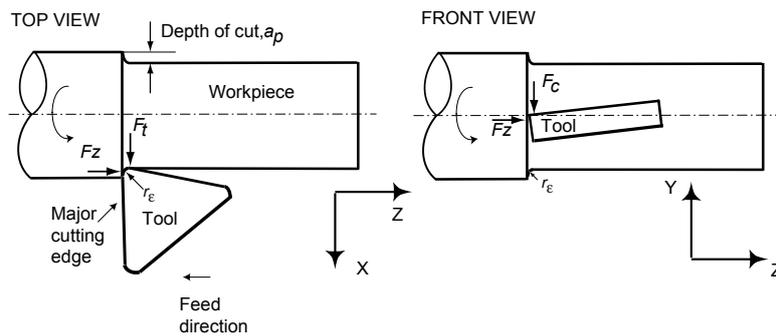


Figure 1.3. Illustration of forces in 3D cylindrical turning

In hard turning, PcBN cutting tools with various edge preparations (see Figure 1.4) are preferred to protect the cutting edge, especially around the insert corner (nose) primarily, from chipping [BYR 03, ÖZE 03, ÖZE 05a, ÖZE 05b, KLO 05a, KLO 05b, MAT 99].

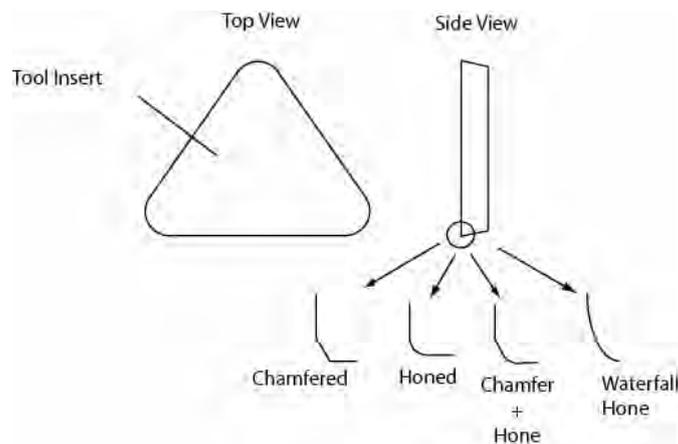


Figure 1.4. Common edge preparations applied to PcBN cutting tools

In order to resist tool wear under these harsh cutting conditions, cutting tool material should have high hardness, high toughness, chemical stability, high thermal conductivity and low thermal expansion coefficients. PcBN tools which possess most of the qualities given above are usually used in hard turning. Other than PcBN tools, cermet or ceramic tools are also used. PcBN tools are comprised of a polycrystalline layer of CBN crystals and a tungsten carbide substrate which are bonded together. PcBN inserts are produced through powdered metal processes. Wafers are cut into slices and brazed to a carbide insert, and then edge preparation is performed. The CBN content, grain size and distribution and composition of the binder material greatly influence the performance of the PcBN tool. Many studies have shown that PcBN tools with a lower CBN content perform better in hard turning applications [DAV 96, DAV 97, ÖZE 05a, ÖZE 05b, KLO 05a]. While low CBN content (40-70%) provides improved edge wear; high CBN content (70-95%) offers higher strength and toughness. In the meantime, thermal conductivity increases with the increase in CBN content of the PcBN tool, yielding higher tool temperatures, and affects the wear behavior of the CBN-binder matrix.

Hard turning is a technology-driven process and therefore depends on machine and workholding technology. In combination with PcBN cutting tools, the development of high precision lathes which have better spindle systems and higher structural stiffness, improved the outcome of the hard turning process significantly. As mentioned before, the elimination of the usage of cutting fluids is the bonus of hard turning. PcBN tools have made dry or near-dry cutting possible because they are durable enough to resist heat generated during cutting. The application of cutting fluids to the cutting zone makes tools vulnerable to thermal shocks which may cause sudden breakages. Therefore cutting fluids, which contain chemical elements harmful to human health, are usually not applied in hard turning.

