

Advances in micro cutting tool design and fabrication

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Abstract

Microcutting is a precision technology that offers flexible fabrication of microfeatures or complex three-dimensional components with high machining accuracy and superior surface quality. This technology may offer great potential as well as advantageous process capabilities for the machining of hard-to-cut materials, such as tungsten carbide. The geometrical design and dimension of the tool cutting edge is a key factor that determines the size and form accuracy possible in the machined workpiece. Currently, the majority of commercial microtools are scaled-down versions of conventional macrotool designs. This approach does not impart optimal performance due to size effects and associated phenomena. Consequently, in-depth analysis and implementation of microcutting mechanics and fundamentals are required to enable successful industrial adaptation in microtool design and fabrication methods. This paper serves as a review of recent microtool designs, materials, and fabrication methods. Analysis of tool performance is discussed, and new approaches and techniques are examined. Of particular focus is tool wear suppression in the machining of hard materials and associated process parameters, including internal cooling and surface patterning techniques. The review concludes with suggestions for an integrated design and fabrication process chain which can aid industrial microtool manufacture.

Keywords: micro cutting tool, design, fabrication, wear, surface patterning

(Some figures may appear in colour only in the online journal)

1. Introduction

The cutting tool remains an integral part of subtractive machining operations. The importance of this machining component is reflected in the growing need for new microtool development which is fundamental to the progress of contemporary manufacturing [1].

Microcutting is a flexible and efficient machining method for producing functional, high quality, advanced material components and has the potential for machining hard, brittle materials, such as glass, superalloys, and ceramics. These materials have wide applications in various fields, such as the biomedical, optical, and mold/die industries. However, the high surface finish required for certain applications and the associated difficulty in producing the features and structures in these materials has created a barrier to their wider use in industry. This reflects the primary mechanism of material removal, i.e. crack propagation and brittle fracture, which results in surface and subsurface damage along with negative modification of physical properties [2].

Developments in the understanding of the microscopic mechanical mechanism underlying the removal of material under specific conditions, known as ductile mode machining of brittle materials, have provided an opportunity to address this difficulty and to further develop this technique. Ductile mode machining, validated by experimental indentation tests [3] and further explained through fracture mechanics theory [4], is typically conducted using a slow speed and feed rate along with a small depth of cut, resulting in a reduced, undeformed chip thickness. Due to a lower energy barrier, as a result of the small material removal rates (MRR), the dominant mechanism for material removal becomes plastic deformation in the form of ductile machining [2].

It has been recognized that a ductile-to-brittle transition exists in the workpiece material during the machining process, which can be controlled if the undeformed chip thickness is below a determined limit. This limit is also an intrinsic function of the material whose properties are governed by fracture/ductile deformation principles [5]. Liu *et al* [6] established that ductile machining of hard-to-cut materials, such as tungsten carbide, is possible if the chip removal dimension is maintained at a microscale.

Despite this progress, ductile mode machining is not without its problems. Liu *et al* [7] showed that cubic boron nitride (cBN) tool wear in the ductile machining of tungsten carbide (WC) was relatively high. This is compounded by the challenge of fabricating multi-edged microcutting tools and the associated finishing problems, which also impose limitations on the extent of the geometrical complexity and asymmetrical features patterned on the tool.

From an industry perspective, the cutting speeds possible in brittle machining and the restriction to basic tool patterning is not sustainable, from both an economic and production standpoint. In addition, the current commercial methods employed to fabricate microtools and the excessive wear experienced by some of these fracture-prone tools when used with non-optimized machining techniques, make the machining of hard, brittle materials not only challenging but unattractive.

Therefore, there is a need for an in-depth analysis and corresponding tooling and machining assessment in terms of the current methods applied and the fundamental understanding in use. This includes the basics of micromachining mechanics in tandem with a corresponding tooling design and fabrication methodology based on the interactions of the tool/workpiece interface. It is envisioned that this approach will be a progressive step in microtooling design and fabrication for the precision machining of brittle and hard-to-cut materials, thereby allowing wider implementation in industrial manufacturing.

2. Design of cutting tools

The cutting tool is of paramount importance to effective precision machining of specific structures and features in workpiece surfaces. Extensive research and development has been conducted to optimize tool design, working lifetime,

precision, efficiency, consistency in reproducibility, and economic viability [8]. There currently exists an extensive range of cutting tool designs and materials, tool configurations, and geometrical shapes corresponding to specific machining operations. Typically, cutting tools with a single point, e.g. a turning tool, or multipoint designs, e.g. milling cutters have inserts with several cutting edges and contain additional components and features integrated into their structure to improve effectiveness and efficiency [9].

Advancements and limitations in microcutting and microtool design are intimately linked to progressive developments in the machining of microcomponents and parts, which also necessitates consistency in the fabrication process and cutting tool performance [10, 11].

Size effects and associated phenomena are one of the core aspects of microcutting. This relates to the scale factor in micromachining in which the size of the cutting edge radius and the corresponding uncut chip thickness (UCT) and material grain size of the workpiece have similar dimensions [11]. This fact is critical to microtool design because it indicates that simply downscaling commercial macrotools based on this miniaturization process would not be sufficient for the required cutting mechanics. Unfortunately, this understanding has not been widely applied in industrial microtool design. In fact, many industrial tool designers still adopt a microtool design regime based on mimicking unsuitable macro features and structures. This results in poor tool wear resistance, breakage, slow machining operations, and uneconomical manufacturing processes. This effect is particularly seen in the cutting of hard and brittle materials, which are much less forgiving to errors in tool selection and poor machining parameters. The materials are limited to wider applications, thus preventing realization of their potential in advanced engineering applications.

The reasons for this can be understood in terms of two critical aspects: (1) an inherent lack of understanding or insufficient knowledge of the nature of microcutting mechanics and (2) limited information on the methodology to used in designing microtools specific to individual materials. For example, conventional macrocutting tools typically have a design which makes the geometrical orientation and shape of cutting edge corners the weakest part of the tool. Thus, the proportionate downscaling in the design and fabrication of microtools produces inferior instruments unsuited to the application [12]. This highlights the essential difference between the two machining operations, where the fundamental characteristics of micromachining can produce uncertainties and deviations from what is expected using macromachining processes, which are encapsulated in the size effect phenomenon [12].

Tool monitoring, therefore, becomes critical in micro-machining, but this is not straightforward due to the dimensions involved. In addition, the form accuracy achievable, the quality, and the integrity of the machined surface are directly related to the microtool properties, geometry, and mode of interaction. It is therefore paramount that the design and manufacture of these instruments be critically analyzed and

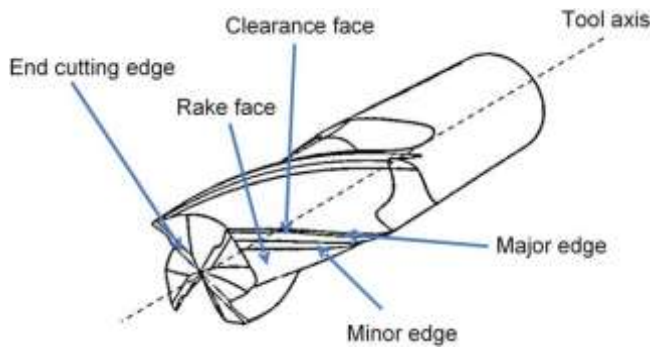


Figure 1. Geometry of a standard end mill.

that fundamental understandings are implanted in the design phase to ensure optimization of the microcutting process.

Cutting tools generally have a main (major) cutting edge and secondary (minor) edges, as shown in figure 1. Variations in the geometrical shape and orientation of the edge and corresponding face and angles affect the machining performance to a large extent [13].

A sharp edge typically results in a weak and brittle tool edge; therefore, it is necessary to prepare the edge radius through honing or chamfering prior to use in order to have a useful, functional instrument [8]. Alternatively, reinforcement of this localized weak area through core design strengthening in tandem with simulation studies can fulfill this requirement while providing information on the mechanics of the problem.

In the case of end mills, generation of the spatial edge geometries is achieved by projecting a cylindrical helix onto a spherical structure normal to the tool axis [14]. In this design (figure 1), typical of macrotooling features, the tool has axial and radial rake and clearance faces that are part of a winding structure following a curved path up the tool's central axis.

From macro- to microtools

As mentioned previously, commercial macrotool designs do not match the geometrical requirements that microtools demand. It is instructive to review recent work done on the causality of this and the consequences to the wider machining process. Li *et al* [15], studied the design of micro end mills and concluded that excessive wear, poor workpiece finish, and premature tool breaks are partially caused by the tool design. Moreover, they suggested that the particular application and geometrical features on the tool are deeply connected. By giving this careful consideration and applying it in the redesign of standardized methodologies employed by industry, superior performance in microtool longevity and quality can be achieved. They also note that commercial microtool designs typically have an edge sharpness that results in weakening the core material structure of the tool and, by extension, the strength of the cutting edge, which ultimately produces chipping and fracture of the edge corners. These tools also have positive rake angles, which result in higher stress generation and rapid wear, thereby reducing the tool diameter significantly [15]. It has been found that for the ductile machining of brittle materials, highly negative angle

geometries are preferred in micro end mills. For better stiffness, a bigger neck angle and shorter underneck design is desired. Research suggests that creation of a cross-sectional design for the cutting edge can reduce edge corner stress concentration.

In an experimental study by Fang *et al* [16], it was postulated that a D-shaped cutting edge would enhance the chip removal performance during micromachining tests. A systematic analysis was performed on various microtool geometries, and it was found that the D-shaped structure end mill design for diameters in the range of ~ 0.1 mm, was the best performer in microfabrication. Following this concept, a variety of circular, D-shaped, triangular, and square polycrystalline diamond (PCD) microtools were fabricated to machine Bk7 glass using a V-shaped slotted block [17]. The results indicated that the D-shaped designs exhibited the lowest cutting force in the x and y directions, which also demonstrated higher performance in terms of surface roughness and wear rate.

Turning tools

Turning involves the selective removal of material from a rotating part or component through the cutting action of an axially positioned single-point edge tool that is fed into the part, such as an insert, to create holes, grooves, edges, tapers, or axially symmetric and contoured structures as illustrated in figure 2. Typically performed using a lathe, turning can remove external or internal part material using a minimal cut depth process that is repeated sequentially at increasing depths until the desired geometry and structure are achieved.

Generally, the cutting tool, in the form of an exchangeable insert, adopts a triangular or diamond configuration that is inserted into a tool holder to enable the machining operation to proceed [18]. When ultraprecision is required, as in the case of nanometer scale surface finishing and form accuracies at submicron dimensions, single crystal diamond (SCD) materials are used. Because of the extreme sharpness of the tool edge and the exclusive machining capabilities for which this process is reserved, it is generally referred to as single-point diamond turning, commonly used in microturning and fly cutting processes [19].

Milling tools

Milling is a coordinated intermittent subtractive process where the tool edge, once contact is initiated, continuously impacts the workpiece surface through a series of linear or multi-axis movements. Surface chips of a specific thickness are removed until the desired pattern or toolpath has been completed [20]. This technique, widely used in manufacturing, can perform fabrication of basic and complex features. It can have positive, zero, or negative rake angles depending on the orientation and workpiece material, resulting in different chip removal mechanisms [21].

Typically, micromilling is conducted using flat or ball end mills with several flutes integrated into the shaft structure. For smaller diameter tools, this is limited to a single- or

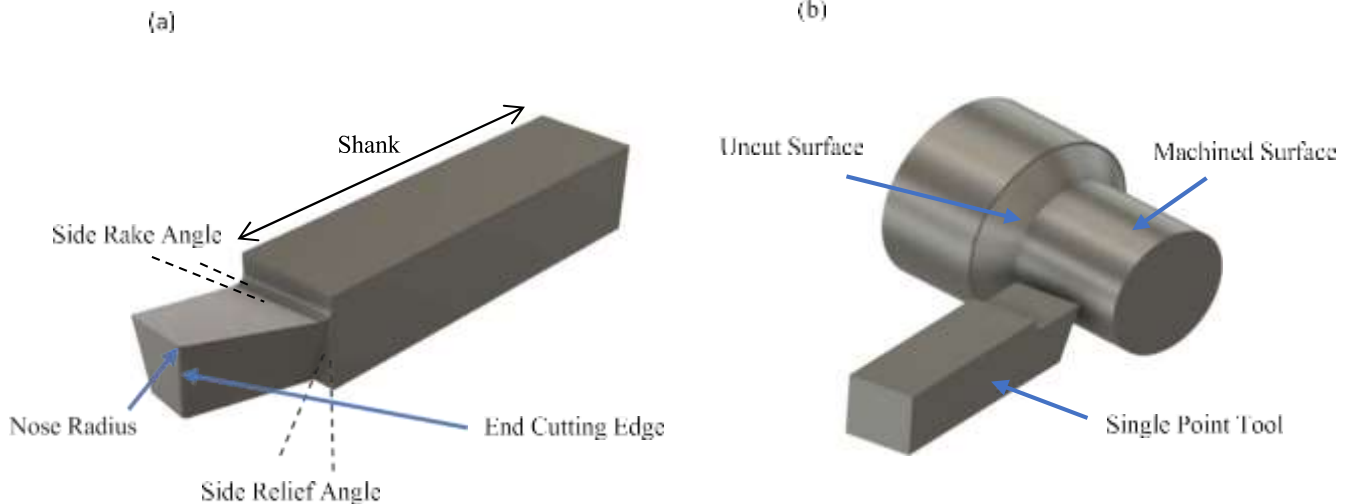


Figure 2. CAD illustration of (a), right-handed turning tool and (b) cylindrical turning operation on a lathe.

two-flute design, as shown in figure 3, due to the fabrication challenges at this scale. The material choice, along with geometric structure, size, and orientation, is critical as it effectively controls the achievable dimensions and surface roughness of a workpiece. High-speed steel (HSS), solid carbides, and ceramic-based materials are the standard choice for micromilling applications. Additional coats of micron-sized layers are added to improve tool life and operational productivity, as required. Commercial tool designs are generally in the range of $25\ \mu\text{m}$ – $1\ \text{mm}$, although larger sizes up to $3\ \text{mm}$ are sometimes employed. These designs are prone to chipping and fracture, particularly when milling hard materials due to the weakened structural design used by commercial manufacturers, which is not optimized for microcutting [19]. Despite the challenges in optimizing tool design geometries and materials, micromilling offers the best flexibility and versatility and can create three-dimensional (3D) structures of high geometric complexity in a relatively rapid process [19].

Drilling tool

Drilling, probably the most recognizable form of machining, owes its helical twist orientation to Stephen Morse, who developed the standard cutting tool design which has been used (with varying modifications) since he created it in 1864 [22]. Drilling corresponds to all forms of cylindrical hole machining and involves the creation of a cross-sectional through hole in a fixed workpiece. It has a defined entrance point with a burr featured exit point, achieved via the cutting action of a high-speed rotating tool [8, 23]. The dynamic drilling action based around the conventional twist or flute drill, differs from milling both in the cutting mechanism and also in that it cannot cut level features due to the pointed end geometry. Drills contain a main cutting edge with an intersectional chisel edge and pointed end. An example of a conventional drill is shown in figure 4. Common variants on standard drills include indexable drills, gun drills, reamers,

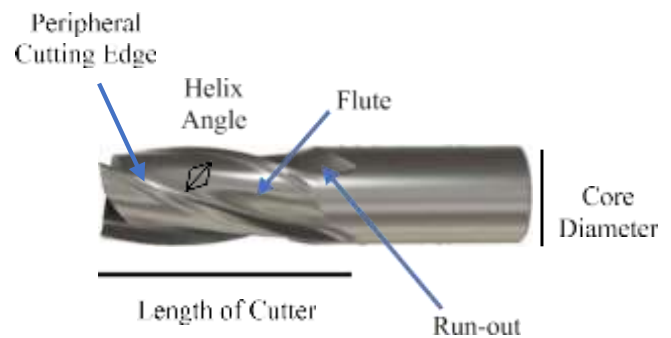


Figure 3. CAD rendering showing the main features of a typical end mill.

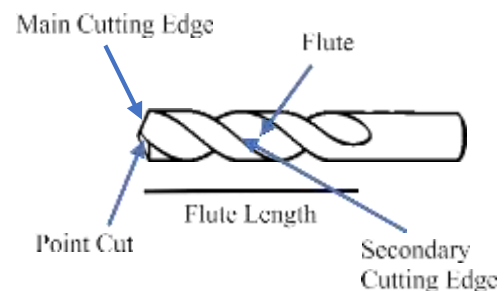


Figure 4. Schematic of a standard drill with main features highlighted.

and special/customized spindle drills. Commercial microtwist drills can produce holes of $50\ \mu\text{m}$ in diameter or smaller.

