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Engineered design of cutting tool material, geometry, and coating for optimal performance and customized applications: A review

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ABSTRACT

Cutting tool materials are the backbone of machining and play a vital role in the manufacturing industry. Innovation in cutting tools is important for customized and demanding applications. This state-of-the-art review is focused on innovations and future research directions for cutting tools covering i) tool materials/microstructure/property relationships, ii) coatings and their effect on tool performance, iii) cutting edge and functional surface preparation and effect on tool performance, iv) tool geometry for high performance and stable machining considering rapid machining, sustainability, and circularity aspects. The vision is to identify tool material/coating/geometry/functional surface relationships for significant improvement in machining performance. This paper includes perspectives from several research groups with a detailed discussion on current advances, capabilities, and challenges in engineered design of cutting tools, materials, coatings, structures and sets a new agenda for future tooling and research directions.

1. Introduction

1.1. Cutting tools and their functional requirements

Cutting tools with defined cutting edges are highly engineered products used in manufacturing, to shape products by removing material from a workpiece by shearing material away as chips. Machining is a challenging industrial process due to the complex thermomechanical loads imposed on the cutting tool, including mechanical, thermal, and chemical loads. Furthermore, tailored cutting tools are required for a variety of mechanical machining processes such as turning, milling, drilling, sawing, boring, reaming and broaching. The development and selection of cutting tools is vital for high performance machining, improved product quality, for reducing cost, maximising productivity and for improving environmental sustainability. Cutting tool materials were first developed from carbon and medium alloys steels to high-speed steels in the late 19th century, while progressively higher performing carbides, coated tools, sialons, ceramics, cubic boron nitride, diamond and whisker reinforced tool materials were developed over the course of the 20th century. In this development, the cutting tool has to be tailored to the thermo-mechanical and chemical properties of the material to be cut, the cutting process, the cutting variables and cutting velocity, the component design and product application and functionality requirements. Moreover, cost of cutting tools produced from specific materials is a key factor when selecting tools in industry. Increases in workpiece hardness and the cutting velocity leads to significant increases in temperature, with cutting temperatures in hard turning approaching 1000^0 C, as shown in Fig. 1 [1–3]. High cutting tool hardness is required especially at elevated temperatures, while sufficient toughness is required to withstand any interruptions or vibrations occurring in the cutting process and to prevent tool breakage.

There is no 'one size fits all' solution that delivers high performance machining in the multitude of possible combinations, see the example in Fig. 2. As illustrated in Fig. 2, the primary and first consideration in

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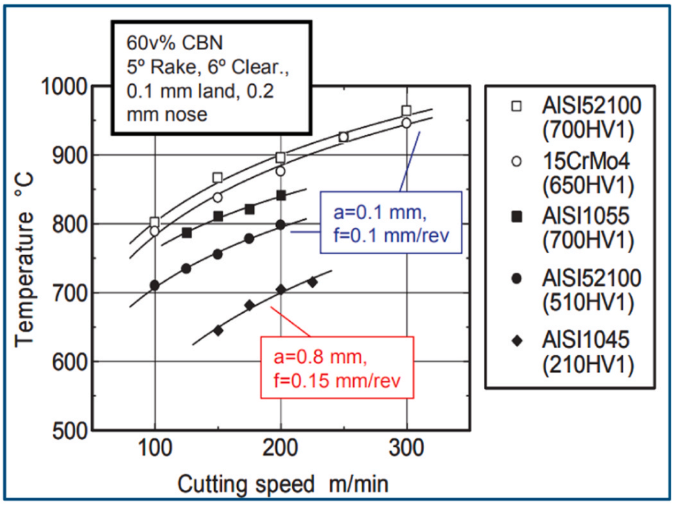

Fig. 1. Effect of material hardness, composition and cutting velocity on maximum rake temperature [1].

designing and selecting a cutting tool is the material to be cut, considering its hardness and thermo-mechanical requirements and need for adequate chip control. The type of machining process for example turning, milling, drilling further provides functional requirements and constraints for cutting tool design. This when considered alongside the application and component functional requirements provides further context for the design of the cutting tool system (cutting tool body, defined cutting edges, functional surfaces and coatings). Thus, for application, an optimized combination of tool material (and coating) and tool geometry (and micro geometry) is required for a modern high performance machining operation. Cutting tool manufacturers address the complexity of and variety of application needs by developing and marketing cutting tool grades and geometries for defined application groups.

1.2. Elements of the cutting tool system and their design requirements

The elements of the cutting system and the functional requirements to address the multi-faceted requirements are outlined in Table 1.

In view of the above functional and performance requirements for cutting tools, this paper presents a state of the art on cutting tool innovations. After the introduction to the drivers and motivation in Chapter 1, Chapter 2 focusses on tool materials/coatings/microstructure/property relationships and how these have been innovated. Chapter 3 presents a state the art on cutting edge and functional surface preparation and effect on tool performance. Chapter 4 focusses on functional surfaces of the cutting tool and the key innovations for improving machining performance. Chapter 5 presents the latest research and advances on tool geometry for stable machining. Chapter 6 presents the key challenges and opportunities for sustainability and circularity of cutting tools. The paper then concludes with Chapter 7 summarising the consolidated knowledge and setting the future research agenda for cutting tool innovations for high performance machining and for sustainability.

Table 1
Requirements for cutting tool system.

	Performance Requirement	Application Challenge Examples
Cutting tool material[4]	High hardness including hot hardness, better wear resistance and fracture toughness, controlled surface residual stresses	The hardness, strength and microstructure of the material to be cut, for example hardness of hardened AISI H13 tool steel can be as high as 56 ± 2 HRC [5], or higher. The cutting tool would be required to have at least double the workpiece hardness.
Cutting tool body and visible geometry[6]	Fracture toughness and dynamic stability, chip control.	The dynamic cutting force regime in machining and high tool rotational speeds. Denkena reported for reference tools passive, feed and normal forces in milling of 56HRC H13 tool steel as 218 N, 524 N and 294 N respectively[7].
Tool coatings[8]	High coating adhesion, High hardness including hot hardness and lubricity, high shear strength, controlled surface residual stresses, preferably compressive	The coating has to enhance the performance of the base cutting tool material. Coating benefits, including both cost and performance, have to outweigh the increase of cost of tooling from the coating process. Thicker coatings with sharp edge preparation may enable novel applications.
Cutting tool rake face[9]	Adequate chip control, ability to help lower heat generation and heat partition and to reduce thermally activated wear modes	Requirements have to be matched to the workpiece material. Micro structuring has been shown to be beneficial, but as with thin coatings, such features are subject to rapid wear[9].

2. Tailored cutting tool materials & coatings for improved dry machining performance

2.1. Sustainability and dry machining

As a result of the tribological friction and deformation-induced that occurs during all cutting processes, significant amounts of heat are generated. This heat leads to high temperatures in the chip, tool, and workpiece, which results in physical limits to the range of feasible process parameters. Thermally induced damage may occur on the workpiece material (white layer and tensile residual stresses) or the tool

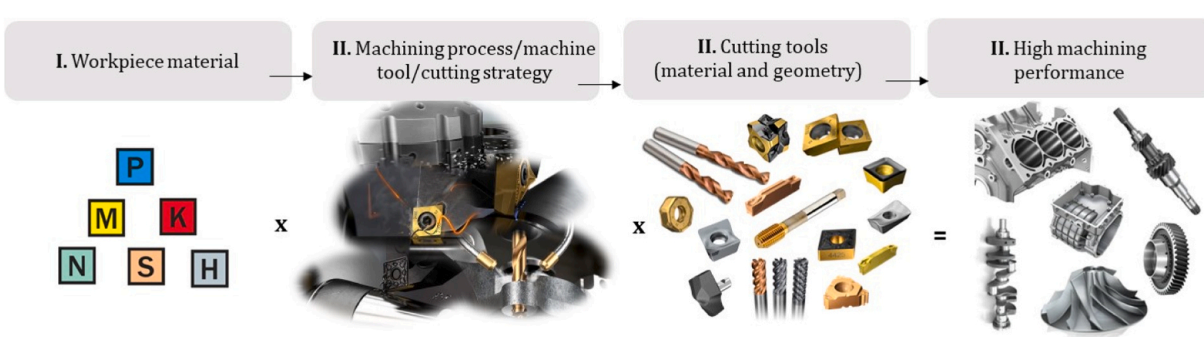

Fig. 2. Different tool materials, geometry, and coatings.

(plastic deformation and rapid wear/failure) [10,11]. To control heat during machining operations various coolants and lubricants are commonly employed. However, studies [12–16] have indicated that exposure to cutting fluids is associated with the development of various types of cancers, dermatitis and respiratory diseases. Abundant and indiscriminate use of cutting fluids in machining operations has also become a significant cost burden in manufacturing as the actual cost of such fluids has been estimated in literature to be between 7–17 % of the total manufacturing cost [17]. According to Ford Motor Company, flood-cooling costs were in the range of 10–17 % of the total powertrain manufacturing costs [18]. A CIRP keynote paper by Brinksmeier et al. [19] in 2015 presented the state of the art in cutting fluids and highlighted the increasing need for sustainable and dry manufacturing operations.

With the introduction of increasingly higher quality (harder yet more ductile) carbide, ceramic tool materials and coatings in the early 1970s, dry machining operations emerged as a promising 'sustainable' alternative for eliminating the use of traditional cutting fluids. At the same time, holistically engineered cutting tools hold the potential to enable significantly more sustainable and efficient machining operations, as outlined in Fig. 3.

However, with over four decades of active research on dry machining and use of minimum quantity of cutting fluids, there is still significant use of water and oil-based cutting fluids. This practice can be traced back to insufficient understanding of the technical capabilities of modern dry machining technologies, as well as the problematic lack of chip clearing in the absence of coolant/lubricant flow. In some applications where the cutting tools withstand the dry machining conditions, cutting fluids are still applied for productivity reasons such as automated cleaning and for enhancing thermal stability of the machine tool. Furthermore, when there are several machining operations in the same component, e.g., face milling and drilling, the cutting fluid is used due to the critical operation (i.e., drilling) even if not needed for milling. There is need to examine process chains for machining to activate cutting fluids only when essential and to challenge the status quo.