The selection of cutting conditions in hard turning is very important and directly affects the performance of the hard turning process. For example, increasing cutting speed increases the temperature at the shear zone and tool-chip interface which softens the steel being cut due to the material's thermal softening behavior, thus reduced cutting forces are observed. Furthermore, low thermal conductivity of the PcBN tools assures that the heat generated is taken away and dissipated with the chips controlling thermal growth of the tool and the part. However, high cutting temperatures strongly influence the tool wear, work piece surface integrity and chip formation mechanism.

PcBN tools can withstand the extremely high temperatures but the binder material in the polycrystalline tool body fails after cutting temperature exceeds a threshold (usually around 1,200°C). Micro-geometry of the insert also has significant influence upon the surface integrity. Hence edge preparation must be carefully selected for a given application because it may generate subsurface damage and result in highly tensile residual stress on the surface of the machined work piece [KLO 05a, KLO 05b, DEN 05, ÖZE 07, ÖZE 08]. Heat generation during hard turning and heat distribution along the insert corner is also affected by micro-geometry due to a change in work material flow around the cutting edge. For example, a chamfered face provides excessive negative angle to the cutting action and results in high heat generation. PcBN tools rapidly wear out during hard turning at high cutting speeds mainly due to dissolving binder material at the high cutting temperatures attained. Flank wear occurs at the flank face of the minor cutting edge whereas crater wear mostly forms on the rake face near the major cutting edge [POU 01]. Often, flank wear is followed by crater wear and catastrophic tool failure (chipping). In order to improve the productivity and reliability of hard turning processes, optimum design of micro-geometry for the PcBN inserts must be accomplished.

1.3.1. Tool micro-geometry

It is without a doubt that the design of the cutting edge micro-geometry is becoming important to achieve high performance in machining with PcBN cutting tools. For high efficiency material removal with a corner (nose) radius (r_e) insert, a constant uncut chip thickness to edge radius ratio ($\lambda = t_w / r_e$) should be maintained along the engagement area between the insert and the work piece. However, most edge preparations are applied uniformly all around the corner radius of the PcBN inserts. Uniform edge design hinders the potential of high performance cutting since it does not provide a constant uncut chip thickness to edge ratio (λ) along the insert corner in all engagement conditions. A uniform edge micro-geometry along the insert corner creates a very low uncut chip thickness to edge radius ratio at the minor cutting edge where uncut chip thickness becomes very small. This causes more ploughing than shearing at the minor cutting edge resulting in excessive stress and heat built-up, hence rapid tool wear. A variable edge micro-geometry along the insert corner as illustrated in Figure 1.5 and Figure 1.6 has the potential to reduce the stress and heat built up and enable hard turning at higher cutting speeds and feeds with less tool wear.

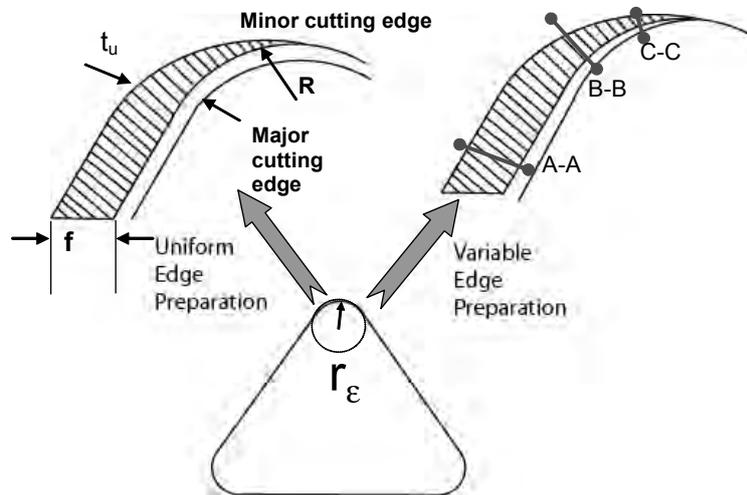


Figure 1.5. Uniform vs. variable micro-geometry design [ÖZE 08]