3. Tool materials

Despite the huge potential for microcutting in the high-precision fabrication of complex and high-quality 3D hard material structures, challenges remain in terms of the tool matrix composition and associated processing techniques. The design of microcutting tools is not a trivial task. Each tool design must be able to endure high temperatures and large mechanical loads, including extreme friction generated at the

tool tip interface. Additionally, the tool material itself (including coatings) should have high hot hardness and high toughness to prevent fracture, along with chemical inertness under these conditions.

Material selection and microstructure

Advanced understanding of the physiochemical properties of the tool and workpiece material are vital to successfully develop a superior cutting tool, as efficient precision machining of hard materials necessitates an understanding of the microstructure and the deformation mechanisms at work. Grain boundaries, crystallographic orientation, defects, impurities, and distribution of densities are important properties that require analysis. Combining these material considerations with tooling specifications and cutting parameters is required to implement the foundations of a systematic design protocol for superior cutting tools and machining operations.

Generally, an acceptable cutting tool material has the following requirements [8, 12]:

- High hot hardness.
- Good fracture toughness and mechanical shock resistance.
- High wear resistance.
- Chemical inertness and lack of affinity between tool and workpiece.
- Good thermal shock resistance.
- High adhesion on tool substrate for coating application.

Currently, no single material can achieve all of these characteristics; therefore, optimizing the material properties and integrating surface modifications/coatings on the cutting tool are required.

Current tool materials for microcutting

The range of materials that can be used for microtools includes HSS, ceramics, cermets, cubic and polycrystalline boron nitride, polycrystalline diamond, and SCD (figure 5). The type of material depends on the particular application and the work material microstructure characteristics and properties. Experiments indicate that as hot hardness and wear resistance increase, fracture toughness decreases. This highlights an inherent feature in the selection of appropriate materials for advanced cutting tools. There is always a compromise required in the choice of material; no single material can provide all of the necessary properties. Another factor that needs to be considered is designing for manufacture. As high hardness increases, the difficulty in fabricating features on the tool increases as well.

For microcutting, size effects also need to be factored into the design process. This requires consideration of the tool edge radius, UCT, and material grain size [1]. A list of the most common tool materials used for microcutting operations follows.

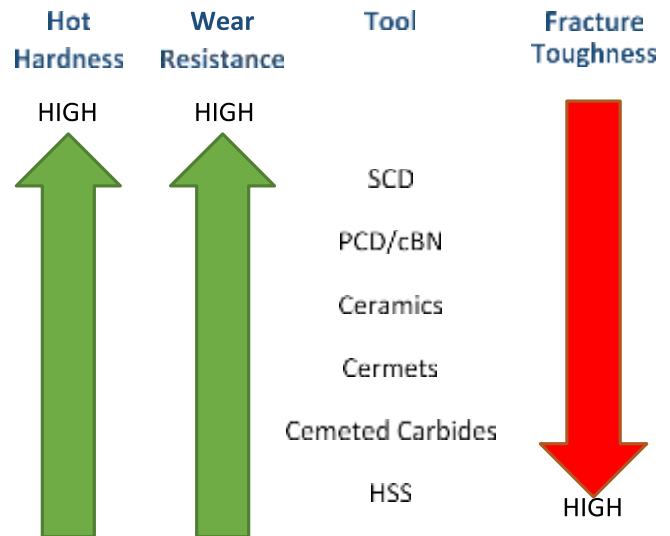


Figure 5. The main classes of cutting tool materials and their corresponding characteristics.

High speed steels. The composition of HSS can be tailored to suit a particular application, which produces varying grades of the tool. These tools contain carbides of alloys mainly consisting of tungsten, cobalt (Co), chromium (Cr), molybdenum (Mo), and vanadium (V), formed as particulates during the heat treatment phase. HSS has good toughness but is limited to operations <550 °C and therefore is seldom used for the machining of hard materials [9]. Recent manufacturing developments in HSS has seen it produced via powder metallurgy, which results in higher structural matrix uniformity thus increasing tool toughness and longevity.

Cemented carbides. Extensively used in microcutting, cemented carbides contain a WC, C, and Co mixture which, when sintered at high temperatures, allows the production of specific geometries and shapes. Variation of the composition during forming allows for modification of the material properties, producing different grades of tools that can operate at ~1200 °C while maintaining hot hardness. Therefore, cemented carbides can machine at higher speeds than HSS [9]. Nonetheless, because it is prone to dissolution of the tool in the forming chip, this restricts its actual machining speeds [8]. This can be somewhat circumvented by the addition of compounds such as tantalum carbide and titanium carbide during synthesis, which also improves cratering resistance; however, this increases the cost of manufacture. Binderless carbides are also widely used in microtools. These exhibit higher hardness and wear resistance compared to standardized WC/Co carbides. Cemented carbides have relatively low fracture toughness, especially when interrupted cutting procedures are used, and are limited to simple shapes once sintered. Typical tooling forms include inserts and solid round cutting tools for turning and milling operations. Current developments in WC tooling production have seen a trend towards reduced particle size (1 μm), which increases densification of the compacted powders thus improving hardness and toughness to varying degrees.

Another development is in Co enrichment of the surface (0.013–0.025 mm thickness) which improves the toughness while maintaining the wear resistance of the material [9].

Cermets. Similar to cemented carbides in their processing route, these tools contain hard particles of TiC, titanium nitride (TiN), and titanium carbonitride (TiCN) with a cobalt binder phase but demonstrate a superior wear resistance over carbides. Again, the general trend is a trade-off in material properties; these tools have reduced thermal shock resistance. Typical applications include semi- and finish machining of hard-to-cut materials with moderate feed rates and high cutting speeds.

Ceramics. Generally containing alumina (Al_2O_3) and other boron nitride (BN) powders fabricated through a powder metallurgical process, these tools are extremely hard

and brittle with high compressive strength and can operate at speeds three times that of cemented carbides in temperatures reaching $\sim 2200^\circ\text{C}$ [9]. Limited in application due to their brittleness, they are usually in the form of disposable inserts for semi- and finishing operations of cast iron, hardened steels, and superalloys. Recent work on increasing fracture toughness has seen the use of reinforced silicon carbide (SiC) whiskers, which redistribute and thus reduce the cutting force on the tool [9].

Cubic boron nitride. Cubic boron nitride is an allotropic crystalline compound with a sphalerite structure, exhibiting superior mechanical, chemical, and thermal properties, resulting from its cubic lattice and covalent linkage [4]. Widely used as an abrasive and integrated into cutting tools to improve their wear profile, it has high thermal conductivity and is chemically inert at high temperatures. However, cBN is restricted in wider applications due to the inherent difficulty in fabricating complex patterns in the tool structure due to its extreme hardness. The cBN content and binder (Co, W, or ceramic) can be varied to accommodate the machining application [8]. Cubic boron carbide tools allow for high cutting speeds due to high wear resistance; and cBN is, after monolithic or SCD, the second hardest material. An increase in its use as a potential substitute for diamond in cutting and drilling applications has been seen. Unlike diamond, cBN has the additional benefit of being stable up to 2000°C and is nonreactant when exposed to ferrous alloys [8, 14].

Polycrystalline diamond and single-crystal diamond. Because of the high hardness and high thermal conductivity, SCD is the ideal tool material for ultraprecision cutting. Polycrystalline diamond and SCD can be made via the high-temperature and pressure synthesis of compacted synthetic diamond particles. Both exhibit very high thermal conductivity; and due to its extreme hardness and potential for creating $<100\text{ nm}$ radii cutting edges, SCD is used for machining hard-to-cut materials requiring mirror quality finish. However, their low fracture toughness, susceptibility to thermal shock, and

high expense restricts their wider use [2]. Polycrystalline diamond has superior toughness due to a Co matrix addition, but it is extremely difficult to fabricate features in a tool surface due to its elevated hardness. Typically used for the machining of super alloys, ceramics, and hard, brittle materials, wider applications include use as thin compounded layers on WC shanks for hard machining operations [8]. Both PCD and SCD are limited to machining with nonferrous workpiece materials due to diamond reactivity (graphitization) and chemical-thermal degradation [14].

4. Fabrication of microcutting tools

To design and fabricate a superior microtool providing good machining quality, reliability, and reproducibility requires a precision manufacturing process [24]. To this end, extensive research has been conducted on improving the performance of microtools using novel fabrication methods and techniques; but challenges in the machining of hard materials still exist. The manufacture of microtools is a critical step in the machining process, requiring knowledge of the optimum geometric specifications, number and shape of cutting-edge radii, and the material properties along with the capabilities, characteristics, advantages, and limitations of different manufacturing methods and associated costs [12].

Typically, microtool fabrication is carried out through a series of individual and, in some cases, combinations of, mechanical, laser, focused ion beam (FIB), electrodischarge machining (EDM), and hybrid fabrication processes. Methods to bond the tool surface and coatings are also employed to achieve the desired performance. Additionally, finishing procedures, such as mechanical grinding processes, are also conducted to achieve a particular shape and surface quality [12]. A brief description of fabrication techniques along with an in-depth discussion of recent developments in this field follow.

Fabrication methods

Commercial microtools are fabricated through sequential fabrication steps starting with a base substrate material and then forming and shaping the structure using advanced machining techniques. The nature and dimensions of microtools, along with the subtractive process used to create the tool, means that in most cases, the thin and brittle structure can be expensive to make. This is because at some point in the fabrication process, the tool material will be subjected to a contact force irrespective of the main type of forming method. As a result of this, the thin structure is prone to fracture which invariably produces occasional breakages during steps in the construction phase and ultimately requires a new base material to restart the process. This is reflected in the high scrap/waste rate in commercial microtool fabrication because of the small dimensions required for machining at this scale. It is, therefore, crucial that consideration is given not only to the material properties of the tool during the design phase but also to the process route used for a particular application, as this

methodology is encapsulated in the design for manufacture philosophy.

The first microfabrication technique considered is EDM. This employs an electrothermal method to selectively remove material until the desired feature is fabricated. This process is typically reserved for hard-to-cut materials. The mechanism of operation uses an electric current which passes between an electrode and the workpiece producing a spark discharge which removes the surface material. A modification on EDM is wire electro discharge grinding (WEDG). Here, a wire electrode generates preprogrammed cuts corresponding to the workpiece material orientation, which has the advantage of quicker machining times and lower contact forces [18]. Although both methods allow for high precision of micro-structure shaping of hard-to-cut materials, they suffer from slow MRRs and are limited to conductive materials only.

Another microfabrication method is FIB sputtering. This technique uses accelerated ions to etch and remove surface atoms from a solid material, providing extremely sharp cutting edges with nanoscale radii. However, it is an expensive process, and, similar to EDM, it results in slow MRR. Therefore, it is generally restricted to the fabrication of tools <100 μm [12]. Despite this, it offers precision control of the forming process with very low forces experienced by the tool substrate.

High-energy, focused lasers are sometimes employed in microtool fabrication: Laser beam machining uses a non-contact ablation method for material removal in which a monochromatic high-energy beam impacts the workpiece surface transferring the thermal energy of the laser onto the material, allowing vaporization/melting of the surface and subsurface material. The advantage of this method is that it is noncontact so it allows for the shaping of brittle materials to be fabricated without potential damage to the structure. However, the thermal generation from the photons impacting on the surface can alter the material properties, which may be problematic particularly for coating requirements. Additionally, initial costs along with energy consumption can be high.

Mechanical machining is currently the main fabrication process employed for microtool fabrication. Examples include milling, drilling, boring, and turning, as well as finishing techniques, such as grinding/ultrasonic grinding, and lapping. These processes involve some form of controlled material removal through the use of specific computer numerically controlled (CNC) machine tools. This produces the required feature in a base material through a series of CNC programmed steps, with the cutting tool being the main contact between the machine tool and workpiece interface. These methods vary in the methodology employed to achieve the end result but are able to achieve high dimensional accuracy (milling, drilling), mirror finishes (grinding, turning, lapping) complex geometries (milling) and internal features (milling, boring). Problems associated with these methods include limited precision for small tool edge radii, and restriction to simple shapes. Additionally, some methods can result in longer operational times to fully fabricate. Moreover, the structural weakness that can be inherent in some tool designs at this scale make mechanical subtractive processes

challenging to use. Here is a case in point. It has been reported that up to 50% of WC 50- μm end mills shaped via grinding broke during fabrication [12]. It was attributed to a combination of larger grain size material matrix, and inadequate design and construction methods originating from commercial macrotool geometries. Smaller grain sizes are, therefore, recommended for microtools as they increase toughness [12]. Nonetheless, the choice of fabrication technique will, to a large degree, depend on the tool material, the size, shape, and ultimately the application and machining conditions to which the microtool is subjected. Finally, hybrid fabrication methods include combining techniques, such as WEDG and micro-EDM (μEDM), as well as modification of existing mechanical and electro-discharge machining methods, e.g. ultrasonic-assisted EDM, to achieve specific requirements [12]. Table 1 highlights the main micro-fabrication techniques.

Current developments in microtool design and fabrication

The fabricating and finishing methods outlined have been used for many years with varying levels of success. Notwithstanding, there is large room for improvement in the fabricating technique, which can be achieved through novel fabrication and forming methods in conjunction with judicious selection and modification of material composition.

Gao *et al* [24] fabricated a helically structured, cemented carbide micro end mill and subjected the cutting tool to a series of grinding experiments to ascertain how the tool grain size and composition affects the cutting edge and surface roughness.

The results showed mainly microfracture generation around the cutting edge from WC grain dislodgement, which was attributed to low bond strength at the WC/Co boundary interface. This suggests that the tool material/matrix substrate might benefit from reduced grain size during synthesis and an improved sintering process. Egashira *et al* [25] developed a 3 μm cemented WC microtool via a modified EDM process and then performed milling on brass plates in tandem with ultrasonic oscillation to reduce cutting resistance. They reported successful cutting of 2 and 3 μm depths in the plates and noted that good chip removal was observed if swarf and debris were evacuated efficiently. However, only one out of four tools, on average, was able to perform this depth without breakage. The moderate result may be from the tendency of the edge to fracture at this scale due to localized thinness/brittleness which acts as stress concentration points.

Zhong *et al* [26] designed and fabricated a single-edge PCD microcutting tool with a reinforced WC shank, based on a design structured around diamond fly cutting and a sawing blade feature, with application for machining microchannels. Fabrication was achieved via welded joining of the PCD/WC structure, followed by shaping of the tool through wire EDM (WEDM), with finishing achieved on a precision grinder. High dimensional accuracy with minimal burring was reported for experimental testing on brass plates.

Oliaeia *et al* [27] manufactured a novel PCD hexagonal microtool incorporating a parallelogram-type structure with a

Table 1. The main microfabrication techniques.

Fabrication technique	Advantages	Disadvantages
<i>Electrodischarge machining</i>	<ul style="list-style-type: none"> • Can produce complex features with very close tolerances • No direct machine/tool contact • Suitable for small hard-to-shape materials • No burring 	<ul style="list-style-type: none"> • Slow material removal rate (MRR) • Difficult to use in some materials/conditions • Electrode wear • Restricted to electrically conductive materials
<i>Wire electrodischarge grinding</i>	<ul style="list-style-type: none"> • No direct machine/tool contact • No burring 	<ul style="list-style-type: none"> • Slow MRR • Electrode wear • Restricted to electrically conductive materials
<i>Ion beam sputtering</i>	<ul style="list-style-type: none"> • Produces very sharp edges with low contact forces • Precise control of material removal process 	<ul style="list-style-type: none"> • Can be expensive • Slow MRR
<i>Laser beam machining</i>	<ul style="list-style-type: none"> • Noncontact technique • Suitable for brittle materials • Offers high-precision material removal with little or no finishing required 	<ul style="list-style-type: none"> • Potential modification of material properties • Expensive • Energy usage
<i>Mechanical machining</i>	<ul style="list-style-type: none"> • High dimensional accuracy • Provides for: Complex geometries Internal features Optical finish 	<ul style="list-style-type: none"> • Longer fabrication times • Limited to simple shapes at smaller dimensions • Can be challenging to avoid chipping/fracture of the substrate

large negative rake angle (figure 6). The authors reported that this cutting-edge design would reduce the contact area between the tool and workpiece surface. The tool was made by brazing the PCD onto a WC substrate followed by WEDM, which was used for shaping the 450–500 μm dimension structure. Ductile regime machining was observed with an improvement in MRR and surface roughness measurements in comparison to commercial PCD end mills. The negative rake angle of -45° may have contributed to compressive stress generation thus improving tool performance. This highlights the influence tool microgeometries and associated machining conditions have on the mechanism and efficiency of the cutting processes in micromilling.

