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High Performance Cutting (HPC) in the New Era of Digital Manufacturing - A Roadmap

G. Byrne*[a], E. Ahearne[a], M. Cotterell[b],

B. Mullany[c], G.E. O'Donnell[d], F. Sammler[e]

[a] University College Dublin, Ireland
[b] Cork Institute of Technology, Ireland
[c] University of North Carolina at Charlotte, NC, USA
[d] Trinity College Dublin, Ireland
[e] Technical University Berlin, Germany

*Corresponding Author: G. Byrne, Email: gerald.byrne@ucd.ie, 00353872429631

Abstract

We are rapidly moving into the new era of digitisation, into an era of the Massive Internet of Things - towards the Gigabit Society and towards 5G Technology. The implications are truly far reaching. Rapid transformation through the implementation of INDUSTRY 4.0 is becoming visible in industries all over the world. Disruption to the more traditional industrial practices and processes is inevitable. High Performance Cutting is no exception. Developments in the Internet of Things (IoT) opens up new and extremely powerful capabilities to help us gain a significantly deeper understanding of the fundamentals of cutting processes and offers entirely new connectivity possibilities at all interfaces, some old and some new, "*between the Chip Root and the Cloud*". This supports us in our attempts since the foundation of CIRP in 1951 to remove technological roadblocks and can lead on a new journey towards new and unprecedented scientific/technological developments as well as new business models for companies involved in the various elements of the supply chain for cutting processes (DIN 8580). "Performance" will take on a new and unanticipated meaning over what was originally meant when we established this CIRP-HPC Conference back in the early 2000's. In this paper a critical review of a previous roadmap is undertaken for cutting processes presented in a CIRP Keynote Paper in 2003 by Byrne, Dornfeld and Denkena [1] and new thoughts and ideas are presented on a vision for a 2020 skeleton Roadmap for High Performance Cutting in the new age of Digitisation.

Keywords: High Performance Cutting, Industry 4.0, Internet of Things, Digitalisation

1. Introduction

In the 2003 review paper on the technology roadmap for cutting technology (see Figure 1.1) the remarkable progress made over the previous decades was referred to. The thrust towards the application of higher performance workpiece and cutting tool materials, towards usage of minimal quantities of cutting fluid, to higher precision and to the application of microsystem was predicted to continue. The technological capabilities of our cutting systems will continue to develop and higher performance with enhanced safety standards, improved levels of environmental cleanliness and lower manufacturing costs can be expected.
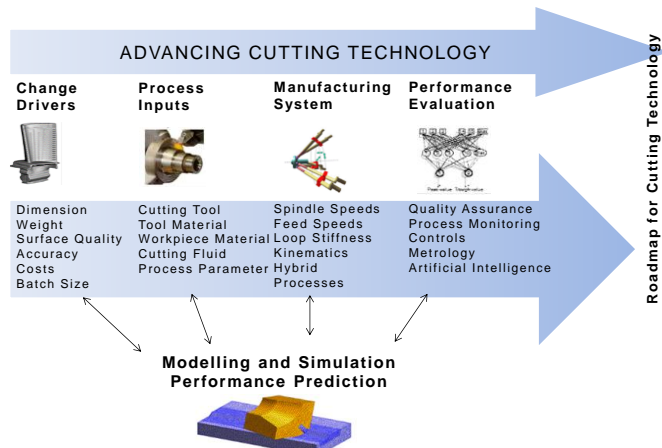

Fig. 1.1. A 2003 Roadmap for advancing cutting technology [1]

2. The New Change Drivers

It was stated in the 2003 CIRP Keynote Paper [1] that an essential element of the roadmap for cutting technology was the integration of manufacturing processes. In the previous decades, simple process elements had been optimized. Progress has been made by focusing on technology interfaces and on the complete process chain. It was also stated that our manufacturing systems for cutting technology would be hybrid in nature and would encompass modularity features for ease of reconfigurability and for minimization of non-productive times. Reconfigurable manufacturing systems when implemented with open architecture control systems for basic machine tool control as well as adaptive control of machining performance could offer substantial improvement in cutting performance by assuring economic flexible systems responsive to changing demands and shorter product cycles. Disparate sensor systems as part of open architecture control were predicted to contribute to the development of "intelligent" machining systems with learning abilities. Substantial research work would be needed to integrate methods of assessment of part quality with operating machining systems. Molecular dynamics modelling was stated to offer potential for coupling micro and nanoscale process features with macro scale processes. The improvement in modelling capabilities from macro to nano scale processes leading to improved process simulation and process understanding was also incorporated.

It is interesting to note here that energy efficiency was not specifically mentioned in the 2003 Keynote Paper [1], nor was sustainable manufacturing. The Internet of Things was not mentioned and also cloud computing was not on the landscape at that time. Digitalisation took on a different meaning at that stage. So it could be argued that significant deficiencies existed in the 2003 roadmap. However it should be noted that the internet then was still at an early stage and cloud computing had not arrived. Connectivity was limited and did not have global reach in the way we have it today. WiFi was also unknown in the factory environment. The self-learning and intelligence in the machining system was referred to in the original paper and is still at an embryonic stage.