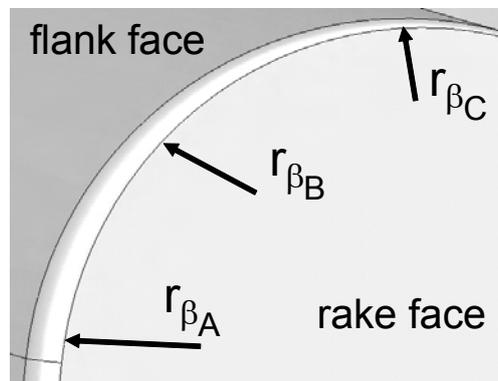


Figure 1.6. CAD model of the variable hone edge design [ÖZE 08]

While the mechanics and dynamics of machining hard metals using tools with uniform edge preparations have been analytically modeled [DAV 96, DAV 97, ELB 96, DAV 97, NG 97, KAR 08a, KAR 08b], finite element (FE) modeling studies have also provided essential information about the influence of edge preparation on the process variables such as chip formation, forces, temperatures and stresses [ÖZE 03, YEN 04, HUA 05a

CHE 06, ÖZE 07, COE 07]. Serrated chip formation is also revealed with increasing cutting speed and feed rate in most experimental and FE studies. Guo and Liu [GUO 02] proposed a 3D FE model for hard turning of AISI 52100 steel using PcBN tools. The model was used to predict the temperature distribution over the cutting edge, the residual stress distribution on the machined surface and cutting forces. Klocke and Kratz [KLO 05b] utilized 3D FE modeling to investigate chamfer edge design in wiper inserts, particularly identifying high temperature zone “hot-spots” on the tool face. Aurich and Bil [AUR 06] introduced 3D FE modeling for segmented chip formation. Karpat and Özel [KAR 07] presented experimental and simulation results for 3D FEA (finite element analysis) of hard turning using chamfered and honed inserts. Özel *et al.* [OZE 08] reported experimental and numerical investigations on the 3D hard turning process in the presence of variable design PcBN cutting tool inserts. Experiments are used in the validation of numerical results. 3D computational modeling is utilized to predict chip formation, forces, stresses, temperatures and tool wear on uniform and variable edge design tools. Predicted temperature and stress distributions and tool wear contours reveal the advantages of variable edge micro-geometry design (see Figure 1.7).

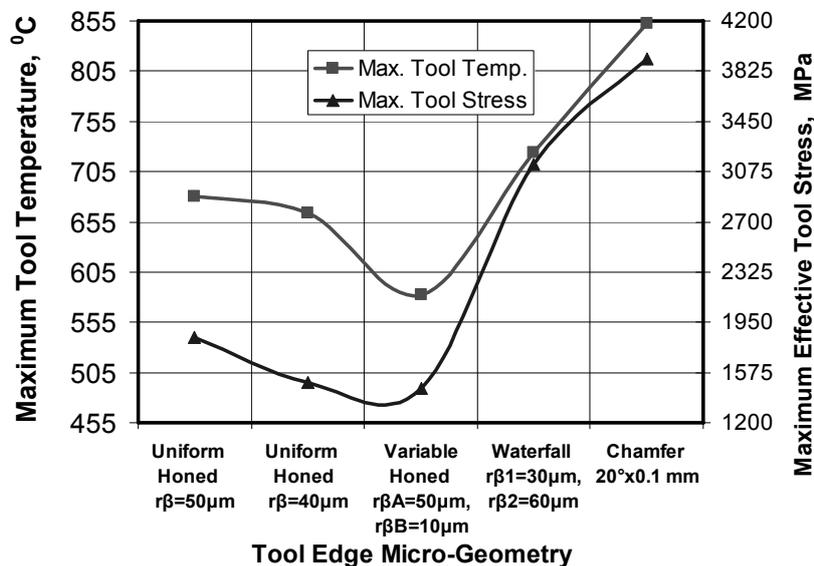


Figure 1.7. Influence of micro-geometry on maximum tool temperatures and effective stresses obtained with FEA [ÖZE 08]