Hajri *et al* [28] fabricated a 100 μm diameter ball nose end mill on cemented carbide blanks using tangential laser ablation. Tests conducted on pure copper (Cu) workpieces revealed acceptable surface quality. However, peeling of the ablated tool surface was reported, likely due to the laser-induced thermal fabrication method used.

Using a robot-guided water jet abrasive system, Biermann *et al* [29] fabricated a preparatory cutting edge on cemented carbide blanks to enable formation of complex shapes and enhance the adhesion strength and stability of coatings. The tests showed promising results; however, more evaluation is required on the suitability of this process for microfabrication.

Uhlmann *et al* [30] used a novel immersed tumbling edge preparation method to assist with edge stabilization of

cemented carbide end mills to reduce operational chipping for cutting tools of 0.2 mm in diameter. A series of cutting tests on molded steel showed improved wear resistance relative to untreated tools, with moderate improvement in machined surface roughness. Overall, the authors reported advantageous performance when edge preparation is used in microtool fabrication.

Hintze *et al* [31] investigated the potential of a three-fluted, chamfered PCD end mill for the semifinished machining of WC. The results showed that mainly abrasive flank wear was present with evidence of wear on the rake face also. They noted that the chamfering provided for predictable tool wear during cutting. A continuous chip was generated during testing indicating plastic deformation of WC with good MRR rates.

Increased productivity with limited frictional contact and increased speed can be achieved using micromilling of WC in tandem with suitable machining strategies. Fang *et al* [32] reviewed developments in microcutting mechanics and corresponding chip formation patterns during a series of experiments. Their analysis concluded that the design of microcutting tools should reflect the requirements of the cutting process, and modification of workpiece surfaces be employed to promote favorable cutting conditions. Moreover, in-depth consideration of the material properties involved and geometrical shapes of the cutting tool should be input into simulation studies, thereby improving predictive results.

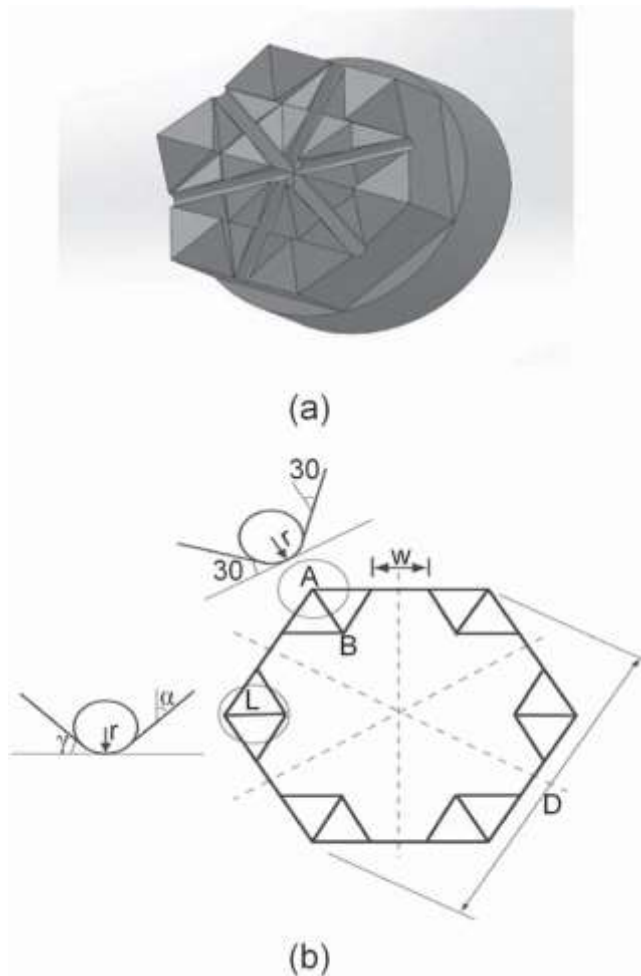


Figure 6. (a) CAD rendering of the PCD micro end mill and (b) schematic of the tool geometry specifications. Reprinted from [27], Copyright 2018, with permission from Elsevier.

Developments in the fabrication of SCD, PCD, and cBN microtools

Fabrication of SCD, PCD, and cBN microtools is a challenging undertaking as the extreme hardness of these materials makes shaping and forming tool structures that can withstand the process intact very difficult. Another issue is the cost; these materials are far more expensive than other hard materials, such as WC. Therefore, it is imperative that they are used judiciously and for the right application. However, these materials can offer superior tool performance that produces a high-quality finish in hard machining; and experiments have shown results that would not otherwise be possible using other tool materials.

Suzuki *et al* [33, 34] designed SCD and PCD microtools with multiple cutting edges for the precision machining of binderless WC molds. The SCD tool was fabricated via laser beam shaping and micropatterning until ten cutting edges with sharp and round geometries were achieved, as shown in figure 7. They used the sharp cutting edge tool with a negative rake angle of -40° and an interrupted cutting protocol to machine the WC workpiece, resulting in reduced localized wear and lower cutting temperatures [33]. Ductile mode

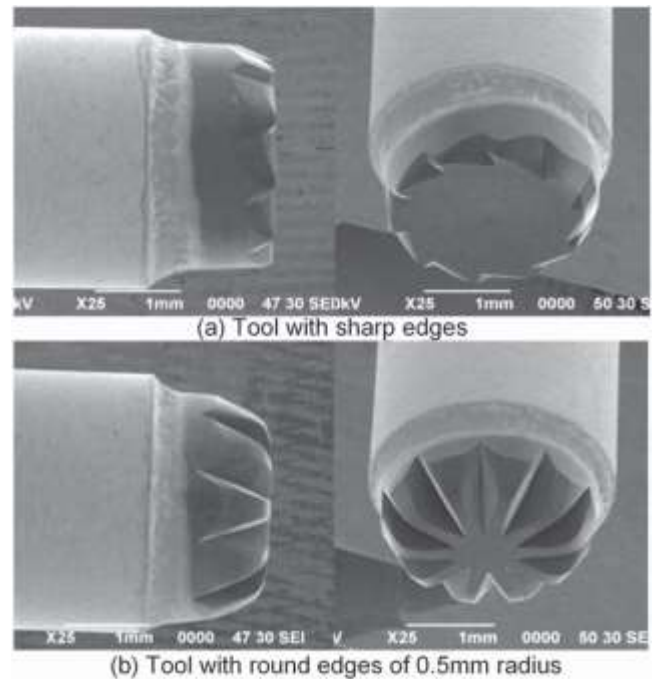


Figure 7. SEM images of a laser-fabricated SCD microcutting tool with multiple (a) sharp and (b) round cutting edges. Reprinted from [33], Copyright 2013, with permission from Elsevier.

machining with continuous chip removal was observed using a $0.5 \mu\text{m}$ cut depth and 0.5 mm min^{-1} feed rate. Secondary experiments using a $1 \mu\text{m}$ cut depth and 0.1 mm min^{-1} feed rate, produced from accuracies of $\sim 100 \text{ nm P-V}$ and surface roughness values of 12 nm Rz [33]. In a prior experiment conducted again on binderless WC [34], a PCD wafer was bonded to a carbide substrate and then shaped via WEDM followed by diamond wheel grinding and polishing. A similar interrupted cutting regime was applied, with a negative rake angle of -20° ; and similar form accuracies were achieved with a surface roughness of 15 nm in Rz .

These results indicate that a negative rake angle appears to benefit ductile machining of brittle materials, which is partially maintained by keeping the edge radius smaller than the UCT. Additionally, this protocol also promotes high hydrostatic stresses which have been shown to generate ductile material removal in glass [35].

The extreme hardness and thermal conductivity offered by SCD/PCD makes them attractive materials for use in high precision microtools. This was highlighted again by Suzuki *et al* [36] who fabricated binderless nanopolycrystalline diamond (NPCD) microtools with a round structured shape, to machine microtextured surfaces on SiC molds in ductile mode.

Nanopolycrystalline diamond is harder, tougher, and has a higher homogeneity than SCD. Analysis of the molds showed better form accuracy and higher precision with superior surface smoothness relative to the SCD tool. Wear analysis characteristics were indicative of crystal orientation dependency. In addition, maintenance of the ductile mode during the test was partially attributed to the large effective

number of cutting edges that remained on the NPCD tool, which was reduced measurably on the SCD tool.

Although these results are generally promising, the physiochemical and economic restrictions on diamond limits their wider application, and alternative materials which can address these limitations are currently being researched for microtool applications.

In view of this, cBN has received more attention as an option both as a base material for microtools and also for its application potential through modification of the binder phase and cBN grain distribution [37]. Costes *et al* [38] found that low cBN composition (45–65 vol%) in combination with smaller grain sizes, displayed superior tool wear on machining Inconel 718. In addition, Slipchenko *et al* [37] analyzed multiple cBN compositions and found that systems with 60 vol% of cBN were the most effective in wear resistance during the machining of AISI 316 L. This may prove useful in modifying compound compositions specific to tool requirements. However, any other properties that may have been modified as a result of compound changes need to also be analyzed to ensure the mechanical and chemical properties of the material are not adversely affected by the process.

Chen *et al* [39] developed a nano-twinned cBN microcutting tool (50–120 nm grain size) via laser contour machining and FIB fabrication (see figure 8) for precision turning of hardened steel (HRC 48). Results revealed mirror surface quality with a surface roughness of less than 7 nm. The cutting edge had a roundness of ~60 nm; and the tool material had a high hardness and fracture toughness of 85 GPa Hv and 12 MPa m^{1/2}, respectively. Abrasive wear was the dominant wear mechanism, with a negative rake angle displaying the best wear resistance. Although FIB can produce good results fabricating features in the microtool substrate (as noted earlier), the slow efficiency may be problematic for upscale fabrication. Aside from the tool substrate, cBN is also used to enhance tool edge performance during machining. Uhlmann *et al* [40] showed that thin cBN coatings applied to carbide substrates through a physical vapor deposition (PVD) process, displayed twice the hardness of conventional titanium aluminum nitride (TiAlN) coatings and exhibited superior chemical and thermal stability under turning of Inconel 718. Their results also revealed higher wear resistance; and, in particular, it was observed that adhesion resistance surpassed conventional coatings. The cBN coatings also increased tool life by 50% in comparison to TiAlN and reduced local cutting forces at a relatively high cutting speed.

Hanel *et al* [41] focused their research on the potential of nanocrystalline binderless BN for cutting of hard materials, which are considerably harder than commercial cBN due to the Hall–Petch effect. Although good material hardness is a requirement for the machining of hard-to-cut materials, the elevated hardness in this case presents a challenge in the shaping and forming of the tool cutting edge owing to its superior properties [42].

The color of the cutting tool may appear a cosmetic irrelevance; however, color can be an important indicator of the material content of a compound. Cubic boron nitride is typically black, brown, or dark red but can also be golden in color. Although at first sight, the color of cBN appears

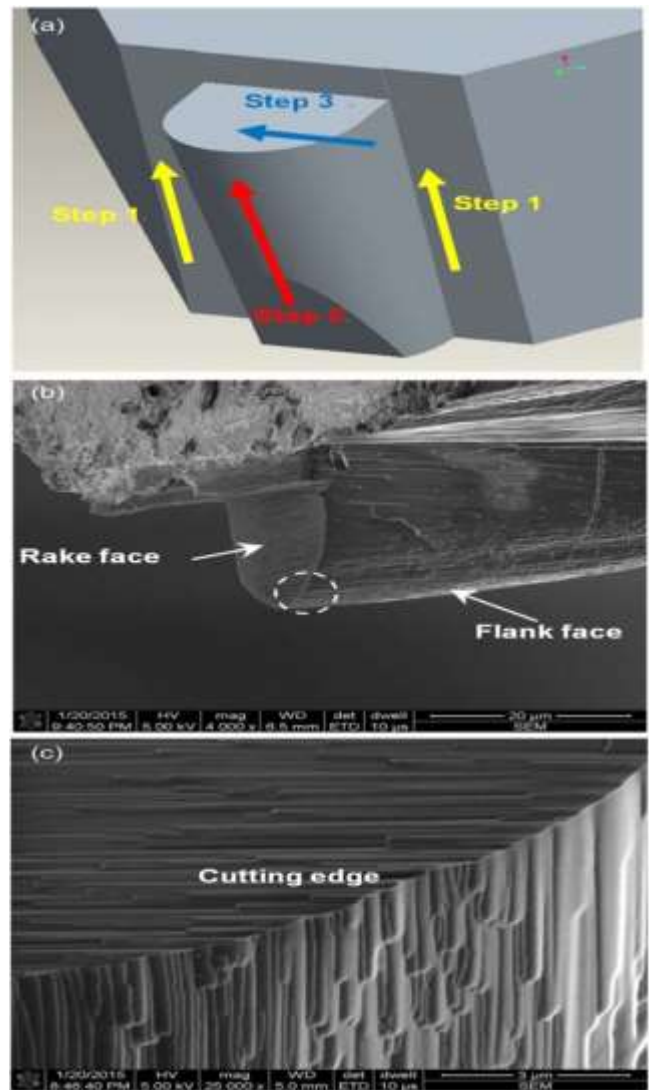


Figure 8. SEM images of (a) FIB track geometry, (b) nanotwinned-cBN microcutting tool, and (c) enlarged region of rounded cutting edge. [39] © Science China Press and Springer-Verlag Berlin Heidelberg 2016. With permission of Springer.

insignificant for tooling applications, it does reveal an indication of its mechanical properties and its processing suitability. Du *et al* [43] showed that the variations in cBN crystals are reflected in diversified properties and morphologies. It is thought to be attributed to the presence of B (along with crystal orientation, defects, and impurities) in the compound, which, when modified in volume, affects the microstructural behavior (figure 9).

Single-crystal diamond, PCD, and cBN offer many advantages in specific hard machining applications. Advancements in the microfabrication methods for these materials will ultimately supplement the progressive developments in the creation of complex structures, thus enabling wider use of these microtools in industry.

Cooling of the tool and associated thermal processes

The problem of heat generation in the cutting zone, which negatively impacts wear and tool life, in addition to the

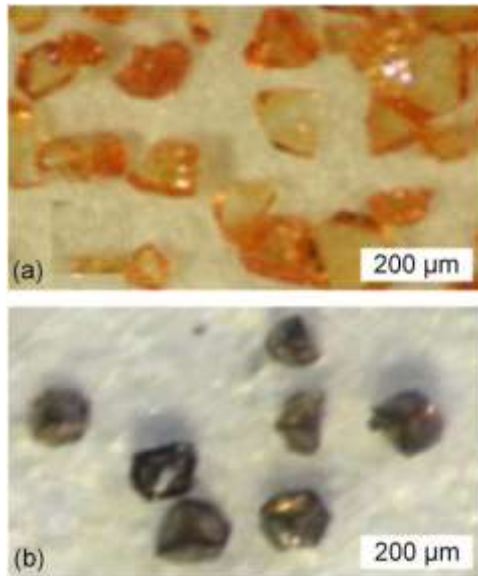


Figure 9. Synthesized cBN crystals displaying variations in color and morphology: (a) without additive boron and (b) with 2 wt% additive boron. Reprinted from [43], Copyright 2007, with permission from Elsevier.

adverse effects on accuracy and surface quality, is a major technical and economic issue with no obvious solution. Nevertheless, a number of developments have been ongoing. Cryoprocessing, a form of supplemental low temperature heat treatment prior to tempering, can improve the physical properties of the tool material. This technique involves immersing the material in liquid helium to enhance the strength, hardness, and wear resistance of alloys and carbide tools. However, it is a relatively slow process due to low atomic movements at these temperatures (-270°C); and, therefore, it may have limited suitability for industrial applications [44]. Despite this, the authors report that cryogenically treated WC tools showed superior performance in interrupted machining (milling) in dry and wet conditions, with enhanced flank wear resistance and chipping reduction [44]. Wu *et al* [45] also reviewed how cryogenic cooling can be applied to the cutting zone to alleviate the high temperatures generated, with results showing improved temperature control, reduced wear, and lower cutting forces.

Kirsch *et al* [46] used a modification on the cryogenic cooling technique that consisted of a liquid metalworking fluid jet at -30°C . It showed good temperature control, improved wear resistance, and good chip formation compared to dry cutting (figure 10). Further studies are needed on the potential of cryogenic microtool cooling to assess its cost effectiveness and optimum application.