2.2. Fundamentals and recent advances in tool materials and coatings

Since dry and/or high-speed machining results in significantly higher cutting temperatures than 'flood-cooled' conventional cutting, the challenges of dry machining can be traced to limitations in the high-temperature performance of tool materials and coating [4,21,22]. Moreover, the ever-increasing application range and complex geometries of modern components and tools alike make it difficult to achieve reliable dry machining in all situations.

Fig. 4 summarizes the physical and mechanical properties of various common cutting tool materials. Two major classes of tool materials can be identified: (1) brittle materials, such as ceramics and super hard materials diamond and cubic boron nitride (CBN), and (2) (quasi-) ductile tool materials, such as cemented carbides (WC and Co binder) and tool (high-speed) steels. Notably, most of these materials have been available for several decades and most scientific and technological advances have been in the area of tool material microstructure, e.g. the development of micro- and recently nano-grain tools and composite reinforcements, such as whiskers, which offer a unique combination of fracture toughness and strength as can be seen in Fig. 4(a). Due to its relatively low cost, high toughness and broad application range, tungsten carbide (WC) continues to be the most widely used cutting tool material. Due to its relatively low cost, high toughness and broad application range, tungsten carbide (WC) continues to be the most widely used cutting tool material [23]. Nevertheless, super hard materials such as diamond and boron nitride compounds offer substantially higher hot hardness than WC and conventional alumina ceramics, as can be seen in Fig. 4(b). Significant efforts have been devoted to improving and fine-tuning the properties of various 'carbide' grades to specific applications, primarily by controlling tungsten carbide (WC), cubic carbides (TiC, TaC, NbC, et.), microstructure (gradients), and binder phase [24]. Using the relationships shown in Fig. 4(d), a broad range of properties can be achieved in carbide tools, from high wear and oxidation resistance in dry finish turning of steels, to high toughness and thermal conductivity in rough milling of titanium alloys or enabling preparation of excellent edge sharpness in drilling of aluminium alloys.

2.2.1. Advances in nano-structured/super-hard materials

Promising developments towards next-generation cutting tools have been in high-hardness nanocrystalline powders of ductile tool materials, substrates, and hard coatings [28–30]. Fig. 5 illustrates a nanocrystalline microstructure in tungsten carbide substrates Fig. 5(a), and nanocrystalline diamond coating, Fig. 5(b), and whisker-like boron nitride Fig. 5(c).

While all these tools exhibit superior hardness when compared to conventional and micro-grain grades of similar chemistry, they are also

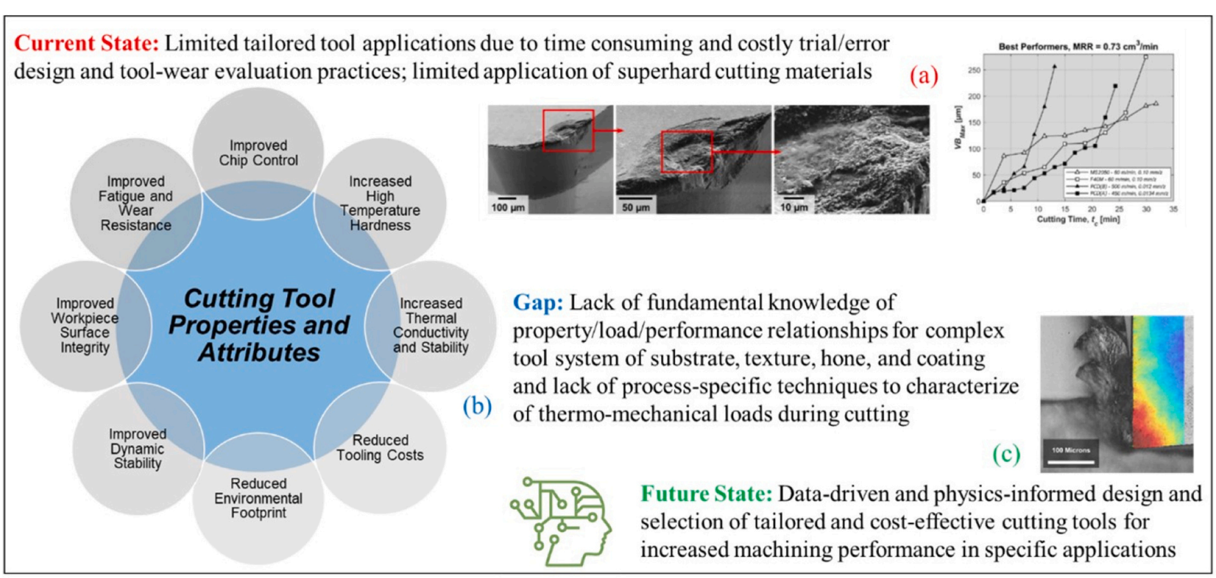

Fig. 3. Illustration of proposed pathway from current state (a, figures: [20] by addressing gap (b) through data-driven and physics-informed design of tailored tools with novel characterization approaches (c).

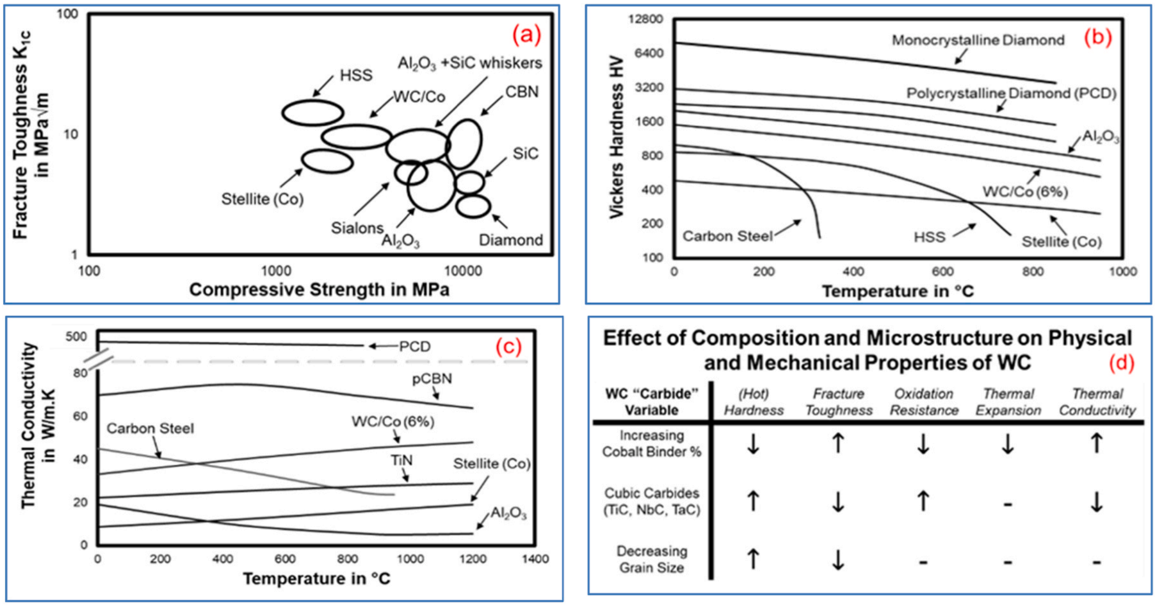

Fig. 4. Overview of physical and mechanical properties for various cutting tool materials. Data Adapted from: (a) [25], (b) [26], (c) [27], (d) [28].

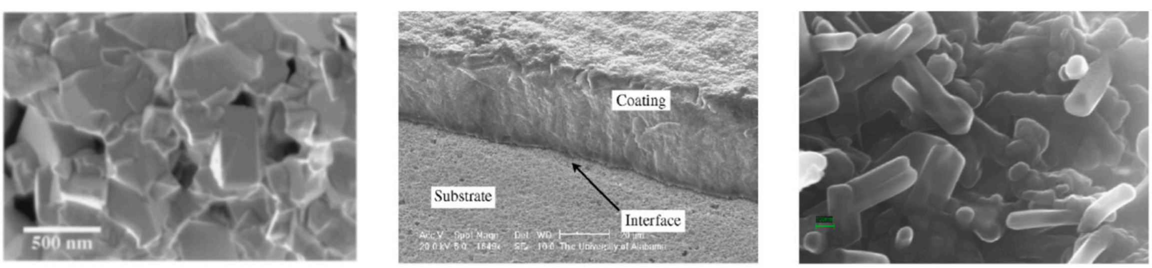

Fig. 5. Examples of nanostructured tool materials and coatings. Electron micrographs of sintered nanocrystalline WC (a) [28] nanocrystalline diamond (b) [29] and nanocrystalline boron nitride (c) [31].

significantly more brittle, limiting their applications under unstable machining conditions. Moreover, while research continues developing more advanced nanostructured tool materials, the inherent trade-off between hardness and toughness in any known engineering material necessitates careful selection and matching of tool material and process parameters for each specific dry cutting operation.

For brittle ceramic tool materials and high carbide content cemented carbide tools, the fracture toughness K1C and the hardness H influence the abrasive wear resistance according to K1C3/4H1/2. Brittle tool materials tend to have higher thermal and chemical stability, which in theory makes these tools ideal for dry machining operations. However, the hardest tool material, diamond, notably suffers from poor thermal stability beyond approximately 700 °C, exhibiting rapid graphitization. In comparison with the cemented carbide, the polycrystalline diamond (PCD) has the possibility to substantially increase the cutting speed in the process (even considering the graphitization limit). The affinity with carbon at elevated temperatures is the core issue. Notable exceptions include the cryogenically cooled finish machining of titanium alloys with PCD tools, which Schoop et al. were able to demonstrate as being capable of effectively suppressing graphitization [32]. In addition, PCD tools excel in dry machining of abrasive aluminium alloys (7–13 % Silicon) [33], carbon fibre composites [34] and metal matrix composites [35], where diamond's chemical stability and high abrasion resistance make it an ideal cutting tool material at low temperatures. Polycrystalline cubic boron nitride (pCBN) was developed as a high-temperature alternative to PCD, with an application range up to 1200 °C. Thus, pCBN is commonly used in dry hard turning of steels beyond 45 HRC, as well as in finish machining of super alloys, such as Ni-based Inconel 718 [36]. However, the high cost of both PCD and pCBN continue to limit industrial adoption in many cases, especially considering the availability of the lower-cost alternatives of advanced ceramic and coated carbide tools.