1.3.2. Surface quality and integrity

Hard turning processes have a strong impact on the surface integrity. Surface integrity requirements can be categorized as geometrical surface integrity (surface roughness, dimensional accuracy) and physical surface integrity (residual stresses, microstructure changes) [MAT 99, KLO 05a, HUA 05a]. Surface roughness, which is maybe the most important customer requirement, is greatly affected by the selection of cutting conditions, tool edge geometry and tool wear. Residual stresses are the stresses which remain in the part after machining. The residual stress values in the work piece are mainly influenced by tool tip and tool-work piece interaction as well as the friction between the surfaces. Edge geometry of the cutting tools is an important factor on the machined surface integrity. Worn tools cause undesirable tensile residual stresses and increasing tool wear values push those residual stresses into deeper regions in the sub-layer of the work piece. Plastic deformation and thermal effects are crucial factors and should be considered in residual stress modeling. Residual stresses affect the fatigue behavior of the part under actual working conditions. Other than residual stresses, the formation of white layers, which appear as a white layer at the surface of the material under metallographic examination, characterizes the surfaces produced by hard cutting process. They can be caused either due to severe plastic deformation that causes rapid grain refinement or due to rapid heating to austenite temperatures and fast cooling (quenching). White layer formation can also be seen in grinding applications.

1.3.3. Tool wear and failure

Tool wear is an important problem for hard turning because it not only affects the economic advantage of hard turning, it also affects the surface quality of the work piece. The friction mechanism and heat generated between tool, chip and work piece determine the tool wear. The cost of PcBN tools are high compared to conventional cutting tools and the downtime during tool change has an additional cost which may hinder the economic advantage of the process. In order for hard turning to replace grinding, the relationships between surface quality, dimensional accuracy and tool wear should be very well analyzed. The tool performance is mainly influenced by factors such as: work piece material, cutting conditions (cutting speed, feed rate and depth of cut), tool material composition, tool geometry (rake angle) and tool edge preparation (i.e. micro-geometry of the

tool tip). Increasing tool wear yields unsatisfactory surface finish and increased power consumption.

Wear is basically removal of material from the body of the tool and is a result of process parameters existing at the tool-work piece interface due to relative motion and cutting conditions. There are various mechanisms and modes of tool wear that have been observed in metal cutting. The investigation of machining wear due to cutting speed and temperature shows that tool wear is due to a complex combination of wear modes and is highly sensitive to cutting conditions (see Figure 1.8).

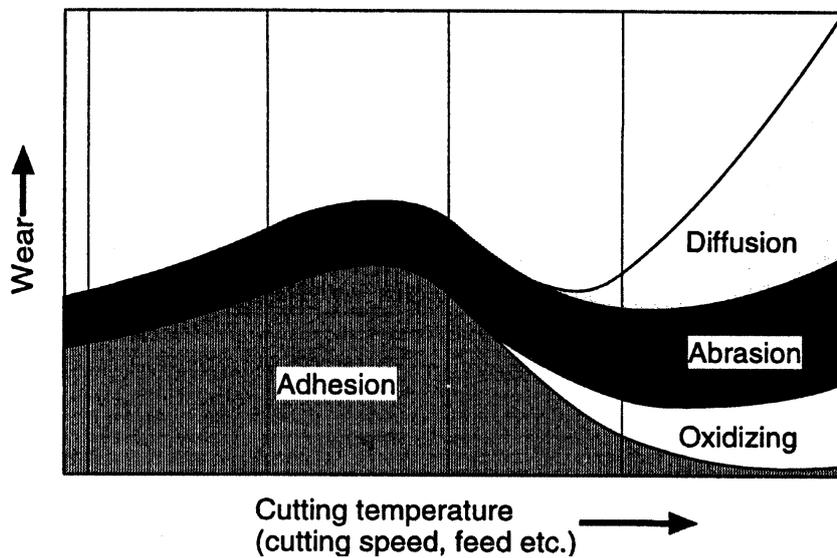


Figure 1.8. Schematic diagram of the tool wear mechanisms appearing at different cutting temperatures corresponding to cutting speed and feed [KÖN 84]