Wu *et al* [45] also highlighted internal cooling strategies for dry cutting, which can help circumvent the high thermal loads and increased friction due to lack of external fluids. They identified two main types of internal cooling systems. Heat-exchanger-assisted cooling, in which a cooling block uses a flow-rate-dependent in/out fluidic system, reduces heat in an insert (which might be adapted as a tip temperature measurement component). This method could also incorporate a

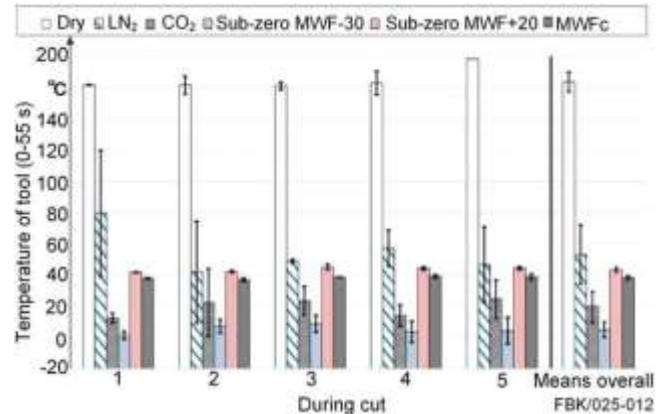


Figure 10. Graph showing average values of temperatures over five cuts under varying conditions. Reprinted from [46], Copyright 2018, with permission from Elsevier.

ryogenic coolant within the in/out flow channel system. Although this research shows promise, the efficiency of heat dissipation in the tool interface remains the main obstacle to real improvements [45]. The second type of internal coolant is heat-pipe-assisted cooling, in which a passive device transfers heat through a two-phase heat sink (figure 11) [45]. However, one requirement for the tool material in this approach is good thermal conductivity, so this needs to be considered during material selection. Although simulation and experimental studies showed that temperature, thermal stresses, and wear reduction improved markedly using this technique, reduced thermal efficiency along with limited testing on microapplications will necessitate further studies to ascertain its suitability at these dimensions. Modifications to this method, such as a pulsating heat pipe cooling system that uses a thermally generated two-phase oscillation, shows promise for microapplications as they can be designed for smaller tools and provide better thermal efficiency.

The ability to accurately determine dynamic thermal variations during the machining process would provide insightful information on the nature of the cutting mechanisms at work. Shu *et al* [47] investigated new ways to measure the temperature in the cutting zone in tandem with a controlled, closed-looped internal coolant within the tool structure. Paramount in the design phase was identifying and evaluating the optimal position and the mechanical effect of the cooling channel, relative to the thermal flux generated in the cutting process. Simulation and experimental tests revealed the average interface temperature was significantly reduced during cutting, and there was a positive correlation between increasing heat flux and the effectiveness of the internal coolant. However, the integrated thermal sensor did not provide accurate reading in this configuration due to time lags between the inlet/outlet coolant valves. Nonetheless, their results showed that adaptive thermal sensors and responsive internal coolants are promising methods for thermal and wear problems associated with cutting tools.

Ghani [48] investigated the design of internally cooled cutting tools and their potential for machining grade 2 commercially pure (CP) Ti. Analysis of thermocouple, pyrometer,

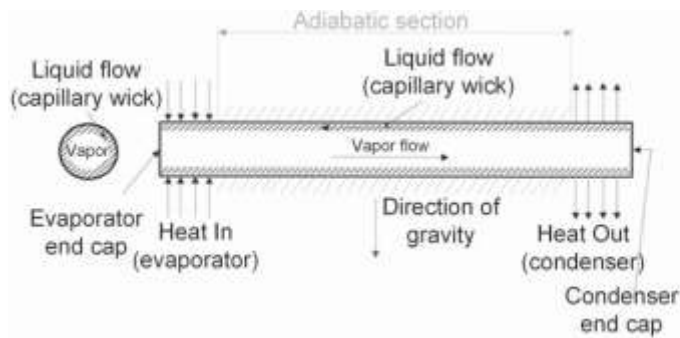


Figure 11. Heat pipe schematic with a proposed model of an integrated axially centric heat pipe in a cutting tool. Reprinted from [45], Copyright 2017, with permission from Springer.

and infrared (IR) cameras indicated that embedded thermocouples were the superior option in terms of reproducibility and accuracy, as measurement of the material surface emissivity proved too difficult for IR sensors. Simulation studies revealed a jet cooling microchannel internal configuration was the most efficient cooling method. For the WC tooling insert used in the study, modification strengthening of the internal tool structure indicated a $0.8\ \mu\text{m}$ channel diameter located 1 mm away from the locus of the cutting edge, provided for improved mechanical strength [48]. However, the effectiveness of the internal coolant in temperature reduction was minimal overall. This was attributed to an increasing friction coefficient between the sliding chip and the tool rake face resulting from lack of lubricant. Nonetheless, these results highlight for the successful implementation of smart tooling integration, it is recommended that a methodological process for the control of thermal and cutting conditions be employed, including machining parameters in conjunction with tool design.

Lu *et al* [49] developed a cryogenic machining technique, which uses an internally structured, low-pressure coolant channel for controlled cyclic flow of liquid nitrogen (N) in a milling cutter, with the coolant supplied via the spindle shaft. They reported that this tool could be used at higher cutting speeds with reduced tool wear due to the reduced temperature. The internal design consisted of a central channel with exhaust holes positioned near the tool edge. The design also allows for expulsion of the liquid in spray form, thus reducing workpiece temperatures. However, one drawback is the safety and cost issues associated with liquid N, as well as the loss of toughness in the tool material, which may make it prone to brittle fracture. More testing and analysis is needed to ascertain its suitability for micromachining.

Modification of the tool surface through micropatterning

The development of high performance microtools requires significant research into microscopic behavior under specific machining conditions. This effort requires a fundamental understanding of physiochemical properties as well as the ability to modify compositional components effectively and to synthesise a specific material and matrix substrate which will provide for the demands required for the machining of hard-to-cut materials. This is a complex undertaking;

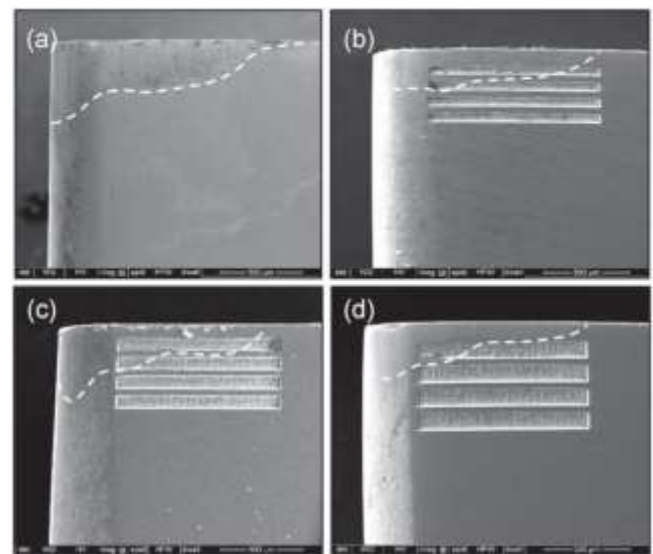


Figure 12. Micrograph showing flank wear on (a) conventional tool, and (b)–(d) displaying variations on textured groove dimensions with enhanced wear resistance. Reprinted from [50], Copyright 2018, with permission from Elsevier.

therefore, alternative approaches have been employed. Modification of the microtool surface through direct patterning offers a relatively cost-effective and less laborious alternative to engineering a new material.

Recent developments in the surface engineering of cutting tools have shown that these micropatterns or textures can have beneficial effects in terms of mechanical behavior during the cutting process [50]. Various geometrical microstructures can be patterned onto the cutting tool providing for enhanced wear resistance (figure 12). Studies have shown the direct advantage of using these novel features; however, their mechanism of action is not fully understood, and the optimum design may strongly depend on the particular tool/workpiece material, application, and cutting conditions.

Using a femtosecond laser to fabricate microscale textured designs on a WC tool, Liu *et al* [50] machined a series of cuts on green body Al_2O_3 ceramics via turning. The results showed higher flank wear resistance as well as improved workpiece surface quality compared to an untextured WC insert. There appeared to be an optimum set of micron spacing parameters for the tool face texture design that achieved

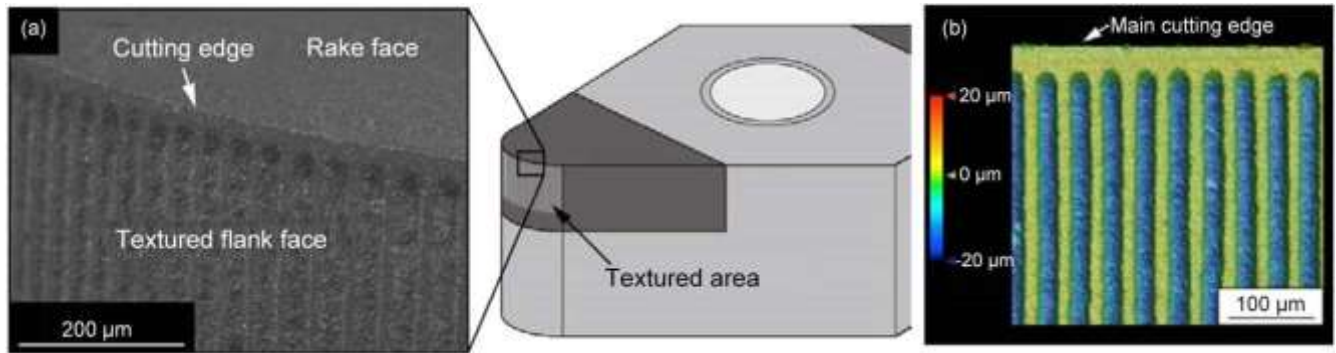


Figure 13. (a) SEM image of cBN textured face showing location on tool, and (b) microgrooves of the structure showing the main cutting edge and reduced contact area. Reprinted from [52], Copyright 2017, with permission from Elsevier.

the best results, which suggests a correlation between the design geometry and the microstructure orientation surface of the workpiece.

Fang *et al* [51] also reported enhanced wear resistance on the flank face of PVD-coated microtextured carbide tools in the turning of Inconel 718 using a jet coolant. They indicated a reduced tool interface temperature and improved chip formation. Again, an optimized geometry was identified for maximum effectiveness. Additionally, it was noted that the cooling action of the fluidic flow, along with the increase in heat transfer coefficient due to the textured surface area, contributed to the reduced temperature.

In another study, Sugihara *et al* [52] investigated cBN thermal and wear behavior while performing high speed dry and wet machining of Inconel 718 using a textured flank face (figure 13). Orthogonal rectangular grooves, with a depth of $10\text{ }\mu\text{m}$ equidistantly spaced at $20\text{ }\mu\text{m}$, were fabricated via a femtosecond laser. The grooves were positioned $30\text{ }\mu\text{m}$ from the tool edge which provided for retention of the localized material strength. The results showed lubricant-assisted machining outperformed the dry test in terms of wear resistance and heat generation. This was attributed to the textured flank face geometry, which reduced the contact area and facilitated the flow of the coolant during machining. These results indicate high-speed machining of hard materials is possible using surface engineering techniques.

Su *et al* [53] dry machined a Ti6Al4V alloy using a microgrooved PCD tool. The results highlighted the positive impact the micropattern had on frictional and cutting force behavior at tool interfaces. The improvement was attributed to the geometry of the grooves and reduction in tool chip contact length which prevented chip adhesion from occurring. Similar findings by [54–57] showed that micropatterning influences the wear behavior of cutting tools, and the diameter of the pattern is likely the most significant feature that affects this process.

Further investigations by [58, 59] using microdimpled, textured surfaces on the rake face of cutting tools have shown promising results. These patterns reduced crater wear under dry cutting conditions through the action of the microfluidic reservoir. When comparing open microgrooves and closed dimpled textures, they found that the closed dimpled design

was superior in testing; and surface anti-adhesion properties were enhanced [59].

Li *et al* [60] also conducted an analysis of the effectiveness of surface patterning a microball end mill. Results showed that the microtextured tools increased tool wear resistance, reduced local temperature and cutting force, and enhanced surface quality when machining Ti alloys. This suggests a positive correlation between surface modification via texturing of the tool and machinability of the workpiece. By designing and fabricating suitable microtextures/grooves onto the surface of cutting tools at specific locations and orientations, it is possible to reduce the temperature and frictional and cutting forces measurably. In addition, the wear profile of the cutting tool and chip formation shows marked improvements relative to plain surfaces when machining, irrespective of the workpiece material. The mechanism of action appears to be related to the geometrical modification of the microtool surface, and the corresponding way in which the tool/workpiece interacts, specifically contact times, although more work is needed to ascertain precisely how this operates. It was also found that the addition of lubricants/coolants in conjunction with this procedure can reduce frictional and thermal generation through microchannel retention of lubricants, which makes these surface-engineered structures worth considering for inclusion in microtool design.

Coatings on the tool substrate

The high heat and frictional forces generated at the tool interface can result in premature wear and poor machinability, which by extension affects surface quality. A cost-effective solution that requires minimal material volume is coatings. Typically, PVD/chemical vapor deposition technologies are employed for this; however, issues such as low cycle fatigue and poor adhesion/delamination in conjunction with weak chemical bonding of the coating have resulted in inadequate performance with some compositions during operation.

Gupta *et al* [61] analyzed PVD-coated cutting tools (TiN, aluminum chromium nitride (AlCrN) and TiAlN) and tested these for the turning of C45 steel. The results showed that all three demonstrated improved wear qualities to varying degrees. Overall, however, the TiAlN-coated tool with its

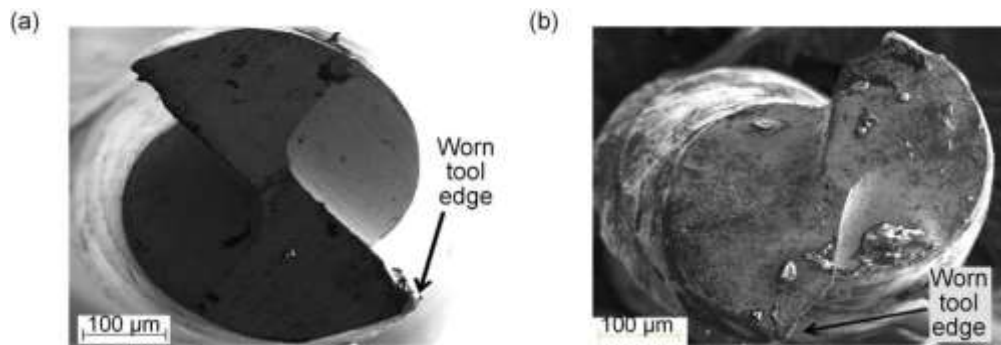


Figure 14. (a) Uncoated WC/Co tool and (b) cBN-coated WC/Co tool after milling of Ti-6Al-4V. Reprinted from [63], Copyright 2013, with permission from Elsevier.

hardness, enhanced lubrication, and anti-adhesion properties proved the most promising.

Conversely, Okada *et al* [62] analyzed the cutting performance using various coatings of TiN, TiCN, TiAlN, and multilayered TiAlN/AlCrN on carbide tools deposited via PVD and compared the results against uncoated cBN on the end milling of hardened steel. They concluded that the uncoated cBN tools performed better at high-speed milling. The results may be associated with the length of tool contact time used; and, significantly, they reported that the coated tools showed no obvious advantage over uncoated cBN tools in terms of surface roughness. Thepsonthi *et al* [63] used finite element (FE) analysis and experimental tests to examine the effectiveness of thin cBN coatings used to enhance the mechanical properties of carbide micro end mills. Analysis revealed increased tool life and improved surface roughness (figure 14). They indicated that the cutting forces increased with the cBN layer, but the temperature reduced. As expected, the temperature and wear rate increased with the increasing feed and cutting speed. Interestingly, the increased edge radius caused by the coating did not adversely affect the accuracy in the machining process, possibly due to the thinness of the cBN layer.

M'Saoubi *et al* [64] also examined the wear profile of PVD-coated (TiN, titanium silicon nitride (TiSiN), TiAlN, AlCrN) polycrystalline cubic boron nitride (PCBN) tools against uncoated PCBN during the turning of case-hardened 16MnCr5 steel. Various results, similar to [61], were found. In particular, TiAlN-coated tools displayed increased wear resistance, which the authors suggest was mainly due to the high cutting stress action producing hardening effects. Breidenstein *et al* [65] reported that the performance of PVD-coated carbide cutting tools is affected by residual stress, originating from a combination of the coating and precoating processes. They postulated that high compressive stress on the tool substrate and coating is required to achieve enhanced tool longevity, which necessitates consideration of adhesive properties during the fabrication process.