Ceramics tools are significantly more cost effective that PCD and pCBN, and whisker reinforced ceramics exhibit excellent toughness, rivalling that of WC (see Fig. 4(a)). However, the poor tensile strength of ceramics, which results from porosity and defects due to the sintering process, necessitates the use of chamfers and hones. While these edge preparations put the cutting edge under compression, where ceramics are exceptionally strong and thus wear resistant, chamfers and hones further increase cutting forces and temperatures, which often limits the application of ceramics to rough machining under stable conditions, where the mode of wear is primarily abrasive [37]. The preparation of cutting edges of the tool and its functional surface is thus another vital area for improving machining performance and for customised applications.

2.2.2. *Coatings for cutting tools*

Coatings are the key to the performance of modern cutting tools and are considered a key enabler for dry and near-dry machining. Regardless of tool material, dry cutting produces higher temperatures at the tool/chip interface than flood-cooled machining, often resulting in thermally induced wear patterns such as crater wear and plastic deformation, which may lead to sudden and unpredictable catastrophic tool failure [38,39]. In the absence of cutting fluids and their cooling and lubrication, the friction between the tool and workpiece material, as well as the tool's thermal properties, determine the thermomechanical loading within the tool [40]. Coatings have been shown to be capable of reducing the apparent coefficient of friction, while also serving as a thermal and chemical barrier, thus allowing for higher cutting speeds or longer tool-life. For example, Rech et al. [8] reported that coatings could significantly reduce heat flow into the tool by up to − 50 %. They can achieve this effect by influencing the total amount of heat generated in a cutting process, and by reducing friction and providing thermal insulation. Most coatings, except highly insulating materials Al_2O_3 [41] generally have little effect on the partition of thermal energy between the workpiece, chip and tool, and their effect on overall cutting forces is typically low (less than −10 %). Thus, the ability of coatings to reduce thermal damage (or abusive machining more generally) in the workpiece material, which comprises the final machined product and process-induced functional performance and useful life, is somewhat limited. Nevertheless, coatings enable more desirable wear patterns and higher productivity in surface integrity-limited operations and are widely considered a key technology for achieving more sustainable dry and/or near-dry machining operations.

Notably, coatings will not always enable completely dry cutting. For example, concerns regarding re-deposition of coating material on or into the machined surface prevent the use of coatings in certain high-performance applications, such as machining of rotating aero engine components and biomedical implants [42]. Moreover, coated tools may offer little to no advantage over their uncoated counterparts in certain materials and cutting applications. Haron et al. reported little to no discernible difference in tool-life behaviour during dry milling of titanium alloy with coated tools compared to uncoated tools. In other materials and processes, such as dry turning of 4340 alloy steel at a speed of 150 m/min, depth of cut of 0.5 mm and 0.2 mm/rev feed, multi-layer coatings have been demonstrated to be capable of improving tool-life up to 30 times [43]. While other researchers have reported limited utility of coated tools in particular applications [44]. Clearly, the utility and benefits of coated tools are highly dependent upon the specific application and material, requiring a strong understanding of the fundamental tribological principles that govern dry cutting. Thus, no 'one size fits all' general conclusions can be offered regarding the use of coatings in dry machining, but further fundamental research and analysis will be required to properly leverage advanced tool materials and coatings to achieve more widespread industrial adoption of dry cutting practices.

The thermomechanical properties of coatings need to be carefully matched with those of the carbide substrate, as well as the thermomechanical loads experienced during cutting a given workpiece material in a set process parameter range. Beblein et al. [40] analysed the impact of coating properties on the coating load and resulting stress distribution in the tool. Their results are shown in Fig. 6. The authors concluded that the adhesion behaviour of the coating is the primary driver for initial surface loads on the cutting tool and that the elastic modulus has a strong influence on coating stresses. The authors furthermore reported that substrate roughness morphology and coating thickness may both lead to increased abrasive wear, albeit due to different mechanisms. While excessive core roughness reduces the load carrying capacity and localized stress intensity, excessive coating thickness leads to heat accumulation and thermal softening of the substrate. Therefore, cutting tool designers need to carefully engineer both the substrate morphology and the coating properties and thickness to achieve desirable machining performance. Moreover, surface preparation and pre-treatment before applying coatings is required and plays an important role in improving coating adhesion. For example, in physical vapour deposition by magnetron sputtering, before depositing the coating, the tooling to be coated is biased to − 500 V or more attracting argon ions, which bombard the surface with high energies, removing microscopic surface contamination at the molecular level [45]. This ensures that the following step of depositing the coating is done on a cleaning surface to enhance adhesion.

The effect of residual stress within the coating and substrate on cutting tool performance has been widely studied by several prominent research groups, such as Denkena and co-workers [46,47] and others [48]. Fig. 7 illustrates an empirical model for the generation of residual stress in cutting tools and coatings, developed by Denkena and Breidenstein [38]. As can be seen, the stress of the tool during application is the result of a highly complex and interactive process chain, which includes both thermal and mechanical effects. Since tensile residual stress is generally detrimental to fatigue life and thus coating life, researchers are pursuing novel processing pathways to reduce and match the amount of tensile residual stresses within coatings and the tool material substrate (see Fig. 7(b)).

Tool coatings are typically applied by one of two processes, chemical vapour deposition (CVD) or physical vapour deposition (PVD) [8]. Chemical vapour deposition does not require line-of-sight but is limited to a smaller number of compounds (primarily titanium nitride), higher operating temperatures up to 1100 °C, resulting in increased tensile residual stresses and relatively thick layers. Thus, CVD is commonly used to coat tools used for high material removal operations [49]. PVD coatings can be applied to sharp edges and at much lower temperatures (typically around 400 °C) and are thus well suited as coatings for finishing tools. There are countless PVD coatings that have been developed, but all such coatings typically feature a metal (e.g., Ti, Al) and a metalloid (e.g. C, N). While many different coatings have been studied in academia and a large number of combinations of coatings, often in multi-layer arrangements, are available commercially, there have been relatively few transformative advances in tool coatings over the past

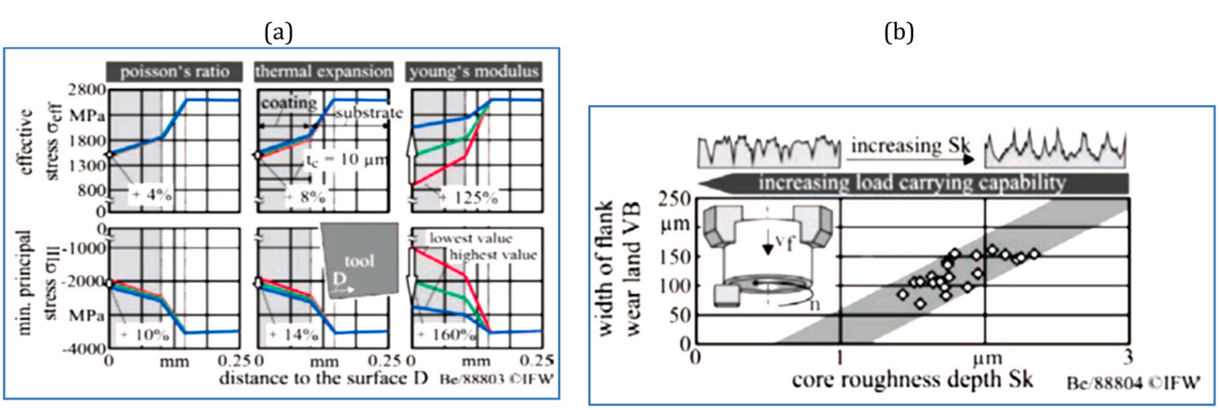

Fig. 6. Effect of elastic properties of tool coating and substrate on stress in orthogonal cutting (a) and relationship between core roughness depth Sk and flank wear VB (b)[40].

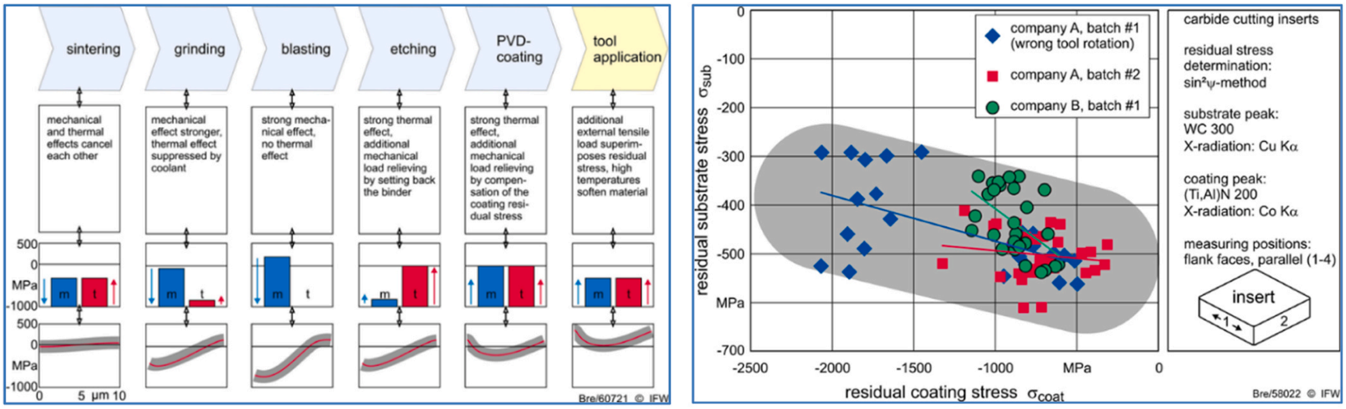

Fig. 7. Empirical model for the generation of residual stress in the substrate as origin for cohesive tool damage (a), based on correlation between substrate and coating residual stress (b) [38].

decade. Despite the many permutations of multi-layer coatings developed in recent years, a relatively small sub-set of coatings have established themselves as reliable and popular performers in specific machining applications, including titanium carbide (TiC), titanium carbo-nitride (TiCN), titanium nitride (TiN), titanium aluminium nitride (TiAlN) and diamond-like carbon (DLC) [49,50]. For PVD coatings, recent advances in multilayer and more complex Ti-based coating materials, such as TiAlSiCrN, have shown promise for increased cutting speeds (i.e., productivity) and better surface integrity in machining of high strength steels and Ni-based super alloys [51,52]. While there is some anecdotal evidence for optimal relationships between multilayer coating morphology and higher-speed cutting, further work will be required to study the influence on (nano-) multilayer arrangements and thicknesses to realize improved performance in PVD-coated tools [53].