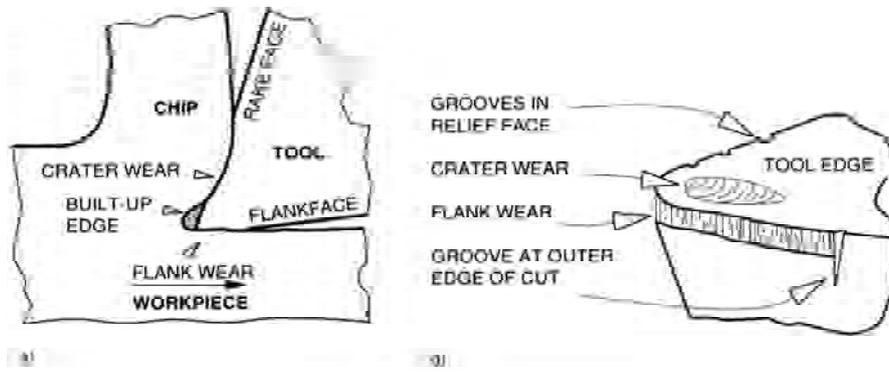


Figure 1.9. Typical locations of location dependent wear on the tool [HOL 94]

Flank wear at the front edge of the tool flank face and crater wear at the tool rake face (see Figure 1.9a) are the most typical modes of tool wear in hard turning. Flank wear is mainly a result of abrasion of the tool by hard particles (but there may also be adhesive effects); it is the dominating wear mode at low cutting speeds. Crater wear is the formation of a groove or a crater on the tool rake face where the chip rubs the tool surface (see Figure 1.9b). Different wear mechanisms, predominantly present in metal cutting, can be classified as sliding wear mechanisms and non-sliding wear mechanisms.

1.3.3.1. Sliding tool wear mechanisms

Sliding wear mechanisms include abrasive wear, adhesive wear and delamination wear. Abrasive wear is caused by the contact of a tool body with a particle, where the particle slides over the body and the movement causes material loss. Adhesive wear occurs between two surfaces rubbing against each other as a result of formation and breakage of the interfacial bonds. Delamination wear is another mechanism of wear when chips are sliding against tool surfaces at low speeds which do not generate very high contact temperatures. In this process, large wear particles are removed in the form of layers by the process of plastic deformation of the surface layer [SUH 73].

1.3.3.2. *Non-sliding tool wear mechanisms*

Non-sliding wear mechanisms include solution wear, diffusion wear, electrochemical wear and oxidation wear and become dominant with the chemical instability where cutting temperatures are very high: up to 1,600°C as in high-speed machining [SCH 95]. Solution and diffusion wear occurs when work piece and tool material react with each other to form a solution. The rate of the solution is dependent on cutting temperature at the interface and increases with the increasing temperature [SUH 86].

The wear due to diffusion is more dependent on the chemical properties of the material rather than its mechanical strength or hardness. Electrochemical wear is caused by a thermoelectric electromotive force (emf) generated at the work-tool junction during the cutting process. The emf causes electric currents to circulate and results in the passage of ions from the tool to the work piece [MOO 75]. Oxidation wear is a result of the chemical bonding of tool material atoms with oxygen. Oxidation in metal cutting occurs in the area where the chips are generated at elevated temperatures, usually above 700°C [KöN 84]. This type of wear is caused due to a chemical reaction between CBN's chemical composition and work piece materials. As an example, since it tends to accelerate chemical wear, ductile iron is not suitable for PcBN machining.

1.3.3.3. *Premature tool failure*

The sudden and premature tool failure caused by chipping of the tool cutting edge is one of the most important aspects of metal cutting and needs further investigation. In production with transfer lines, cutting tools should have a longer life than the predetermined period of time to facilitate tool changes at the end of the shifts. Premature tool failure not only damages the work piece, but also causes production downtime. In the past, chipping of the cutting edge was attributed to the impact loading resulting from the sudden engagement of the tool into the work piece material. Thermal fatigue wear is usually seen in interrupted machining where the cycle of heating and cooling stages results in thermal cracks and therefore tool breakage.

It must be noted that some of these wear mechanisms may become more dominant under different cutting conditions. Depending on the area where tool wear occurs, three types of tool wear pattern can be identified: flank wear, crater wear and chipping. Flank wear occurs between the tool and the work piece due to a rubbing action. In real life applications, the maximum

permissible value of flank wear is usually used as a decision factor on tool life since it is easy to measure flank wear. It also has the biggest influence on the surface quality of the finished component. Crater wear occurs on the rake face of the tool because of chemical interaction between tool material and work piece. Chipping results from small broken pieces of the tool and is reduced by increasing the toughness of the tool. The tool wear patterns are shown in Figure 1.10.