Progressive tool wear at high speeds is a major concern for manufacturers, especially for hard-to-cut materials in dry cutting conditions. DeCristofaro *et al* [66] tested a selection of various coatings on four-flute WC microtool-coated flat end mills for the machining of 62 Hardness Rockwell C (HRC)

hardened steel at high cutting speeds. They reported low silicon monolayer nanostructures exhibited high deposition homogeneity in forming on the surface, providing a very sharp cutting edge. The high wear resistance along with progressive wear formation made it a good candidate for further analysis. Romanus *et al* [67] analyzed the micro-milling of sintered zirconia ceramics using cBN and diamond-coated end mills. The results showed that although the tool performance was initially better, the diamond-coated tools suffered delamination with subsequent wear of the substrate. The cBN-coated tools exhibited fast breakage mainly due to adhesion of zirconium dioxide (ZrO_2) on the tool surface.

Bandapalli *et al* [68] used PVD-coated AlTiN and TiAlN WC end mills along with uncoated WC cutting tools for the high speed (10 000 rpm) dry milling of grade 12 Ti alloys. They reported diffusion, oxidation, abrasion, and adhesion wear mechanisms occurred on the cutting edge during the tests. Moreover, the results indicated that the uncoated WC end mills performed better than the coated tools. This was attributed to delamination of the PVD layers which influenced the accelerated wear rates.

Chowdhury *et al* [69] deposited architectural variants (mono/multi/bilayer) onto mirror-polished WC-Co substrates with a TiAlCrSiYN system via PVD, in order to test the efficacy of the wear resistance and bonding mechanism. The bilayered 3 μ m thick coating performed best under the dry cutting of hardened steel, due to formation of a protective tribo-ceramic film on the surface during milling. They suggested this thermal barrier critically improves the wear performance of the coating layer, and by extension the tool life. The results indicate modification through optimization of the TiAlCrSiYN system architecture improves protection of coatings under harsh machining conditions. Experimental tests on various hard materials and machining conditions appears to validate the advantages of applying selectively deposited coatings onto tool substrates in terms of wear suppression.

However, some research suggests that tool coatings are not always advantageous to microtool longevity and surface quality [63, 67, 68]. Moreover, the addition of the coating increases the cutting edge radius; and for small diameter microtools (<200 μ m), this proves impractical as the thickness would invariably be \sim 100 nm minimum. The process

itself may damage the brittle structure. More problematic is the lack of detail in the literature as to the technique used in coating the material substrate. Coupled to this is the experimental and unsystematic method used in choosing the best coating for a particular material and application [12].

In summary, although clearly beneficial for macro-machining operations, the use of thin coatings as a means to enhance microtool properties requires more in-depth, critical analysis. In particular, fabrication methodologies and size effects relating to the cutting edge radius need clarification and further research.

Lubricants on the tool substrate

Dry or near dry machining has seen an increase in research recently due to health and environmental concerns around the use of coolants. However, dry machining results in reduced tool life and increased production costs. A potential solution to this is solid lubricants. These are typically applied as coatings to the tool substrate surface or are integrated as part of a filler via self-lubricating compounds to aid as a friction-reduction mechanism. Chemical stability, wear resistance, and good adhesion between the two surfaces under applied loads are some of the requirements for solid lubricants. Therefore, the range of compounds currently suitable for this application is limited. Lian *et al* [70] deposited a tungsten disulfide (WS_2) solid lubricant onto a cemented carbide substrate and tested the cutting tool on quenched and tempered steel. The performance was compared against uncoated cemented carbide. Results showed the cutting force and local interface temperature was reduced for the coated tool even at high cutting speeds, which was attributed to the high-temperature/oxidation resistance of the soft coating and the reduced average shear strength at the tool/chip interface. Wu *et al* [71] reported on a type of Ni/CaF_2 coated self-lubricating cutting tool for the dry cutting of hardened steel, which when compared to a standard calcium fluoride (CaF_2) tool exhibited superior antifriction and wear resistance (figure 15). However, although better homogeneity was observed in the coating, it still remains a challenge. Additionally, analysis revealed that transgranular and intergranular fracture were present in the microstructure. A summary of the techniques employed to reduce friction and wear in microcutting tools are shown in table 2.

Gomez *et al* [72] investigated how modification of an adhesive chromium nitride/chromium (CrN/Cr) interlayer might improve the interlocking mechanism of diamond-coated tungsten carbide/cobalt (WC/Co) tool inserts. These were then tested during dry cutting on high silicon aluminum ($SiAl$) alloys. However, during testing, the adhesion suffered a dramatic fracture and ultimate dislodging of the coating. This was attributed to weak chemical binding energy and the directional workpiece surface features perpendicular to the tool edge, which provided an initiation of preferential pathways that led to crack propagation at localized points on the tool substrate/coating interface.

Muthuraja *et al* [73] developed WC cutting tools with a $WC-10Co-5CaF_2$ and $WC-10Co$ solid lubricant for the dry

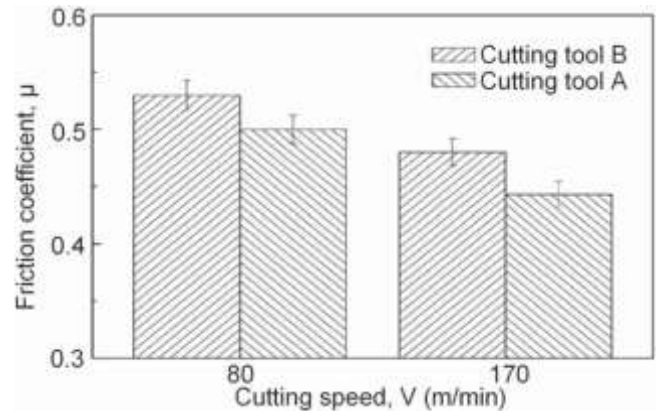


Figure 15. Chart showing the different friction coefficients between (A) the tool–chip interface of $Al_2O_3/(W, Ti)C/CaF_2@Ni$ cutting tool (A) and (B) the $Al_2O_3/(W, Ti)C/CaF_2$ cutting tool (B) at different cutting speeds. Reprinted from [71], Copyright 2016, with permission from Elsevier.

machining of AISI 1020 steel, which was then compared against unlubricated WC tools. The results revealed that the solid lubricant $WC-10Co-5CaF_2$ tool exhibited reduced cutting force in all directions during turning. It also had superior resistance to thermal generation on the tool interface, better chip morphology, and better surface finish. Although the methodology for temperature measurement was likely inaccurate, the results indicate heat was reduced.

5. Tool performance and evaluation

The ability of a cutting tool to perform precise, reproducible machining operations is a core attribute needed to meet the demands of industry. All cutting tools should be capable of performing the function for which they were designed. Careful analysis of microcutting tools reveals that this is not always the case. The need for consistency in quality and reliability of performance and productivity output is a fundamental critique which has yet to be extensively applied to microcutting. What follows is a critical analysis and discussion of microcutting tool performance during hard machining operations with a particular focus on brittle materials.

Geometry of the cutting edge

A key aspect of microcutting technology is the geometry of the tool edge, angle of cut, shape, and sharpness. The tool edge determines, to a large extent, the mechanism of tool/interface interaction and, by extension, how the tools physicochemical properties, including temperature, hardness, toughness, and inertness, would affect the material removal rate and chip formation mechanism [74, 75]. This influence is particularly significant in microcutting when the dimensions of the tool edge become comparable to the UCT (figure 16). Research has also found that a minimum value of UCT exists below which ploughing occurs [76].

Cutting edge geometrical designs have a direct impact on the magnitude of mechanical and thermal stresses generated at

Table 2. Summary of methods and materials to reduce friction and wear in microcutting tools.

Methods to reduce tool wear	Technique/Material	Challenges
<i>Cooling of the tool/cutting zone</i>	<ul style="list-style-type: none"> • Cryoprocessing of the tool • Cryogenic cooling of the cutting zone • Heat exchanger assisted cooling • Heat pipe/pulsating heat-pipe-assisted cooling • Internal microchannel 	<ul style="list-style-type: none"> • Slow process • Safety • Cost • Material properties • Efficiency in heat dissipation • Requires good thermal conductivity • Structural weakness/dimensions of tool • Internal friction • Poor accuracy
<i>Solid lubricants</i>	<ul style="list-style-type: none"> • WS₂ solid lubricant • Self-coating Ni/CaF₂ WC-10Co-5CaF₂ and WC-10Co 	<ul style="list-style-type: none"> • Homogeneity • Intergranular fracture • Bonding between substrate and lubricant • Chemical compatibility/inertness • Wear resistance
<i>Coatings</i>	<ul style="list-style-type: none"> • TiN, AlCrN, and TiAlN • Multilayered TiAlN/AlCrN • TiSiN, AlCrN • TiAlCrSiYN • Biofilms 	<ul style="list-style-type: none"> • Delamination/bonding problems • Low cycle fatigue • Coating processes—residual stress • Chipping/fracture • Increased cutting edge radius • Size effects
<i>Micropatterning</i>	<ul style="list-style-type: none"> • Microtextured features • Open/closed grooves • Dimpled textures 	<ul style="list-style-type: none"> • Better understanding of the mechanism of action • Optimum geometry/shape/location • Use of fluidic lubricants in conjunction with micropatterns

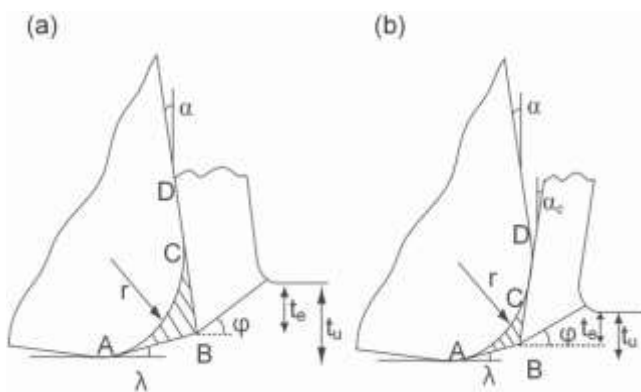


Figure 16. Schematic illustrating the relationship between (a) inclination angle and uncut chip thickness and (b) effective rake angle. Reprinted from [75], Copyright 2009, with permission from Elsevier.

the tool interface, thus increasing tool wear and affecting the burr formation and surface quality [4]. Therefore, the importance of the geometrical cutting edge design in micro-milling should not be ignored. Appropriate cutting edge designs *specific* to the material workpiece and process conditions will enhance tool life and machining reliability [77]. Furthermore, the cutting edge shape, sharpness, *and* condition greatly influence the form and quality of machining operations. Tool condition monitoring, e.g. optical and tactile characterization methods, should be dually integrated as standard into any machining process to ensure consistency in performance during service.

Microcutting should employ minimization of surface roughness strategies during machining. This can be achieved by reducing surface elevation through elastic recovery (ploughing effect) by creating and maintaining a superior

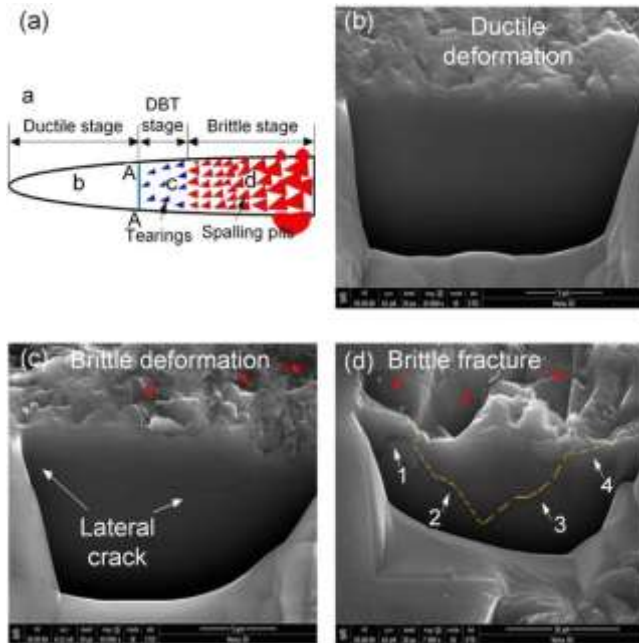


Figure 17. (a) Diagram illustrating the mechanism of material removal and SEM images (b)–(d) showing these respective zones during cutting. Reprinted from [78], Copyright 2018, with permission from Elsevier.

sharp cutting tool, which additionally aids the reduction in burr formation by optimizing the machining conditions for the specific workpiece [11]. Prior surface preparation as outlined by Denkena *et al* [77] show how a prefabrication step can create a superior tool with enhanced mechanical strength, edge stability, and wear resistance. Additionally, this technique also improves any coating adhesion that may be required. The geometry of the tool edge also affects the ductile-brittle transition during machining.

In a recent study, Gu *et al* [78] investigated geometrical cutting parameters on sapphire, highlighting how cutting edge designs directly influence stress distribution and, by extension, the initiation of the brittle-ductile transition zone (figure 17). They found that dimensional increases in the truncated section of cutting tools tend to produce brittle fracture during this process. Consideration of this should be included in design parameters. In terms of cutting edge geometry, the optimum design depends on many factors including tool and workpiece material as well as cutting conditions, so it is highly dependent on the application.

Nonetheless, simulation and experimental work has shown some geometrical designs are better suited to microcutting. Heamawatanachai *et al* [79] showed that a circular cross-section diamond tip design in orbital micromachining was less prone to fracture (figure 18). This technique utilizes a large negative rake angle which results in a very small UCT. This, along with the tip geometry, consists of a conical and spherical region and produces a variable tool radius along the center of the tool tip in a circular trajectory around the central axis. The resulting shallow cut provides for ductile regime machining of brittle materials [79]. In addition to noting that negative rake angles increased the strength of the cutting

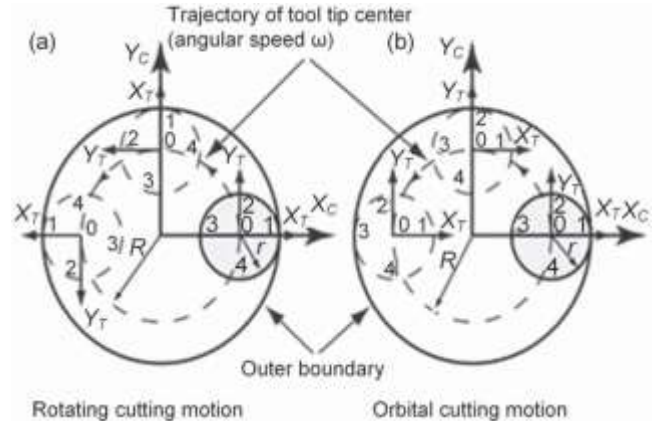


Figure 18. Schematic highlighting the different cutting kinematics between (a) conventional rotating tools and (b) orbiting tools. Reprinted from [79], Copyright 2010, with permission from Elsevier.

edge, Denkena *et al* [80] reported that designing the cutting edge for specific applications can improve the cutting tool performance and improve tool longevity.

Furthermore, it has been suggested that using a cyclic process map that captures tool and cutting parameters along with corresponding process effects would benefit the micro-tool design and fabrication process chain [11]. This could be integrated into the overall machining process in order to design a systematically optimized and effective microcutting tool. High performance and superior quality machining products require this type of multifaceted approach.