CVD coatings may be particularly relevant for achieving more sustainable dry and near-dry cutting operations due to their greater thickness and microstructure control [50]. As mentioned previously, CVD coatings are applied at high temperatures to realize chemical reactions between a gaseous compound and heated (carbide) substrate, which typically leads to pronounced tensile residual coating stresses. Moreover, there are relatively few viable CVD coating materials that can be applied below 800 °C, with Al_2O_3 being routinely applied above 1000 °C. Despite its limitations, CVD provides the ability to deposit significantly thicker coatings (i.e., higher deposition rates than PVD) and CVD may tailor the orientation of Al_2O_3 grains. The former (thicker coatings) is relevant to dry cutting, as temperatures and associated wear rates are inherently higher when no coolant or lubricant is provided. To enable tools to cut at higher speeds, and realize longer tool-life, thicker coatings are therefore desirable. However, coating thickness must always be balanced with the cutting tool micro geometry (hone), a highly relevant aspect that will be discussed further in the following section.

Textured Al_2O_3 coatings have been studied by a number of researchers to further improve the wear performance of this coating material. Al_2O_3 does not exhibit dissolution and diffusion at elevated cutting speeds (i.e., high temperatures), but rather wears by plastic deformation, fatigue/fracture, and abrasion/adhesion mechanisms [54]. In order to promote more predictable abrasive wear modes, structuring of Al_2O_3 coatings may be achieved by altering the CVD deposition parameters, typically to deposit a (0001) texture parallel to the tool surface [55–57]. Work by Ruppi [57] showed that CVD process conditions have a strong influence on the deposited coating, and multi-layered textured coatings (see Fig. 8) can be generated by altering the H_2S concentration at constant CO_2 levels, although the author noted that ratio of these two compounds could also be altered in other

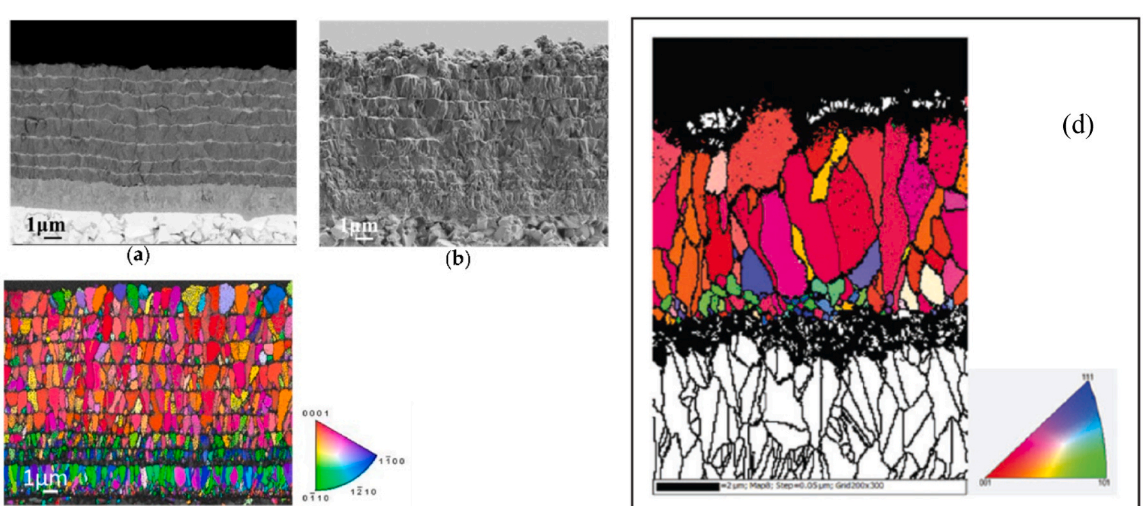

Fig. 8. Cross-section SEM micrographs of α-Al_2O_3 multilayer coatings. (a) Back-scatter SEM image of the coating deposited at CO_2 = 4 vol%, (b) Bright-field SEM image of the coating deposited at CO_2 = 6 vol% and (c) Cross-section EBSD IPF map of the coating deposited at CO_2 = 6 vol%. [58], and (d) inverse pole EBSD map of textured single layer α-Al_2O_3 coating (color) on WC substrate (black/white) [58].

manners. In a recent study, Bejjani et al. [58] investigated the shift of wear mechanism in textured alumina-coated tools for different ferrous workpiece materials. An EBSD figure from this study in shown in Fig. 8, highlighting the strong directionality of the coating. Their detailed analysis showed that a shift between flank and rake/crater wear modes may be affected by small amounts of trace elements (e.g., Ca) in the workpiece material. SEM, Auger analysis by Bejjani et al. showed that adhesive/chemical interactions between trace elements and the surface layer of the coating may substantially alter the contact length and surface morphology of the worn region, which may also influence subsequent chip formation behaviour.

Because of the small range of viable CVD compounds, development of novel CVD compounds is of interest for increasing the application range of coated tools. While CVD diamond coatings were first introduced in the 1990s, recent work by Ramasubramanian et al. [59] comparing micro-structured, nano-structured and boron-doped CVD diamond coatings has shown significantly improved wear performance in machining of highly abrasive Al-SiC MMC material. Moreover, post-processing of CVD diamond coatings with femtosecond laser pulses was shown by Liu et al. [60] to improve the crystallization of the diamond film by about 20 % when compared to as-deposited films at 20 μm layer thickness. In a separate study, Liu et al. [61] also showed that such CVD diamond films may be readily machined with femtosecond lasers to generate high-quality cutting edges in CVD-coated tools. Consequently, there exists potential for further hybridization and coupled efficiencies in diamond machining/processing of CVD diamond coatings to improve their total machining performance.

Recent work by Montazeri et al. [62,63] and Ahmed and Veldhuis [64] has shown significant promise of soft coatings, along with micro-texturing of the tool's rake surface to offer significant improvements in machining performance under dry conditions, as shown in Fig. 9. The authors noted that unlike hard coatings, the soft AlSi coatings evaluated in their study did not exhibit an influence of the deposition pressure and bias voltages on coating hardness, nor did the coating roughness and thickness have a significant effect within the investigated regime ($t < 10$ μm). This increased ease of deposition, along with a lack of residual stress within the coating, may allow soft coatings to become more widely used in the cutting tool industry going forward. Although the majority of the soft coating is squeezed out due to the high cutting pressures, XPS results showed the persistent presence of a thin tribofilm, which may be further, enhanced and retained through micro texturing of the rake face.

3. Preparation of cutting edges and functional surfaces as contribution to customized cutting tools

A central topic for the customization of cutting tools is the modification of the cutting edge geometry and the topography of the functional surfaces. In order to enhance the performance of cutting tools for a certain application and to realise efficient process chains in the production of cutting tools there is a need for tailored preparation techniques. In this context, recent developments concerning the preparation of cutting edges and functional surfaces of cutting tools are introduced and discussed.

3.1. Design and preparation of cutting edges

3.1.1. Characterisation and design of cutting edge micro shapes

The main objective of the preparation of cutting edges is to remove defects resulting due to the initial tool grinding process and from directly pressed inserts, in order to create a homogeneous cutting edge geometry and subsequently to increase the performance and to enhance the wear behaviour of the cutting tool. There are several research works, which show, that a suitable cutting edge preparation can increase tool life and thus, a preparation can provide a relevant contribution to the sustainability of a cutting tool. For instance, cooperative work by CIRP partners compared different cutting edge preparation processes in milling varying materials as hardened and stainless steel, Inconel 718 and Ti6Al4V. These investigations show the great potential of the preparation especially for difficult to cut materials [21]. Nonetheless, the cutting edge design and the preparation process have to be adjusted specifically with respect to the machining process, the workpiece material and the thermomechanical load.

A key issue in comparing different cutting edge geometries is the characterisation method, which is used to describe and quantify the cutting edge rounding. Concerning the characterisation, different approaches exist [65], whereby the form-factor method is a widely used method as illustrated in Fig. 10. With respect to the nomenclature concerning the characterisation of cutting edges, a recent guideline was developed, that enables standardisation of the description of cutting edges with different specifications [66]. On this basis, some researchers defined additional parameters and extended the form-factor method. For instance, Aßmuth et al. recently introduced the so-called profile factor K_β, which is the quotient of the average cutting edge rounding $\overline{S}$ and the profile flattening S_β [67,68]. The profile factor shall provide more detailed information concerning the shape of the cutting edge

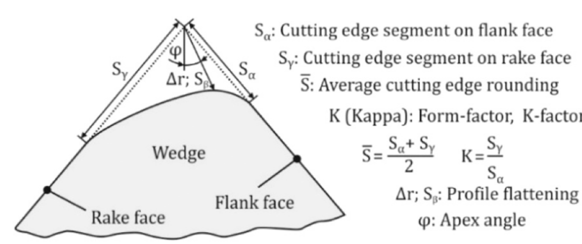

Fig. 10. Characterisation of cutting edge geometries according to the form-factor method [65,66].