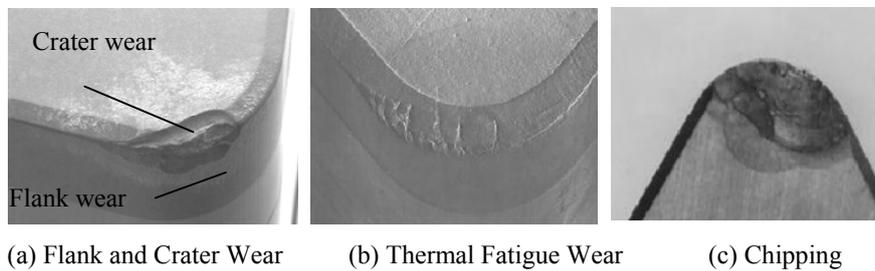


Figure 1.10. Tool wear patterns in hard turning

1.4. High-speed milling

The concept of high-speed machining and consequently the term *high-speed milling* (HSM) has changed in recent years, and thus a certain amount of historical background is required for a better understanding of the current meaning.

1.4.1. Historical remarks

The first reference to the possibility of machining at high cutting speed is to be found in Carl Salomon's patent [SAL 31], dating back to the late 1920s (German patent #523594). The essence of the patent was that tool wear and temperature increase along with cutting speed to a maximum value, the so-called *critical speed*; over this speed, temperature and wear may decrease along with speed, as Figure 1.11 shows. Therefore, machining carried out in excess of this value would obtain optimum tool life and productivity.

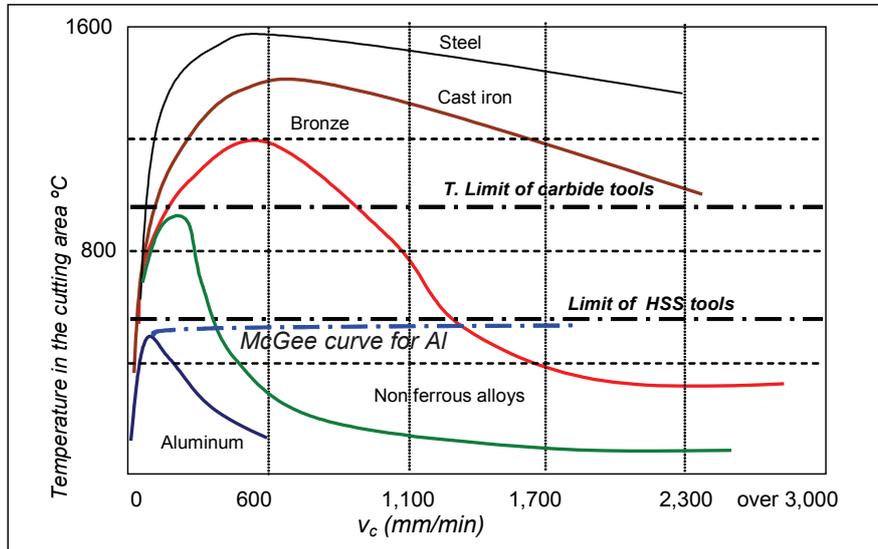


Figure 1.11. Salomon's curves, cutting speed vs. tool/chip interface temperature

Figure 1.11 also shows the McGee proposal [MCG 78]. For the reader's reference, in this figure the dashed lines show the maximum temperatures that current carbide and *high-speed steel* (HSS) tools can withstand.

All Salomon's work disappeared in 1945 during the Second World War, and so there is a wide gap in our knowledge of the experiments carried out during that period, although the patent does make a number of references to milling experiments at speeds in excess of 15,000 m/min.

New ballistic experiments were conducted in the 1960s and 1970s, shooting projectiles against material sheets in order to simulate the material deformation at high cutting speeds [KRO 61].

In 1979 a four-year project with a generous budget, known as the Advanced Machining Research Program (AMRP), commenced in the USA. The program [FLO 83][FLO 84] sought to reduce missile manufacturing costs and times by acquiring a scientific database on machining processes. The materials studied were steels, tool steels, lead, aluminum alloys,