Tool edge radius

The cutting mechanism, cutting forces, and chip formation are intimately linked to the magnitude of the edge radius of the tool. These effects are particularly pronounced when the scale of the undeformed chip thickness corresponds to this size [73]. The microcutting edge is not perfectly sharp which, along with the aforementioned size effects, means that the cutting edge radius behaves differently at microscales as it does not scale proportionally with the tool diameter. Wu *et al* [74] showed how a smaller work material grain size increases the magnitude of the cutting force and specific cutting energy, which was attributed to the larger proportion of grain boundaries due to the smaller grain matrix (figure 19). This influenced the ploughing, extrusion, and shearing mechanisms during cutting, the magnitude of which increased as the edge radius increased. This result reveals that the higher material strength generated by the reduced grain dimensions requires larger magnitude cutting forces. Moreover, the increase in the ploughing force correlates to the extent of the plastic deformation mechanism in the material, which has a larger effect as the cutting edge increases, highlighting the connection between size effects and cutting forces in microcutting. Using a combination of simulation and experimental work, multiple studies [81, 82] have investigated how the tool edge radius affects chip formation and morphology, which, along with the rake angle orientation, influences the

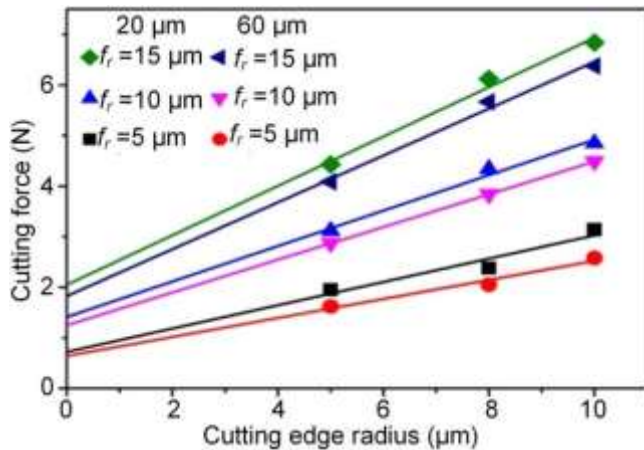


Figure 19. Variation of cutting force against cutting edge radius for different material grain sizes. Reprinted from [74], Copyright 2016, with permission from Elsevier.

generation of hydrostatic stresses, which affect ductile mode machining. Additionally, work done by Woon *et al* [20] demonstrated how the tool edge radius affects the contact phenomenon, which correlates to lubrication, wear, and removal rates. Karpát [75] also highlighted through variants on the Atkins machining model how the radius is related to the fracture toughness of the micro tool material. Rahman *et al* [83] described how surface quality and the mechanism of chip formation correspond to compressive stresses from the small undeformed chip thickness, which is ultimately linked to the tool edge radius.

Varying the size of the edge radius also has an influence on the machining process. Arif *et al* [84] investigated how varying the edge radii in the ductile mode machining of WC affects the surface quality and wear rates; specifically, they found that a large radius not only increases undeformed chip thickness and MRR, but also increases ploughing effects.

Moreover, increasing the radius reduced the specific cutting energy in this machining regime but also resulted in pronounced subsurface damage.

The inherent difficulties associated with microcutting have been at the forefront of research. In particular, issues around the microscopic removal mechanisms and chip thickness are fundamental issues that need better understanding. Özel *et al* [85] reported that unwanted ploughing effects during micromachining can be minimized by reducing the tool edge radius, thus producing a thinner initial chip thickness. Fang *et al* [86] investigated the cutting mechanics and corresponding work material flow at the microscale and how the cutting tool edge is a major influence on material separation mechanisms. As observed in microcutting, not only is the UCT less than the average workpiece material grain size but the minimum UCT also correlates to the mechanism by which the workpiece material is separated during the tool edge interaction [86]. The tool edge radius and corresponding size effect phenomena are therefore important factors to be considered in tool design and are often overlooked by industrial designers.

Cutting speed

The type of chip produced is directly related to the cutting conditions, with the cutting speed being one of the most important considerations [9]. The rate of material removal greatly affects the cutting mechanism and surface finish; therefore, it is important to understand how the cutting speed corresponds to chip formation. At relatively high cutting speeds, a continuous chip is formed through a shearing process in the primary deformation zone which, during ductile machining, is typically associated with good surface quality and reduced cutting forces.

Conversely, at low cutting speeds during ductile removal, a built-up edge (BUE) can occur due to the large frictional forces between the tool and the surface. This welded material grows onto the tool in layers making the tool blunt and increases cutting forces [9]. Another form of material removal occurs during the machining of brittle materials. During this process, excess strain is produced at the surface resulting in fracture propagation in the primary deformation zone during partial formation of the chip. These conditions produce a cyclic segmentation chip-forming process called discontinuous chips. The type of chip produced, therefore, is directly affected by the cutting speed, material workpiece properties, and local machining conditions.

The effect of cutting speed on WC was demonstrated by Liu *et al* [87]. Using a cBN cutting tool to dry machine a WC workpiece, they observed, via scanning electron microscopy analysis, good surface integrity at higher cutting speeds ($714 \text{ m min}^{-1}/10\,000 \text{ rpm}$). Surface roughness values initially increased as the depth of the cut was increased but evened out past $4 \mu\text{m}$ with unvarying changes in roughness as the cutting speed was raised. Using a different machining regime, cBN was also used as a cutting tool in the wet machining of Inconel 718 [88]. It was observed that crater wear via tool flaking dominated at lower cutting speeds. Thermal and workpiece material diffusion was identified as the main cause of crater wear, resulting from the localized high temperature generated by a high-speed cutting regime. Interestingly, at these higher cutting speeds, they indicated that smoothing of the tool surface increased the cBN wear resistance measurably. However, the loss of edge profile can also increase cutting forces significantly. This may indicate that the cutting-edge shape and the machining parameters were not optimized for the specific application.

The effect cutting speeds have on the workpiece material is a critical issue as this determines the mode of material removal to a large degree. Wang *et al* [89] investigated how ultrahigh-speed machining affects the brittle-ductile transition. This work revealed that increasing the machining cutting parameters above the critical cutting speed (5000 m min^{-1}) produces brittle fracture chip removal due to the large strain effect and that surface quality is adversely affected by ultrahigh-speed cutting (figure 20). Chip analysis supported the findings, and a fragmented morphology was observed. The results of these tests strongly support the restriction of ultrahigh-speed machining for roughing/semi-finishing applications.

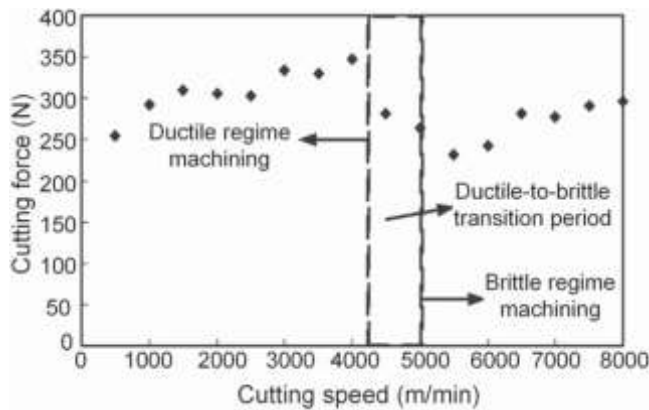


Figure 20. Experimental high-speed machining results showing the relationship between cutting force, speed, and machining regime. Reprinted from [89], Copyright 2015, with permission from Elsevier.

Inclination of cutting tool and machining conditions

Damage free machining is critical for the surface quality and integrity of the workpiece. Brittle materials such as WC, exhibit a brittle-ductile transition zone. To obtain a satisfactory surface morphology free of cracks and microstructural damage, it has been found that ductile machining is required [78]. To achieve this mode of machining, the use of highly negative rake angles has proven beneficial in this regard [10, 16, 32]. This is a vital parameter that requires in-depth analysis to achieve optimization of the cutting process. However, the geometrical design of the cutting tool would also affect the following during material removal: chip formation, fracture propagation, and cutting force magnitude. Moreover, the tool shape also affects, to a large degree, wear rates, temperature generation, and distribution [78].

The design of the geometrical features during the manufacture of a new tool is, therefore, critical as it determines the effectiveness and efficacy of the machining process. To illustrate this point further, Gu *et al* [78] demonstrated how rake angles directly influence the critical cutting depth which, by extension, affects the initiation of the ductile brittle transition (DBT) zone. Their work also revealed that the shape of the cutting edge corresponds to the degree of friction and stress distribution generation in the workpiece material, which is also a factor in DBT initiation [78]. As previously documented, the undeformed chip thickness is directly correlated to the tool inclination, which in turn influences crack initiation and propagation [90]. It, therefore, requires careful analysis and should be part of the design considerations in terms of the neck orientation of the tool.

The milling mode can also affect the workpiece surface integrity and nature of material removal. Liu *et al* [91] performed experimental microball end milling of a potassium dihydrogen phosphate (KDP) crystal. The results revealed that pull and down milling modes are favorable to ductile machining regimes, while up and pushing modes create fractures on the crystal. As indicated, negative rake angles favorably influence the machining mode of hard-to-cut materials. In a study conducted by Lai *et al* [92], large

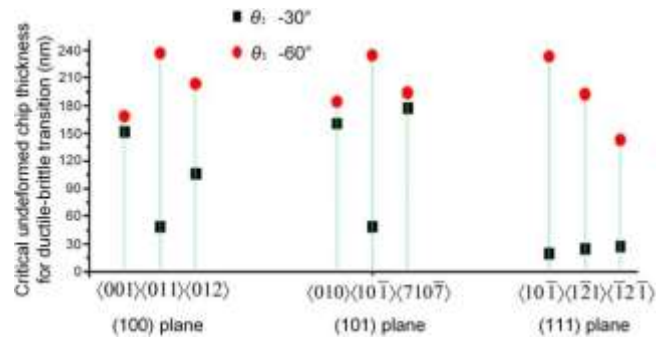


Figure 21. Mean values of the critical uncut chip thickness for the brittle-ductile transition corresponding to variations on rake angles and cutting orientation. Reprinted from [92], Copyright 2018, with permission from Elsevier.

negative rake angles (-60°) were found to modify the mechanism of surface crack initiation and pattern forming on anisotropic monocrystalline germanium (Ge), which in turn influences the brittle-ductile transition (figure 21). Primarily at this angle, the subsurface behavior is dominated by a crystalline-to-amorphous-structure phase transformation. This finding underlines the importance of the micromechanical and cutting parameter correlation which is inexorably linked to successful optimization of the micromachining processes.

Tool wear

Apart from the economic benefits of preserving tool life, the cutting efficiency is directly related to a tool's ability to resist wear and degradation, which can result in inferior quality and lost productivity. Wear dictates the accuracy and precision of the machined parts, achievable tolerances, and surface roughness, which is reflected in the economic costs [11]. Tool wear may also ultimately lead to sudden and catastrophic tool failure, so it is important that this fundamental mechanism is understood, preferably through determinable wear behavior, in order to identify the measures necessary to suppress tool wear and enhance the life of the cutting instrument [93].

The four main types of wear that occur in mechanical machining are: abrasion, adhesion, oxidization, and diffusion. In addition, for milling processes, it has been found that the main mechanism of wear and pattern formation on the tool is located on the flank and rake face [14]. The generation of microfractures in the tool surface also facilitates the wear of the material, which in turn affects the quality of the machined surface and the cost of the process. Moreover, the rate of wear is directly related to the properties of the tool, matrix and associated coatings, and the tool/workpiece interaction [94].

The wear mechanism extends beyond the mechanical properties of the surface/subsurface. In fact, it has been found that the crystallographic direction of the material's microstructure affects the mode of material wear and the rate of wear. This influence extends into the mode of machining [7]. If the microstructural mechanism of action can be further understood at a deeper level, it might prove instructive as to how the ductile brittle regime behaves in microcutting and thus provide a predictable behavior mechanism during the

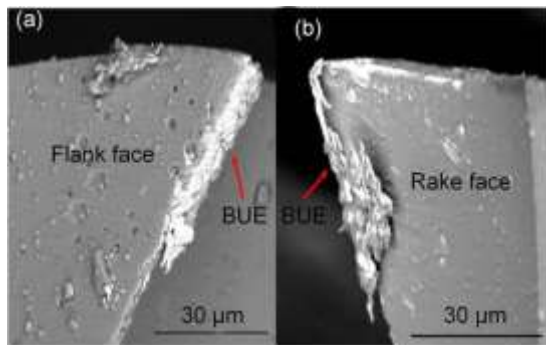


Figure 22. Built-up edge (BUE) formation located at (a) flank and (b) rake faces. Reprinted from [96], Copyright 2018, with permission from Elsevier.

removal process. This knowledge can be used to design and fabricate specific requirements using appropriate tool materials and geometries, which could be also reflected in the machining parameters and processes.

In light of this, one of the primary concerns that must be addressed in tool design is the suppression or reduction in the wear of the cutting tool, which is critical for optimum machining quality.

To achieve this, the following aspects needs to be considered:

1. Tool geometry and the location of wear.
2. Temperature cutting conditions, coolants, and lubricants.
3. Machining conditions, such as speed, feed rate, depth of cut, angles etc.
4. Tool material and matrix properties, coatings, and surface engineering options.
5. Workpiece properties and crystallographic orientation.

This list is not exhaustive and would depend on the machining conditions during operation.

As the suppression of wear is such a critical aspect of tool design, it is instructive to summarize and evaluate some of the recent developments in tribological tool research.

Sadik *et al* [95] investigated the mechanism of wear in PCBN tools on hard machining of various steel workpieces. The results showed clear relationships between tool wear, chemical composition, and the associated heat treatments of the workpiece. It was also noted that the corresponding surface/subsurface workpiece microstructure would significantly affect tool life and surface quality finish.

The difference between the mechanism of microtool wear compared to conventional macrotool wear was studied by dos Santos *et al* [96]. Using TiN-coated carbide micro tools for the milling of duplex stainless steel, they emphasized the connection between cutting speeds, coolants, and corresponding wear rates. Specifically, they found that in micro-machining, adhesion wear dominates at the cutting edge; and higher cutting speeds result in reduced tool wear resistance, attributed to increased localized temperatures in the cutting

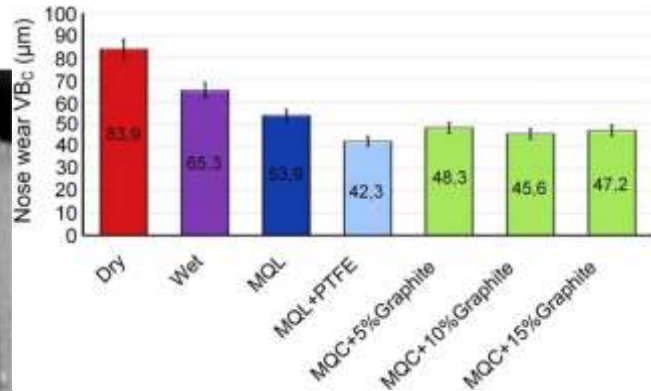


Figure 23. Variants on lubricant and coolant methods with corresponding nose wear VB_c . Reprinted from [98], Copyright 2018, with permission from Elsevier.

zone. This decreased the strength of the tool material which ultimately affected tool performance and longevity. Concomitantly, they noted that the BUE was observed at lower speeds (figure 22), which was likely due to the dry cutting regime employed, as coolants increase lubrication and, therefore, reduce interaction in the tool interface. The BUE can protect the tool edge and increase tool life; however, it also modifies tool edge geometries and produces poor surface finish, so for high precision applications, it is generally an unwanted feature.

Experimental testing can be time consuming and expensive, so simulation is typically used in conjunction with actual testing, which can be a cost-effective and valuable addition to the design and analysis of tool performance. Despite this, most current commercial modeling software, e.g. FE methods, adopts a two-dimensional orthogonal cutting analysis with limited 3D testing; therefore, it does not accurately describe how the tool/workpiece interface behaves under given conditions [96]. These models focus on progressive wear phenomena (abrasion, adhesion, etc) with restricted concentration on localized microscopic crack propagation. To address this, a tribological experimental/modeling approach was adopted by Rech *et al* [97]. They simulated the local surface conditions at the material interface through a tribometer and implemented a numerical model based on the local dissipated energy. The results were compared experimentally and were in good agreement on the dominant flank wear mechanism with some expected deviations observed.

Another approach to reducing tool wear based on minimal quantity lubrication (MQL) and minimal quantity cooling methods was evaluated by Sartori *et al* [98]. They found that solid lubricants used in conjunction with MQL in the turning of Ti6Al4V displayed better crater and nose wear resistance, while maintaining surface integrity of the workpiece when compared to dry, wet, and standard MQL techniques (figure 23).

Khan *et al* [99] also looked into MQL effects on wear on the turning of CP-Ti grade 2, and compared results against dry and flood cooling cutting methods. Using a vegetable-oil-

based lubricant, they reported that MQL had the lowest cutting temperature and recorded a flank tool wear reduction of 57%. In addition, MQL use revealed significant (16%–46%) reduction in cutting forces and produced the best surface finish overall.

Bian *et al* [100] investigated the performance of self-developed PCD square micro end mills, consisting of WC substrates on the ductile mode machining of sintered zirconia. A single straight cutting edge was fabricated via WEDM and diamond wheel sharpening. The results showed the focus of tool wear was at the tip, which was attributed to the small feed per tooth and the ductile machining mechanism of removal. The main wear mechanism was loss of diamond particles from the abrasive/adhesion process. They also note that the surface quality improved from the fine particle size in the PCD tool edge, but this resulted in reduced tool longevity.