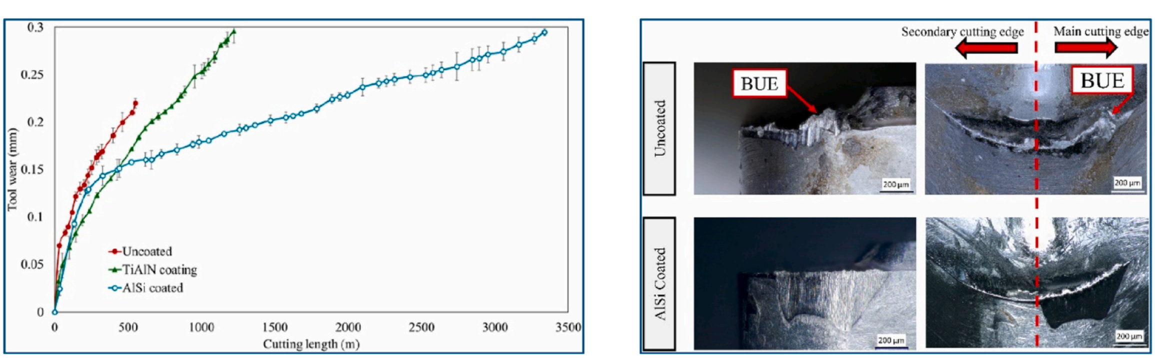

Fig. 9. Tool-wear behaviour (left) and micrographs (right) for cutting of Inconel 718 with uncoated, TiAlN (hard) coated, and AlSi (soft) coated tools. Adapted from Montazeri et al. [62].

rounding.

The specific design of the cutting edge mainly depends on the material to be machined and the process that is applied. Hence, an individual cutting edge geometry and preparation process route has to be designed, which is suitable for the respective process. Therefore, there is a need for a high effort for experimental investigations to optimise cutting edge designs [68,69]. With the objective to reduce the number of experiments, there are approaches to design and optimise the cutting edge design for example based on Finite Element simulations and statistical modelling [68,69]. The procedure according to [68] is shown in Fig. 11. Moreover, Bergmann and Grove present an approach to design the cutting edge rounding depending on the workpiece material [70]. Recent studies by Denkena et al. take the material properties of the cemented carbide cutting tool material into account [4].

3.1.2. *Processes for cutting edge preparation*

Engineered cutting tools require flexible preparation processes to create suitable and varying cutting edge geometries. This includes chamfers but also symmetrical and asymmetrical cutting edge rounding. Each preparation process exhibits specific characteristics, which were summarized by Denkena and Biermann [65]. Based on a survey of twelve cutting tool manufacturers, wet abrasive jet machining and brushing followed by drag finishing are the main preparation processes in industry [67]. If there is the need for flexibility, the wet abrasive jet machining using a robot system to handle the cutting tool enables preparation of asymmetrical cutting edge rounding as well as the opportunity to prepare local parts of cutting tool [71] or locally different cutting edge micro shapes [72]. Beside this, wet abrasive jet machining is not limited to the preparation of macro cutting tools. Experimental investigations show promising results concerning the preparation of micro-milling tools [73]. Immersed tumbling is a further preparation process that was analysed concerning the cutting edge preparation of cemented carbide micro-milling tools. Research work has revealed a decrease in tool wear as a consequence of the preparation process [74,75].

Recent research work concerning preparation processes often focuses on the development of alternative preparation processes and its implementation into the existing process chain of cemented carbide cutting tools or existing machine tools. In this regard, Bergs et al. present research work on the preparation of cutting edges for solid tools using a diamond-brushing tool. This preparation process can be conducted on a grinding machine and allows the creation of symmetrical and asymmetrical cutting edge rounding depending on the applied process parameters [76]. A further approach, which can be conducted on grinding machines, is the use of elastically bonded diamond grinding wheels. This finishing process is established for milling tools [77,78] and can be used for the preparation of cutting inserts as well [79]. An additional method for the preparation of shank tools based on the machining of elastically bonded abrasive material, which can directly be realised on tool grinding machines, is described by Bathe [80]. Denkena et al. present a further approach using flexible diamond tools on a five-axis milling machine tool [81]. All the above-mentioned approaches have in common that they can be conducted without the necessity of additional machine tools.

In addition to the micro shape and the local topography, the cutting edge preparation processes affect the subsurface of the substrate as well. This is of major interest regarding following coating processes and wear behaviour [82]. The performance of cutting tools is also influenced by the integrity of the cutting edge [83,84].

3.2. *Preparation of functional surfaces of cutting tools*

The preparation of cutting tools on microscopic scale is not limited to the cutting edge. The specific characteristics of functional surfaces of cutting tools exhibit further potential for an increase in tool life and performance. This is evident for uncoated and coated cemented carbide tools, where the focus of research in this field is on topography and surface integrity. There are several processes and approaches for the modification of cutting tool surfaces [9], whereas the following section deals with the application of abrasive processes to prepare the functional surfaces of cutting tools.

In the field of machining Ti-6Al-4 V alloy, the smoothing of the surfaces of inserts using a magnetic abrasive finishing process leads to an increase in tool life [85–87]. This is attributed to reduced friction in the contact zone [86,87]. With regard to turning of the titanium alloy investigations reveal, that the finishing of the rake face shows the most relevant impact on tool life, whereas the flank face and the nose are of less importance [85]. Moreover, it is shown, that the reduction of irregular peaks on the surface is the key for enhancing the tool life [85]. In fundamental investigations, Saelzer et al. analysed the influence of different topographies of the rake face on thermomechanical load and friction using a special chip formation machine [88–91]. Within this research, the rake faces of cemented carbide tools were prepared using wet abrasive jet machining to create a typically blasted surface topography characterized by a dimple structure, by a fine-finishing process to create a smooth surface topography and applying a micro finishing process, which is characterised by a cross-groove structure. Comparing a blasted and fine-finished surface topography it was shown, that the surface modification influences the resulting passive force depending on the cutting velocity and the uncut chip thickness as well as the friction behaviour [91]. Moreover, the surface topography of the rake face indicated an impact on the thermal load in orthogonal cutting of AISI 1045 [89]. Furthermore, models for the friction coefficient for Finite-Element chip formation simulations were developed based on the results depending on surface topography [90]. Further investigations, considering an additional intermediate medium, revealed that the influence of the surface topography on the friction coefficient becomes of minor importance using a lubrication film[88].

The modification of the rake face topography is even of great importance for drilling tools. Recent research deals with the use of elastically bonded diamond grinding wheels to prepare the flutes of twist drills [92,93]. It is the objective to smoothen the initial ground surface without affecting the contour of the twist drills negatively. If the surface topography of functional surfaces of the cutting tool is modified after grinding, it is of great importance, that a subsequent cutting edge preparation process allows a local modification of the cutting edge and does not affect the neighbouring surfaces. For the purpose to prepare twist drills with fine-finished flutes, Biermann et al. used a cutting edge preparation process on the basis of the machining of an elastically bonded abrasive, which can be conducted on the tool-grinding machine [92]. This allowed influencing the rake face only to a small extent as illustrated in Fig. 12. Hence, the interactions between the surface modifications and the cutting edge preparation processes have to be considered for customized cutting tools as well.

Elastically bonded grinding wheels are used in investigations regarding the pre- and post-treatment of coated single lip deep hole drills as well. The preparation of the circumference of the drilling tools is a focus, with the finishing process leading to positive effects on coating adhesion [94]. In addition to surface modifications, also contour adaptions as a result of the preparation process can enhance the performance of the cutting tools for example in drilling. Investigations with single-lip deep hole drills show positive effects of a rounded face chamfer transition on the surface integrity of the bore hole [80,93]. Moreover, the preparation of guide pads of BTA (Boring and Trepanning Association) deep hole drilling tools realised with a micro finishing process leads to an increase of the surface quality of the workpiece as a result of the contour modification of the guide pad [95].

Both a modified shape of the cutting edges as well as a preparation of the functional surfaces are relevant factors to improve the performance of customized cutting tools. Nonetheless, it is necessary to consider the interdependence between the preparation processes in order to exploit the full performance potential of customization.

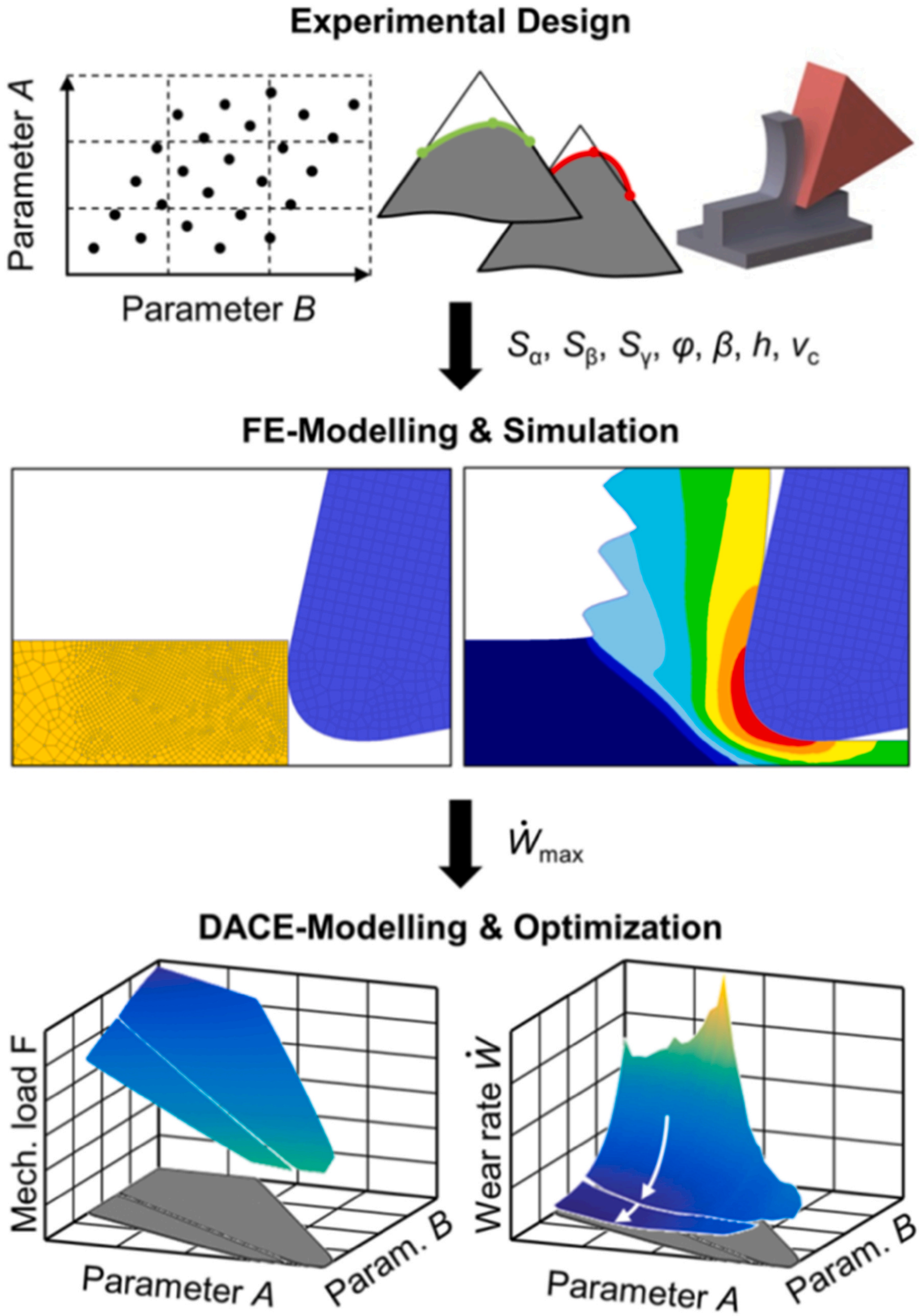

Fig. 11. Approach for the optimisation of the cutting edge micro shape [68].

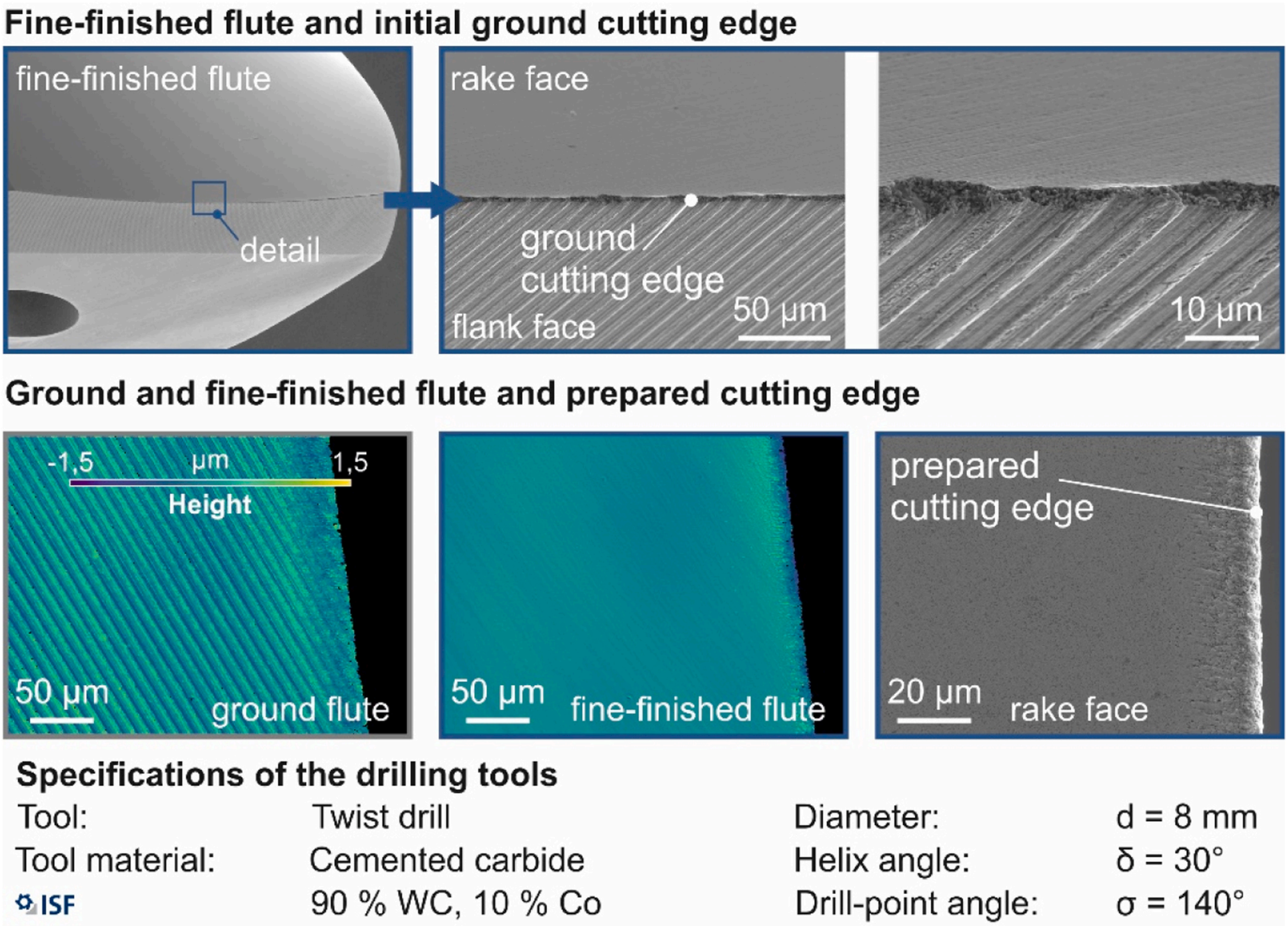

Fig. 12. Interaction of the surface topography of a fine-finished flute and the cutting edge preparation [92].

4. Surface-structure-property interactions for sustainable cutting tools

The cutting tool as an industrial consumable product with high volume of utilization in machining processes present distinct challenges in terms of sustainability. These include being able to extend the cutting tool life as much as possible, maximize the reliability of the cutting tools so that premature failure can be avoided and their useful life can be efficiently employed, and re-cycling/re-use of the cemented carbide cutting materials primarily tungsten, cobalt, after separating from the coatings and other elements. Recycling processes include, at first, sorting, cleaning, and combining with zinc in a vacuum furnace which breaks down the cemented carbide to the point where it can be pulverized and up to 98 % of the powder, composed of tungsten and cobalt, and can be reclaimed. This salvaged powder material is used in new cutting tools (about 40 %) and the remainder (60 %) is typically used in other products such as wear parts and mining tools [96]. Other new processes are being developed to better utilize tungsten carbide for recycling and combine with nanomaterials including spark plasma sintering [97].

4.1. Surface structuring and tooling performance and sustainability

In a recent CIRP keynote paper, Özel et al. [9] covered the state of the art in the use of structured and textured tools in machining. The interfaces of tool-workpiece/tool-chip in advanced machining operations embodies mechanical contact and thermal tribological conditions. Conventional cutting fluids cannot penetrate and reach to the high contact pressure and high temperature zones making the application of cutting fluid inefficient [98]. The idea of providing a reservoir effect for the lubricant on the cutting tool surface via micro scale structures and textures serves a functional purpose and opportunity to reduce and more effectively the use cutting fluids and support sustainability [99]. The positive effect of such lubricant reservoirs has been obtained at tool-chip interface in cutting processes [100]. The structures that can be applied to the entire tool faces enabling the supply of the cutting fluid evenly throughout the tool-chip and tool-workpiece interfaces providing significant improvements in tool performance, such as reducing friction, forces, build-up layer formation and chip adhesion [101]. These structures can also be a combination of micro and nano scale geometric features that can be fabricated with various precision fabrication methods including, electrical/electrochemical discharge machining, laser induced periodic surface structuring (LIPPS) and focused ion beam machining among others [9]. Furthermore, the potential benefits offered by structured cutting tool surfaces with solid lubricants also recognized as reduction in cutting fluid and energy consumption through reduced friction and improved anti-adhesion properties, and improved tool life, hence, contributing to the sustainability of the machining operations [102].

4.2. Effects of surface structuring on resultant properties

These combined structured surfaces consisting of both micro- and nano-scale geometric features work together as micro-features act as reservoirs and supply retained lubricant to nano-scale features. Some of the engineered cutting tools with nano-/micro-scale surface structures when covered with solid lubricants exhibit self-lubricating tool behaviour [103]. These solid lubricants may include molybdenum disulphide, MoS_2, tungsten disulphide, WS_2, calcium fluoride, CaF_2, and graphite, burnished or embedded into the surface structures [104]. During the cutting process, the solid lubricants which are released from the textures onto the tool surface, resulting in the formation of a tribofilm with low shear strength. This type of textured cutting tools may have a good potential for dry cutting operations since the lubricating effect can be obtained as if the cutting tool itself supplies lubricants at tool-chip interface [105]. Further developments included macro-channels on the rake face of the cutting tools which connect with the micro-channels for irrigating and delivering the coolant into the chip-tool interface to reduce the friction effect.

4.3. Benefits of coated structured cutting tool surfaces

There is a great interest in reducing friction forces, creating reservoirs for cutting fluid and debris, reducing friction, and reducing tool wear. The reduction of the contact area, decrease in temperature and in cutting forces, and in friction, tool wear, adhesion, and surface roughness were the most evaluated parameters. The literature review indicates that the application of structured and textured cutting tools promotes better machining conditions in different materials. Even without using cutting fluids, micro-scale surface features on tool faces may provide hollow areas at the tool-chip and tool-workpiece interfaces that are filled with air and affect the tribological behaviour at these interfaces. The research has shown that those micro-scale features fabricated on tool surfaces can also act as micro-pockets of air under dry cutting conditions, resulting in the improvement of cutting performance [106]. Many research studies have shown that surface structures are able to control chip adhesion on tool surfaces due to their effects on lubricant action and reduced contact area. Severe chip adhesion on tool faces may lead to the formation of built-up edge (BUE), or built-up layer (BUL) [101]. Although, the BUE can act as a protective layer against tool wear, it is often unstable and can repeatedly dislodge and re-form during the cutting process. The research also shows that the structured cutting tool rake face influences the stabilisation of BUE and conserves an effective protective layer on a cutting tool for longer cutting times [107]. Some micro-scale structures on the tool faces not only can destabilize BUE/BUL, facilitate frequent flaking off of chip adhesion, and but also maintain a small amount of chip adhesion on the tool surface [108].