Wu *et al* [101] reported on using a single-flute PCD micro end mill (average grain size $2\ \mu\text{m}$) on a polished WC workpiece, which was fabricated via WEDM with a precision grinding finishing process. The results revealed an initial rapid wear concentration at the tool tip (radius $8\ \mu\text{m}$) followed by steady wear rates, mainly through adhesive, abrasive, and micro-chipping, with increasing cutting forces observed as tool wear progressed. The reduction in the tool edge sharpness corresponded with increased cutting force, which produced a brittle fracture removal mechanism with evidence of micro-chipping on the workpiece surface. The wear mechanism was attributed to the WC/Co phase matrix which, during machining, alternates between hard and soft phases resulting in surface abrasion and adhesion from particle loosening on the workpiece. The cause of the rapid wear was likely due to loss of PCD particles during milling which exposed the substrate to the extreme conditions in the cutting zone. The fine-grained PCD layer on the microtool may explain why the material tends to disassociate with the tool substrate so readily in this case.

Dai *et al* [102] investigated the relationship between microstructure and wear mechanisms on SiC using SCD grinding. Results showed that flank wear was the dominant mechanism in precision grinding for SiC. Additionally, it was found that increasing the cutting edge radius while keeping it below the critical value improves the SiC surface quality and also results in a larger negative rake angle that is preferred for the ductile machining of brittle materials (figure 24). This suggests that an optimum tool edge size can partially enhance its performance.

Wainstein *et al* [103] reported on the adhesive wear mechanism in the high-speed dry machining of hardened steels using nanostructured single layer and nanolaminated multilayer PVD coatings. They recommended that the composition of deposited coatings should, to minimize adhesive wear, contain minimal amounts of elements that are similar to the substrate.

As the variation and fluctuation in cutting forces influences tool wear, temperature, and, ultimately, tool performance, it is important to understand how this correlates to cutting speeds. The high-speed cutting of hardened steels has been shown to reduce cutting forces, which improves

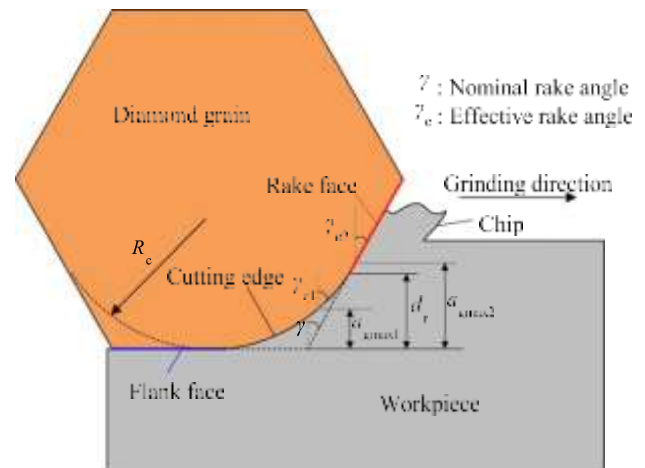


Figure 24. Schematic showing effective rake angle on a diamond grain cutting edge. Reprinted from [102], Copyright 2017, with permission from Elsevier.

efficiency and surface quality and provides for faster cycle times [104]. Fang *et al* [105] performed experimental testing and analysis of the cutting force and specific cutting energy dissipation during the high-speed milling of hardened 4120 steels. Fang *et al* [106] also conducted high-speed milling studies on hardened steel using chlorine mist and chilled air. As highlighted by [96], the results show that cutting speed variations can modify the cutting force and, by extension, wear resistance; but the type of coolant used, localized cutting zone temperature, and tool/workpiece material properties all contribute to the overall wear mechanism and surface quality. Aramesh *et al* [107] investigated a method to reduce tool chipping in the machining of Inconel 718, whereby a $40\ \mu\text{m}$ layer of aluminum–silicon (Al–Si) was deposited onto a carbide substrate which actively melted during the machining process. This produced a viscous metallic liquid that filled cracks and cavities on the tool surface thus preventing crack propagation and chipping and reduction in oxidation wear and cutting forces. The results revealed noticeable improvement in surface integrity; furthermore, it was noted that the formation of a thermal barrier tribofilm contributed to enhanced tool life and the reduction of BUE.

Simulation and modeling of the microtool design

Although numerical and modeling methods are extremely useful tools for giving insights into the micromechanics of the tool/workpiece interface, this review will not focus on this in-depth. Suffice it to say that the main focus will be on types of commercial software programs available and their pros and cons. Molecular dynamics (MD) offers modeling of atomistic dynamical processes; and although it can provide insight into the mechanism of microcutting, it is limited to smaller systems, and, therefore, is more suited to analysis of nanometric cutting processes. Nonetheless, it is a very useful tool; but the empirical methods it employs reduce the magnitude of accuracy and, therefore, may not be suitable for all materials [86].

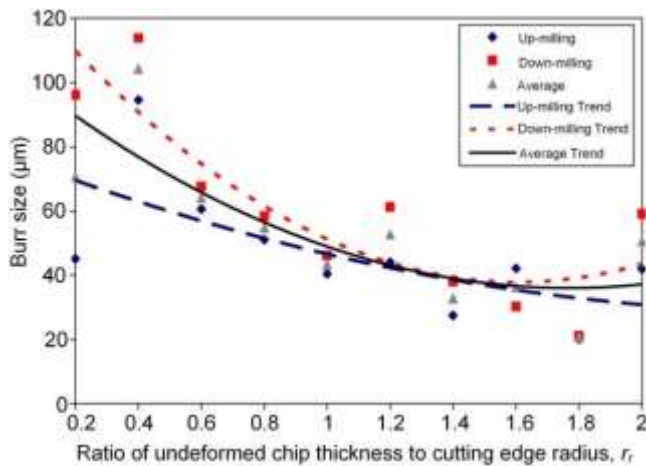
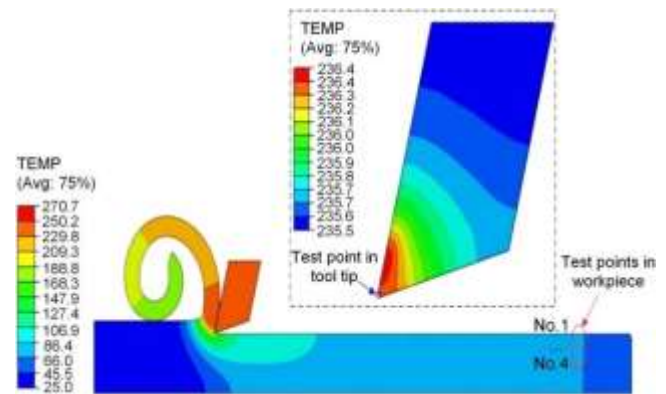


Figure 25. Graph showing the relationship between burr size and the ratio of r_r . Reprinted from [109], Copyright 2009, with permission from Elsevier.

The choice of modeling method depends strongly on the type and scale of the system under analysis and the form of results required. The finite element method (FEM) is better suited for micromachining modeling and is typically employed to predict tool boundary interactions, which may not provide highly accurate results but is a powerful analytical tool in computational continuum mechanical modeling that can save many hours and much expense on experimental tests [108]. The development of multiscale models can provide better accuracy in microcutting analysis, these combine both atomistic and continuum scales. Examples include the finite element atomistic and quasicontinuum methods [19]. These combinatorial methods employ localized atomistic simulation dynamics to predict small-scale, discrete mechanisms and also use a homogenous deformation process at larger scales. This dual approach can capture the microcutting mechanisms at work with a high degree of accuracy, thus improving the predictive ability of simulation software to describe the micromechanical behavior with good agreement on actual physical systems [19]. However, the inherent complexity of the micromechanical machining process and the associated limitations of 3D modeling of microcutting mechanics highlight the challenging obstacles that currently limit the predictive capability of software tools.

In-line inspection of the tool performance

During the cutting process, high temperatures are generated in the tool/workpiece interface which have a large effect on the magnitude of frictional forces and flow stress created locally and on the extent and rate of tool edge wear [9]. Because this, a large focus of research has been on identifying the mechanism of heat generation in the tool interface and the corresponding influence this has on the material properties and mechanical interaction during machining, including phase transformations, mechanical and structural integrity, and oxidation wear of the tool [11]. Corresponding to this is a need for the *in situ* inspection and metrology of microtools.



This is an important aspect of machining design as it allows

Figure 26. FEM simulation showing temperature distribution in a microcutting process along with selected test points in the workpiece and tool tip. Reprinted from [110], Copyright 2013, with permission from Elsevier.

defects and wear to be identified quickly, ensuring that the workpiece surface integrity and quality are maintained. Additionally, unmonitored wear results in the cutting edge radius increasing, leading to eventual burring (figure 25) and also to an increase in cutting forces and edge dulling during machining, which contributes to catastrophic tool failure [11, 109].

Therefore, the importance of accurate thermal metrology in machining cannot be overstated. Currently, methods to measure the tool interface include variants on the thermo-couple technique (work-tool, direct method) but are limited in accuracy and prone to errors along with the additional pro-

blem of installing an active sensor in the cutting zone. Coupled with the intrusiveness and, in some cases, impracticalities of thermocouples, makes the task important. Infrared cameras are also employed; however, the inherent spatial and temporal variances along with the small target area and slow acquisition rates associated with the cutting process make accurate measurements challenging [11]. Thermal and infrared cameras along with radiation pyrometers are also problematic in that they cannot be used with coolants, and the camera's orientation restricts its tool positional accuracy [19].

Unfortunately, there are limited developments in temperature measurement monitoring due to the nature of the machining process, which is particularly acute in microcutting [110]. Simulation studies, such as FEM, have attempted to model the temperature behavior of the cutting process; however, actual real-time metrology is required to ascertain the process *in situ*.

In light of this, Chen *et al* [110] used a rapid responsive/self-renewing thermocouple to simultaneously measure temperatures of a microcutter tip and cylindrical aluminum workpiece. Their results showed that the tip temperature, on average, was three times higher compared to the workpiece surface (figure 26). Additionally, an increase in cutting speed corresponded with a decrease in chip curvature formation, which is typically attributed to a rise in the magnitude of frictional coefficients and thermal softening of the tool tip [110].

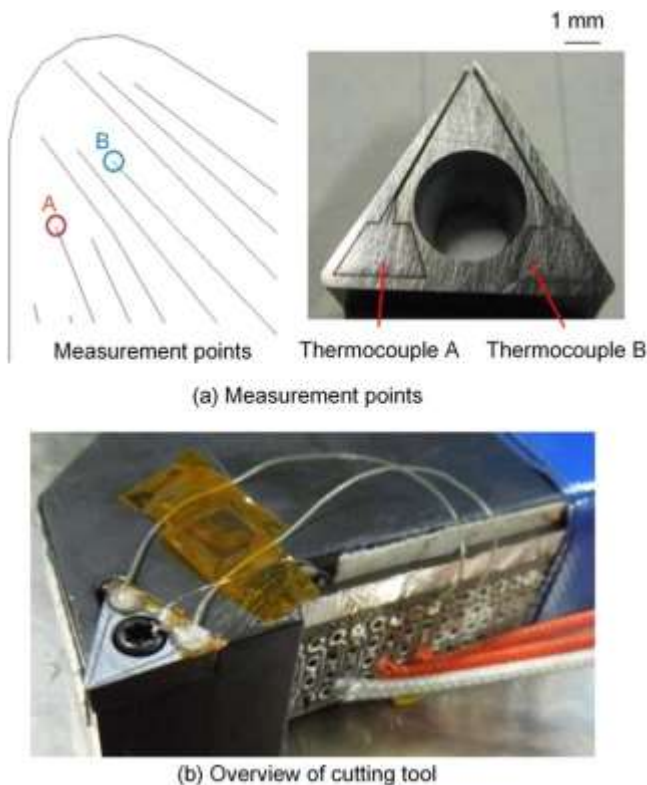


Figure 27. (a) Two sensor points on the cutting tool rake face and (b) image showing the sensor setup. Reprinted from [112], Copyright 2017, with permission from Elsevier.

Cui *et al* [111] performed theoretical and experimental testing on the tool temperature in end milling considering the flank wear mechanism. Using a Ti6Al4V workpiece and a four-flute carbide end mill with an 8 μm , TiN-coated layer, the heat in the cutting zone was measured using a calibrated thermal imager. Results highlighted the dependency of the tool temperature and cutting force on feed per tooth and cutting speed corresponding to flank wear. They report that as the flank wear began, the temperature rise was greatest at wear initiation and then reached a steady state as the tool material rounded.

Sugita *et al* [112] developed an integrated microarray of thermocouples on the rake face of a cutting tool. Two sensor points embedded in the tool showed accurate simultaneous thermal measurements (figure 27), which holds promise for potential implementation in thermal sensor tool design. It is vital that accurate and reproducible tool monitoring devices are integrated into the machining platform to enable optimum quality part production.

Coolants

The addition of coolants and lubricants to the cutting zone and tool interface is an industry standard (except where dry cutting is required) commonly used in machining operations primarily for heat reduction where high cutting speeds are employed in material removal and to act as a lubricant at lower speeds [9]. The function of a cooling lubricant is to actively reduce thermal, mechanical, and chemical stresses in

the cutting zone interface by (a) minimizing frictional and heat generation while thermally stabilizing the active cutting zone (tool edge/workpiece) by absorbing and removing heat production, and (b) the flushing away of material chips and debris from the active zone, thus maintaining a clean machining environment [113]. The type of coolant, additives, and level of concentration on localized operating conditions

determines the efficiency of the coolant. Moreover, this effectiveness is intimately linked with the type of workpiece material to be machined. It is, therefore, imperative that the material properties of the workpiece and also the tool itself is considered prior to selection of an optimum cooling lubricant.

Nonetheless, despite its recognized advantages in industry, coolants are relatively expensive to use requiring regular changing and monitoring to ensure contaminants do not enter into the machining system. In addition, for superior surface quality, each workpiece material requires a particular coolant composition to maintain optimum machining conditions.

This can be problematic, particularly as some of the older coolant formulations are being modified or withdrawn due to stringent health and safety regulations.

Environmental considerations

Along with the technical, operational, and monetary issues associated with coolants, there are additional concerns that have increasingly been brought to the fore in recent times [9]. Physiological and environmental impacts are now viewed as negative side effects, which if this trend continues, may see coolants and the use of them in manufacturing industries as an unsustainable feature. In light of this, when designing microtools for industrial applications, it is imperative environmental factors are given consideration during the design phase. Promising alternatives include integrating an internal coolant within the tool structure in conjunction with appropriate MQL methods. This has been shown to improve localized wear resistance by controlling the heat generated in the cutting zone, and is also an economically viable option to maintain, environmentally sustainable, and safe to use.

Internal coolants

As mentioned, a promising alternative to external coolants is an internal coolant. The main issue around this is the difficulty in fabricating an effective design within a hard and brittle tool material, which is generally restricted to simple internal geometries. However, simple designs are in keeping with the design for manufacturing considerations; however, the ability to construct an internally walled structure with focus at a particular thermal point on the cutting tool is a valuable feature for reducing cutting zone temperatures. Moreover, the ability to maintain high structural integrity while providing for the channeling of a coolant at high flow rates within hard tools could offer progress in the semi/dry machining of hard materials. One option is 3D printing, which is a highly flexible additive manufacturing process that affords the opportunity to construct complex tool structures

Table 3. Summary of tool performance, considerations, and associated challenges.

Tool performance	Considerations	Challenges
<i>Cutting edge geometry</i>	<ul style="list-style-type: none"> • Geometrical designs specific to material workpiece • Cutting conditions • Shape/symmetry • Core strength • Angle of cut • Tool design and fabrication process map 	<ul style="list-style-type: none"> • Friction and wear rates • Stress distribution and chip formation • Cutting force magnitude • Temperature distribution • Elimination of stress points in tool design • Complexity of process • Specific design criteria
<i>Tool edge radius</i>	<ul style="list-style-type: none"> • Edge dimensions • Edge sharpness • Edge stability • Material grain size • Strength • Fracture toughness 	<ul style="list-style-type: none"> • Size effects • Chipping • Fracture • Cutting force/specific cutting energy • Tool contact phenomenon • Surface quality • MRR
<i>Cutting speed</i>	<ul style="list-style-type: none"> • High cutting speeds • Speed specific to work material and cutting tool • MRR • BUE • Surface roughness 	<ul style="list-style-type: none"> • Temperature • Diffusion • Chip formation • Crater wear • Loss of tool edge profile
<i>Simulation for tool design</i>	<ul style="list-style-type: none"> • Molecular dynamics • Finite element method • Finite element atomistic and quasicontinuum methods 	<ul style="list-style-type: none"> • Scale factor; nano/micro dimensions • Empirical methods lack precision • Complexity of the microcutting mechanical process limits accuracy in current models
<i>Tool wear</i>	<ul style="list-style-type: none"> • Preferential crystallographic orientation of workpiece surface and subsurface • Tool matrix and heat treatments/modifications of workpiece • Temperature reduction methods • Modes of wear suppression • Prefabrication surface preparation of tool substrate • Optimized edge size with associated cutting speeds • Maintain good geometric fidelity and cutting edge profile • Dual simulation/experimental studies in 3D with focus on localized crack propagation models • MQL • Machining conditions 	<ul style="list-style-type: none"> • Better understanding of microstructure and tool interaction • Simulation/experiments of BDT zone and corresponding wear mechanisms • Identifying determinable wear behavior and processes • Integrating microscale approaches to existing macro design methods • New more accurate simulation techniques and software • Correlating the connection between types of wear in microcutting and reflecting this in tool design • Optimizing the tool design to limit the disruption to existing systems and fixtures

Table 3. (Continued.)