4.4. Future directions of coated structured cutting tool surfaces

The latest research on structured cutting tools increasingly focuses on the ability to increase the heat dissipation of cutting tools, especially in the machining of heat resistant alloys, suggesting that the improved tribological and thermal properties of structured and coated cutting tools require even more research in the advanced machining applications [109–111]. It is evident that the micro- and nano-scale structures can be useful in reducing adhesion. The adhesion behaviour needs further research and understanding for various combinations of tooling and workpiece material. Micro and nanoscale structures on cutting tool surfaces act as reservoirs for cutting fluids. There is good evidence that in machining of ductile materials, there needs to be a continuous supply of cutting fluid during the cutting process in order to fully reap the benefits of tool surface structures. Structures applied on cutting tools can be of mixed dimensions, both in terms of micro and nanoscale. This has the potential to aid the supply and retention of cutting fluids. A significant amount of research has focused on the friction reduction aspects of structured tooling, while the benefits in terms of tool-life extension needs to be further explored for optimised structures. The reduction in friction force is more significant than the reduction in cutting forces. These benefits can be contributed to a marginal reduction in specific cutting forces. A set of proper optimization steps for achieving optimized structures and textures for a new material and new cutting tool must be well established for a broader use of this technology in machining applications with enhanced sustainability. The research so far has focused on structures applied after the cutting tool is manufactured [9]. A vision for future cutting tool development with structured surfaces through surface-structure-property interactions is given in Fig. 13. Future research should address such vision and the concurrent fabrication of structures during tool manufacture to enable production of textured cutting tools consistently and cost-effectively on a mass scale. In addition to the materials, coatings, functional and structured surfaces presented above the body of the cutting tool is another key design parameter in the cutting tool system for enabling rapid and stable machining.

5. Innovations in cutting tool geometry for chatter avoidance

This section deals with customized tools for high performance application and rapid machining while addressing the dynamics and stability of machining.

Vibrations due to the flexibilities and natural frequencies of tool/workpiece are inevitable when optimal production rates are demanded. Considering the wide variations of flexible tool/workpiece machining systems, there needs to be customised/bespoke tooling and tool path solutions to increase both the performance and productivity while handling the critical dynamic characteristics. While chatter vibrations are the priority to avoid, forced vibrations need to be controlled as well to achieve desired dimensional accuracies. With the progress in modelling the mechanics, the forces, vibrations and dimensional errors of the machining process can be predicted fairly accurately [112]. The mechanism of chatter vibrations was a research focus for many previous works as shown by Altintas et al. [113]. Using such models, one cannot only tune the cutting conditions (e.g. spindle speed, depth of cut and feed rate), but they can also design the tool geometry and the tool path itself. As summarised in Fig. 14 this section is devoted to the recent progress in optimizing both the cutting tool geometry and tool path of multi-axis machining operations. The research direction and the best practices will be discussed.

5.1. Visible (macroscopic) geometry

The effect of geometry on vibration characteristics of machining operation is experimentally shown through the comprehensive works of Wertheim et al. [116] and a recent study by Agic et al. [117]. Tool geometry can be generally modified in two ways. The first way is to change the macro-scale parameters such as number of teeth, helix angle and pitch angles. The second way is to change the micro-scale parameters such as edge radius. For the first method, there have been numerous studies to show that increasing the number of teeth or reducing the cutter diameter for constant radial depth of cut will cause more vibrations in the system [113]. A novel milling tool concept was achieved when the pitch angle variation was introduced; it was mathematically proven that the angular spacing between the consecutive teeth can be tuned to counterbalance and cancel chatter vibrations. It is one of the most common solutions provided by tool manufacturers today. Knowing that the variable pitch tools would be effective in a certain frequency band, it is required to design the pitch variations by taking the machine tool's natural frequencies into account.

Another solution is the variable helix solution, which is very effective for machining higher depths of cut. The effective pitch angle at higher axial locations would be equivalent to the variable pitch effect, hence these tools will also disturb the chip regeneration and cancel the chatter vibrations. A combination of variable pitch and helix was implemented in the cutting tools by Sims et al. which formed the basis of optimization framework from the same authors [118]. The afore-mentioned tools change the effective pitch angles of the tool but there is another group of cutters where the variation is achieved in radial direction; they are called serrated end mills – see Fig. 14(a). Similar to the variable pitch

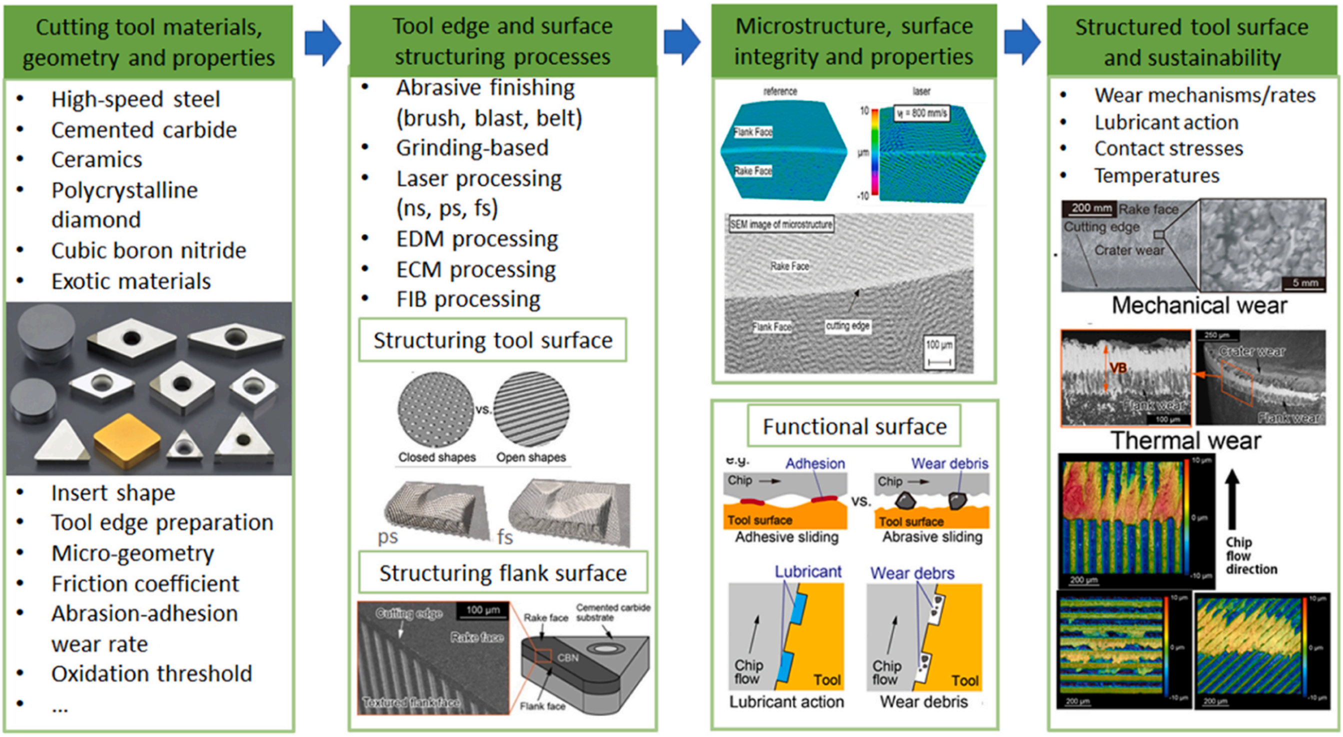

Fig. 13. A vision for cutting tools with structured surfaces and consequential sustainability.
Adapted from [9].

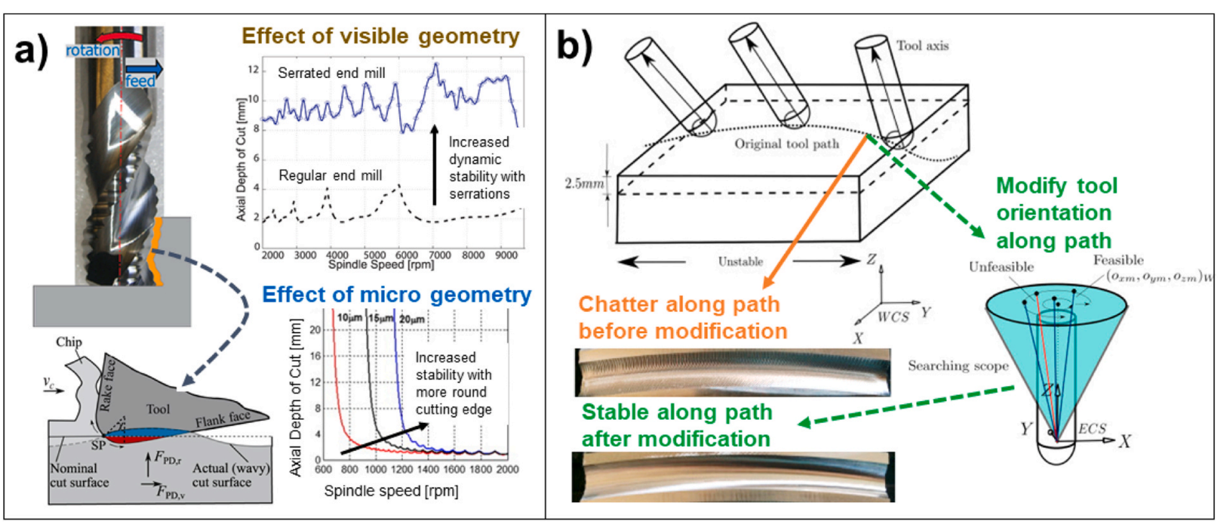

Fig. 14. Achieving improved dynamic characteristics through innovative cutting tool geometry and tool path designs: (a) Effects of changing the visible (with serration profile as example) and micro geometry (with edge roundness as example) on the dynamic stability (b) avoiding chatter by optimizing the tool orientation along the entire machining tool path [115].
Adopted from [113] and [114]

tools, serrated tools also disturb the regenerative chatter by interrupting the cut. Fast optimization of such geometries is still an open research field, however, a recent study has brought a state-of-the-art methodology to find the best geometry for a given machine tool/workpiece system [6]. Tools with harmonically varying helix angle profiles were also investigated by the industry, bringing more parameters to improve the dynamic stability [113]. For milling tools, the tool manufacturers keep trying new ways to break the chip which in return reduces tool vibrations [116], and it is an open research area to control the effects of such geometry.