Tool performance	Considerations	Challenges
<i>In-line inspection</i>	<ul style="list-style-type: none"> • Integration of tactile/thermal and optical metrological systems <i>in situ</i> • Thermocouples/rapid response thermocouples • IR cameras • Pyrometers 	<ul style="list-style-type: none"> • Nature of the machining process—robustness • Tool integration • Cutting zone conditions • Precision and accuracy • Slow acquisition rates • Liquids and coolants
<i>Machining conditions</i>	<ul style="list-style-type: none"> • Maintaining sharp cutting tool • Large negative rake angle (for brittle materials) • Ductile regime machining • Tool orientation • Milling modes • Environmental/coolants 	<ul style="list-style-type: none"> • Brittle–ductile transition • UCT • Crack initiation and propagation • Microcutting mechanics • Thermal and stress generation

using hard, rigid materials which could be combined in a micromechanical fabrication process.

Commercially designed micro end mills are effectively miniaturized versions of the macrotool, which are simply not suitable for micromachining applications [114]. This results in a weakened core structure producing a tool that is not robust and easily broken. Therefore, specific geometric reinforcement and the elimination of stress concentration points at cutting edges is key in terms of the strength of the microtools. However, one of the main barriers is the lack of specific design criteria for custom microtool fabrication. Outlined below are the fundamental requirements adapted from [15, 115] for an efficient micro end mill tool:

- High stiffness with corresponding large core radius combined with large neck angle.
- High cutting edge sharpness with increased strength at edge.
- Simple geometry for ease of manufacture.
- Provides for good chip formation and evacuation.
- Elimination of contact with tool flank and workpiece.
- Reduction of stress concentration points at cutting edge corners.
- Manufactured through a reproducible and efficient process.

Additional factors to consider are tool edge dimensions and corresponding size effects which, based on the micro-mechanics of the tool/workpiece interaction, should be reflected in the tool design. Another issue is the standardized oversimplification of microtool geometries, partly due to the difficulty in fabricating complex features in hard materials. However, it also results from insufficient consideration given to the properties of the material to be machined and the specific cutting edge geometries. Therefore, implementation

of microcutting principles in conjunction with an effective, reproducible, cost-efficient design and fabrication process is needed.

In summary, it can be seen that there is no systematic design strategy for microtool fabrication. What currently exists is a mixture of various findings which, in some cases, conflict with each other. It is, therefore, a priority to develop a precise, reproducible systematic method for microtool design and fabrication specific to each type of cutting tool material and corresponding workpiece. What is required is a high-level descriptive method that captures the fabrication stages in a process chain, from the selection of tool material to geometric specifications, to processing capabilities and restrictions, to machining parameters and process control, relative to the material workpiece under consideration.

Based on the review and analysis of the current design methodologies and fabrication techniques employed, it is envisioned that the approach outlined below can provide measurable progress in the design and fabrication of micro-tools for the milling of brittle materials.

A summary of tool performance and corresponding challenges are shown in table 3.

- Avoidance in downsizing commercial tool designs. The standard two/four-flute helical end mill is not optimised for microcutting loads and conditions; moreover, the structure does not scale appropriately, resulting in localized weakening of cutting edges and low stiffness, ultimately producing chipping and fracture.
- Have a sharpened cutting edge of suitable strength and toughness which produces minimal undeformed chip thickness.
- High stiffness; this reduces tool run out and maintains cutting force magnitude thus improving tool life.

- Highly negative rake angles with specific radii relative to the brittle material for ductile machining.
- The tool should be designed for specific applications and also for fabrication. Micro end mills of small dimensions can prove challenging to shape using traditional methods. Therefore, the complexity and dimension of the features on the tool should be achievable through the fabrication method chosen.
- Avoid single edge microtool designs. This results in increased stress concentrations, tool wear, and poor surface finish. Symmetrical designs with multiple edges distributes the cutting force more evenly, thus improving tool wear.
- Modular design; this provides for efficient and cost effective machining.
- Reduced tool contact times; limit peripheral engagement through design parameters and machining conditions.
- Design the microtool with sufficient chip disposal features to allow good evacuation/of chips from the cutting zone.
- Excess heat and friction in the cutting zone; environmentally sustainable alternatives to flooding coolants. Can be addressed through an appropriate internal cooling mechanism with MQL methods.

6. Conclusions and perspectives

Advancement in the fundamental research of microtool design and fabrication, along with associated machining processes, has led to a better understanding of the mechanics involved in the tool/workpiece interface. New tool designs based on the underlying micromechanical interactions and behavior have allowed great progress in this field in recent years. Microcutting is a promising yet developing process, and specific tooling requirements need to be addressed if it is to realize its full potential. This review of the developments in microtool design and fabrication has highlighted the inherent complexity and challenges which are part of the development process.

From an applications perspective, it is imperative that industry embraces the essential difference between macro- and microtooling designs and fabrication approaches. The proportionate geometric feature reduction methodology which is currently employed by the majority of commercial tool manufacturers cannot be transferred to microscale tooling.

A systematic, structured design methodology should be engineered into the core fundamentals of microtool design, which is based on a complete machine tooling design philosophy. It can be concluded, based on the comprehensive review outlined, that the following aspects require focus in terms of design and fabrication methods.

- Customized designs specific to applications based on microcutting mechanics and dimensions.
- High structural stiffness and rigidity to prevent early tool damage and breakage.
- Modular design providing for ease of replacement and economic viability.

[6] Liu K, Li X P and Liang S Y 2004 Nanometer-scale ductile cutting of tungsten carbide *J. Man. Proc.* 6 87–195

The structural and cutting-edge geometry can be improved through:

1. Optimizing the design through preparation of the tool edge for enhancement of stability and wear resistance.
2. Core reinforcement of the tool structure and localized cutting edges.
3. Allowance for good chip formation and evacuation.
4. Reduction of localized stress concentration points in the design phase.
5. Symmetrical design with multiple cutting edges to distribute cutting forces evenly.

Additional factors that should be taken into account include:

1. Selection and modification of tool substrate materials, based on specific application and fabrication methods.
2. Patterning of tool surface features relative to material properties and microstructure.
3. Integration of a suitable minimum quantity lubricant onto the tool structure.
4. Consideration for internal coolants within the tool structure. This has the potential to greatly improve the tool life in conjunction with optimization of process parameters and machining strategies to reduce excess wear conditions.

Implementation of these tooling and machining protocols will help provide a springboard to the currently specialized microtooling industry, enabling expansion of the use and application of hard-to-cut materials.

References

- [1] Whitney E D 1994 *Ceramic Cutting Tools: Materials, Developments and Performance* (Hoboken, NJ: Noyes Publications)
- [2] Arif M, Rahman M and San W Y 2013 A study on the effect of tool-edge radius on critical machining characteristics in ultra-precision milling of tungsten carbide *Int. J. Adv. Manuf. Technol.* 67 1257–65
- [3] Marshall D B and Lawn B R 1986 Indentation of brittle materials *Micro. Tech. Mat. Sci. Eng.* (Philadelphia, PA: American Society for Testing and Materials) pp 26–46
- [4] Puttick K E, Rudman M R, Smith K J, Franks A and Lindsey K 1989 Single-point diamond machining of glasses *Proc. R. Soc. A* 426 19–30
- [5] Bifano T G, Dow T G and Scattergood R O 1991 Ductile regime grinding—a new technology for machining brittle materials *J. Eng. Ind.* 113 184–9
- [7] Liu K, Li X P, Rahman M and Liu X D 2003 CBN tool wear in ductile cutting of tungsten carbide *Wear* 255 44–1351
- [8] Smith G T 2008 *Cutting Tool Technology: Industrial*

- Handbook* (London: Springer)
- [9] Boothroyd G and Knight W A 1998 *Fundamentals of Machining and Machine Tools* 3rd edn (New York: Taylor and Francis)
 - [10] Fang F Z 2016 Atomic and close-to-atomic scale manufacturing—a trend in manufacturing development *Front. Mech. Eng.* 11 325–7
 - [11] Camara M A, Campos Rubio J C, Abrao A M and Davim J P 2012 State of the art on micromilling of materials, a review *J. Mater. Sci. Technol.* 28 673–85
 - [12] Oliaeia S N B, Karpas, Davim J P and Perveen A 2018 Micro tool design and fabrication: a review *J. Manuf. Process.* 36 496–519
 - [13] Luo X, Cheng K, Webb D and Wardle F 2005 Design of ultraprecision machine tools with applications to manufacture of miniature and micro components *J. Mater. Process. Technol.* 167 515–28
 - [14] Davim J P 2011 *Machining of Hard Materials* (London: Springer)
 - [15] Li P, Oosterling J A, Hoogstrate A M, Langen H H and Schmidt R H 2011 Design of micro square endmills for hard milling applications *Int. J. Adv. Manuf. Technol.* 57 859–70
 - [16] Fang F Z, Wu H, Liu X D, Liu Y C and Ng S T 2003 Tool geometry study in micromachining *J. Micromech. Microeng.* 13 716–31
 - [17] Perveen A, San W Y and Rahman M 2012 Fabrication of different geometry cutting tools and their effect on the vertical micro-grinding of BK7 glass *Int. J. Adv. Manuf. Technol.* 61 110–5
 - [18] Nee A Y 2015 *Handbook of Manufacturing Engineering and Technology* (London: Springer)
 - [19] Cheng K and Huo D 2013 *Micro Cutting: Fundamentals and Applications* (West Sussex: Wiley)
 - [20] Woon K S, Rahman M, Neo K S and Liu K 2008 The effect of tool edge radius on the contact phenomenon of tool-based micromachining *Int. J. Mach. Tools Manuf.* 48 1395–407
 - [21] Dimitrov V 2015 Types, geometries and measurement of tool parameters of single flute end mill cutters *Int. J. Sci. Eng. Res.* 6 1263–9
 - [22] Morse S 1863 Improvement in drill-bits *US Patent* 38,119
 - [23] Houser D E 1996 Single flute drill for drilling holes in printed circuit boards and method of drilling holes in printed circuit boards *US Patent* 5,584,617
 - [24] Gao P, Liang Z, Wang X, Zhou T, Li S, Zhang S and Liu Z 2017 Cutting edge damage in grinding of cemented carbides micro end mills *Ceram. Int.* 43 11331–8
 - [25] Egashira K, Hosono S, Takemoto S and Masao Y 2011 Fabrication and cutting performance of cemented tungsten carbide micro-cutting tools *Prec. Eng.* 35 547–53
 - [26] Zhong L, Li L, Wu X, He N, Zhao G and Yao C 2017 Fabrication of PCD micro cutting tool and experimental investigation on machining of copper grating *Int. J. Adv. Manuf. Technol.* 88 2417–27
 - [27] Oliaeia S N B and Karpas Y 2018 Polycrystalline diamond end mill cutting edge design to improve ductile mode machining of silicon *Prec. Eng.* 51 403–14
 - [28] Hajri M, Pfaff J, Buttner H, Voegtlin M, Kaufmann R and Wegener K 2018 Fabrication of a ball end nose micro milling tool by tangential laser ablation, 2018 *8th CIRP Conf. on High Performance Cutting. Proc. CIRP* vol 77, pp 654–7
 - [29] Biermann D, Aßmuth R, Schumann S, Rieger M and Kuhlénkötter B 2016 Wet abrasive jet machining to prepare and design the cutting edge micro shape *3rd CIRP Conf. on Surface Integrity. Proc. CIRP* vol 45, pp 195–8
 - [30] Uhlmann E, Oberschmidt D, Löwenstein A and Kuche Y 2016 Influence of cutting edge preparation on the performance of micro milling tools *7th HPC—CIRP Conf. on High Performance Cutting. Proc. CIRP* vol 46, pp 214–7
 - [31] Hintze W, Steinbach S, Susemihl C and Kähler F 2018 HPC-milling of WC-Co cemented carbides with PCD *Int. J. Ref. Metals Hard Mater.* 72 26–134
 - [32] Fang F Z and Xu F 2018 Recent advances in micro/nano-cutting: effect of tool edge and material properties *Nanomanuf. Metrol.* 1 4–31
 - [33] Suzuki H, Okada M, Fujii K, Matsui S and Yamagata Y 2013 Development of micro milling tool made of single crystalline diamond for ceramic cutting *CIRP Ann.* 62 59–62
 - [34] Suzuki H, Moriwaki T, Yamamoto Y and Goto Y 2007 Precision cutting of aspherical ceramic molds with micro PCD milling tool *CIRP Ann.* 56 131–4
 - [35] Arif M, Rahman M and San W Y 2011 Ultraprecision ductile mode machining of glass by micromilling process *J. Man. Proc.* 13 50–9
 - [36] Suzuki H, Okada M, Asai W, Sumiya H, Harano K, Yamagata Y and Miura K 2017 Micro milling tool made of nano-polycrystalline diamond for precision cutting of SiC *CIRP Ann.* 66 93–6
 - [37] Slipchenko K, Petrusha I, Turkevich V, Johansson J, Bushlya V and Stahl J E 2018 Investigation of the mechanical properties and cutting performance of cBN based cutting tools with Cr₃Cr₂ binder phase *Proc. CIRP, 51st Conf. on Manufacturing Systems* vol 72, pp 1433–8
 - [38] Costes J P, Guillet Y, Poulachon G and Dessoly M 2007 Tool-life and wear mechanisms of CBN tools in machining of Inconel 718 *Int. J. Mach. Tools Manuf.* 47 1081–7
 - [39] Chen J Y, Jin T Y and Tian Y J 2016 Development of an ultrahard nanotwinned cBN micro tool for cutting hardened steel *Sci. Chi.* 59 876–81
 - [40] Uhlmann E, Oyanedel Fuentes J A and Keunecke M 2009 Machining of high performance workpiece materials with CBN coated cutting tools *Thin Solid Films* 518 1451–4
 - [41] Hanel A, Hasterok M, Schwarz M, Schimpf C, Nestler A, Brosius A and Kroke E 2018 Investigation on the grinding characteristics of binderless nanocrystalline cubic boron nitride (BNNC) as cutting material for the machining of hardened steels and superalloys *Proc. CIRP, 8TH CIRP Conf. on High Performance Cutting* vol 77, pp 493–6
 - [42] Monteiro S N, Skury A L, de Azevedo M G and Bobrovnitchii G S 2013 Cubic boron nitride competing with diamond as a superhard engineering material—an overview *J. Mater. Res. Technol.* 2 68–74
 - [43] Du Y *et al* 2007 Synthesis of black cBN single crystal in hBN-Li₃N-B system *Mater. Lett.* 61 3409–12
 - [44] Gill S S, Singh H, Singh R and Singh J 2010 Cryoprocessing of cutting tool materials—a review *Int. J. Adv. Manuf. Technol.* 48 175–92
 - [45] Wu Z, Yang Y, Su C, Cai X and Luo C 2017 Development and prospect of cooling technology for dry cutting tools *Int. J. Adv. Manuf. Technol.* 88 1567–77
 - [46] Kirsch B, Basten S, Hasse H and Aurich J C 2018 Sub-zero cooling: a novel strategy for high performance cutting *CIRP Ann.* 67 95–8
 - [47] Shu S, Cheng K, Ding H and Chen S 2013 An innovative method to measure the cutting temperature in process by using an internally cooled smart cutting tool *J. Manuf. Sci. Eng.* 135 1–12
 - [48] Ghani S A B C 2013 Design and analysis of the internally cooled smart cutting tools with the applications to adaptive machining *Doctoral Thesis Brunel University*