For drilling tools, the most recent achievement is to model the drills with arbitrary geometry [119]. Since they bring a high number of parameters, performance of drill bits can be optimized by varying the rake and clearance angles along the cutting edge. By changing the web profile, thrust forces, radial forces as well as vibration performances can be improved. For turning, besides the insert's nose radius and rake and inclination angles given by the tool holder angles, wiper edge geometry will bring a balance between surface finish and stability with increased friction forces [120].

5.2. Micro geometry and process damping

The second way to modify the tool geometry is to change the small-scale features near the rake and clearance faces [116]. As discussed in Section 3.1, a widely applied and accepted method falling under this category is the so-called edge preparation in the industry. If the tool has a sharp edge it is more prone to chipping, but this can be avoided by making the edge more round or blunt as shown in Fig. 14(a). However, as explained in Section 3.1.1, the characterisation of cutting edge geometries is a key issue to control the impact of edge preparation on tool life and sustainability. As shown in Fig. 14(a), an additional advantage of edge preparation is to increase the process damping effect which reduces the risk of chatter. Process damping can be explained by a counteracting force that is caused by the vertical vibration motion of the tool's flank face on the machined workpiece surface. Therefore, tool wear and edge radius are the main influencers of the process damping [114]. Similarly, Denkena et al. developed a new chamfered tool that performed well in both roughing and finishing operations [121]. Additionally, Suzuki et al. textured flank face of an insert to improve chatter stability in turning process [122]. Experimental approaches thought time consuming, give very accurate results on the effectiveness of candidate geometries [117]. Jin and Altintas modelled the process damping coefficient through numerical simulations with no need for experiments; such models need to be developed further for complete model-based development and optimization of micro-edge geometry of cutting tools [123].

5.3. Modification of tool orientation for chatter resistance

The tool geometry modifications could improve machining stability as shown in the previous sections, but stability also depends on the designed tool path. Presuming that the translational (linear) tool motions cannot be changed because of the required component geometry, another way to improve the process would be to change the tool orientation angles. Therefore, the third and last way to improve stability is the setting of tool orientation. In 5-axis milling, Chao and Altintas modified the lead and tilt angles of the ball-end mill to eliminate chatter vibrations along the tool path [115]. If instability is encountered along the tool path, the authors changed the lead/tilt angle and recalculated the cutter workpiece engagement map until they stabilized that section. As shown in Fig. 14(b), they validated their modelling with experiments. For boring operations, the flexibility in two radial directions of the boring bar causes a small limiting depth of cut for chatter stability. It is a challenge to handle such flexible boring bars but changing the orientation of the boring bar showed that the stability can improve very well [124].

Machining with industrial robots is attracting interest and especially for large-scale workpieces. Lee et al. suggested that to improve machining productivity without changing the size of the robot, a cable-assisted robotic system could be used to enable higher stiffness [125]. Multiple tensioned cables were connected parallel to the end-effector of the robot and overall compliance was increased. Milling tests revealed that tensions from cables can suppress chatter vibrations.

Recently, Cai et al. planned the tool orientation to minimise dimensional surface errors by matching the cutting force direction with the maximum stiffness direction of the flexible tool/workpiece system [126]. Compared to the machine tools, industrial robots may have kinematic redundancy which can serve to change the cutting force directions. Indeed, for machining with high-compliance industrial robots, posture optimisation has been a well-established topic to improve stiffness and dynamic capabilities along the tool path [127]. Therefore, innovations in cutting tool design could provide more ways to change the force directions and complement the limitations of posture optimisation methods, e.g., when there is a risk of collision.

6. Circular cutting tools

Life cycle assessment (LCA) can be used for evaluating the environmental impacts throughout a products' life cycle from raw materials extraction (cradle), through the product's manufacture, distribution and use, to the end of life options such as remanufacturing, recycling or final disposal of the materials (grave) [128]. This requires the definition of the goal of the assessment, the scope of the assessment (system boundaries) and the inventory. The future of tooling requires a fundamental understanding of the associated emissions for the cutting tool over its life cycle. Fig. 15 shows the cradle to grave life cycle environmental impact according to global warming potential, stratospheric ozone depletion, water consumption, freshwater ecotoxicity, when cutting tools are used in a linear economy.

As shown in Fig. 15, the mining and cutting tool manufacture dominate the global warming potential when considering the total life cycle of the cutting tool. Reducing the global warming potential is a key focus for net zero manufacturing. Fig. 15 also shows that the mining operations are a dominant impact when considering the life cycle environmental burden of freshwater ecotoxicity or consumption. A solution to this linear economy for cutting tools is to consider and develop a circular economy for tooling.

In a circular economy, remanufacturing cutting tools by resharpening and reusing them can have significant impact on the reduction of energy footprint and life cycle impacts. The embodied energy of a coated carbide end mill that is used only once is 17.76 MJ (9.01 MJ for the blank and 8.75MJ for the manufacturing process) [130]. If it is reground four times this embodied energy increases to 36.96 MJ. When this is normalised per use the re-use scenario has a far reduced embodied energy of 7.4 MJ per use compared to the 17.76 MJ for the single use. In general avoided production from tooling re-use can help to generate environmental credit and reduce the life cycle impact of tooling as well as improve the security of material supply.

It is clear that in order to reduce the life cycle impact of cutting tools new innovations are required to enable remanufacture and re-use of cutting tools and to produce more components and economic value from each cutting tool. This requires a circular economy for tooling.

7. Future of tooling and research directions

This review of the innovations of tooling was contributed by international experts and has provided the state of the art for innovations for cutting tools considering the essential elements of a cutting tool system.

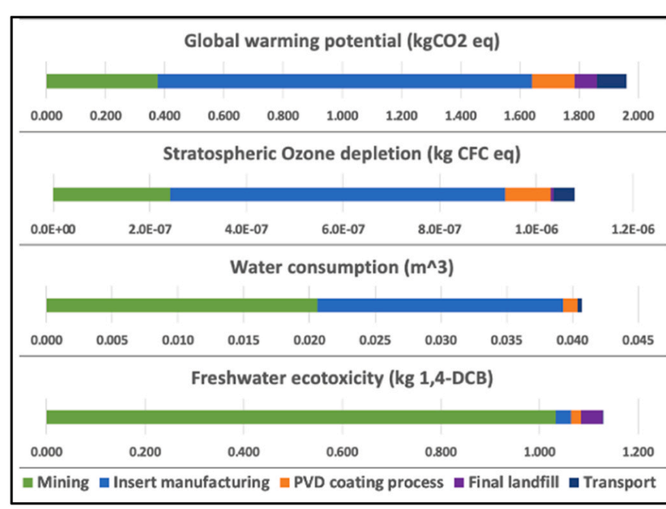

Fig. 15. Environmental impact of a) global warming, b) stratospheric ozone depletion, c) water consumption, d) freshwater ecotoxicity for different carbide cutting tools in a linear economy [129].

The following can be concluded and suggested as research steps that could set a new agenda for the future of tooling.

7.1. Integrated tool design and development

- To address the research challenges and opportunities for customised cutting tools, collaborations between academic researchers with cutting tool industry groups is key. This will ensure that research advances are considered for industrial development of cutting tools and that the academic community is informed and engaged in the cutting tool innovation and needs landscape.
- More holistic approaches in engineered tool design should be adopted by considering joint benefits of macro and micro-geometries, surface structures, coatings on all faces of cutting tools. More fundamental knowledge of cutting process is needed based on advanced experimental techniques and advanced modelling efforts at micro tool geometry, micro/nanoscale surface structures on cutting tools to understand the multi-physics of material flow, cutting fluid action and wear debris.

7.2. Coated Tooling

- Residual stress in the tool substrate and coating is a key parameter and variable of importance for tooling systems. Since tensile residual stress is generally detrimental to fatigue life and thus coating life, research progress needs to be made in novel processing pathways to reduce and match the amount of tensile residual stresses within coatings and the tool material substrate and to transform from tensile to compressive residual stress.
- Effective coatings for machining are highly dependent upon the specific application and material, requiring a strong understanding of the fundamental tribological principles that govern cutting. Further fundamental research and analysis will be required to develop an application robust coating system and to properly leverage advanced tool materials and coatings to achieve more widespread industrial adoption of dry cutting practices.
- Research and development could allow soft coatings to become more widely used in industry for applications enabling better residual stress control for tooling systems, reduced friction and energy demand in machining.

7.3. Cutting edges and functional surfaces

- Innovations on functional surfaces are very important and have already been shown to significantly influence total machining performance of drilling tools. The interactions between the surface and form modifications and the cutting edge preparation processes have to be considered and optimised for engineered cutting tools.
- Mixed structures with multiple length scales dimensions can be applied on cutting tools to achieve and maintain multi functionality. Proper optimization schemes for achieving optimized engineered cutting tool material, geometry, structures and textures, coatings for a new work material and new cutting tool must be established.
- New and innovative cost-effective mass-scale production methods should be developed for concurrent fabrication of micro-geometry, structures, and coatings during industrial tool manufacture process chains.

The research and engineering challenge in innovating tool geometry for chatter avoidance is to develop optimized solutions when many possibilities are available for large- and micro-scale features as well as for deciding tool orientation. For future research, generalized models should be improved to analytically simulate the micro-effects with no need or minimum need for experimental calibration. This needs to be expanded to design multi-axis machining tool path and be further integrated into virtual machining simulation software to enable automated process optimization.

7.4. Cutting tools in a circular economy

- The cradle to grave life cycle impact of carbide cutting tools is dominated by mining and cutting tool manufacture. This combined with the supply chain risks of tungsten and cobalt suggest that a key innovation and goal could be the design and manufacture of cutting tools that can be remanufactured and re-used or are self-healing by design or by assisted self-healing methods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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