In looking forward and in considering a new 2020 roadmap for High Performance Cutting [HPC] is it important to undertake a deep and critical review of what has been achieved to-date. We need to recognize that the new capabilities at our fingertips will be multiples of what was available to us in the past. The data available to us will be considerably richer. There is high potential for innovation in for example: 1) accurately controlling and manipulating the thermal status of our cutting processes, 2) optimization of the cutting fluids and flushing strategies and ensuring that the fluid actually reaches the zone of cutting, 3) optimising tool changing strategies, 4) our capability of producing surfaces with defined integrity e.g. predictive residual stress and microhardness profiles, 5) provision of better process understanding through enhanced analytical and experimental data on chip formation mechanisms etc. This is but a sample of a long list of important issues where deeper insight is needed.

The paper now continues with an appraisal of the key areas associated with high performance cutting as summarised in Figure 1.1 above.

3. The Process Inputs

The digital manufacturing era will produce innovations that directly and indirectly impact on the most basic inputs to the cutting process. The inputs of interest include: the cutting tool, the tool material (including coatings), the work material, the cutting fluid and the "process parameters", referred to here as the "control parameters". These parameters are controlled locally and easily varied spatially and temporally, while the other parameters are "quasi-fixed".

Cutting Tools
 Perhaps the most direct impact of digital manufacturing technologies on future cutting tools is in the potential use of additive manufacturing technologies for generating "near-net shape" tools with here-to-fore challenging geometric structures and sub-structures as well as the potential for producing functionally different sub-structures in optimised materials and with graded properties (4D printing). Research work on the production of tungsten carbide tools using additive manufacturing technologies is being carried out at Fraunhofer IPK [2] under the leadership of Professor E.

Uhlmann. The work focused on the process behavior of the agglomerated and pre-sintered tungsten carbide-cobalt (WC-Co) powder material in the SLM process. The further development of this technology will significantly advance tool design and production and enable sensor integration and process monitoring of cutting tools.

Some of the authors were involved in organising the precursor HPC workshops at the CIRP winter meetings. One of the four industry defined themes was so called "integrated tooling" based on the potential for reduced cycle times and improved quality in high end, batch type manufacturing. This theme was further developed and the term "intelligent tooling" was coined. This refers to the aforementioned embedding of sensors, actuators etc. close to the tool to both improve signal sensitivity and signal to noise ratio and to provide "additional functionalities". An example of commercially available additional functions in this regard is the superposition of ultrasonic vibrations in milling generally to increase material removal rates.

More speculative tool-related innovations would include the biomimetic mechanism of regeneration of bio-surfaces subject to friction and wear (eg skin, teeth etc). The inference here is that the worn tool edges, rake and flank surfaces would regenerate. While there is no known technological break-through or route to realise this for cutting tools during use, additive manufacturing technologies have the potential to be developed to realise this "offline".

Cutting Tool Materials

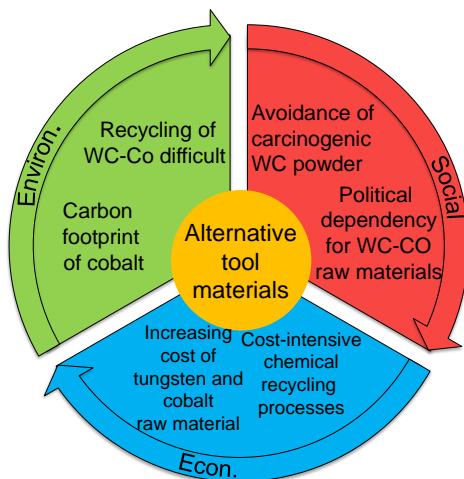Research continues into new tool materials, drivers for which are shown in Figure 3.1.

Fig. 3.1. Change drivers for new tool materials

Currently the most common tool material is cemented carbide invariably with a coating deposited either by Physical Vapour Deposition (PVD) or Chemical Vapour Deposition (CVD) [3]. The most common coatings are based on the (Ti, Al)-N coating systems, however, Diamond Like Carbon (DLC) and diamond coatings are also finding increasing use.

Significant research work has also been undertaken on the development of new coating types and coating processes, such as HiPIMS coatings [4], for example, or nano-particle reinforced hard coatings. Recently, thin films for coating of cBN substrate material have been developed, with a thermal

and chemical barrier between the cBN material and the cutting zone being the main drivers. Results show significant tool wear reductions particularly in the machining of hardened steels and nickel-based alloys [5].

Ceramic tool materials such as Si_3N_4 are also finding increasing usage, for example for turning of nickel-based superalloys. However, the high cost of ceramic raw materials and the high brittle indices have mostly limited their use to simple tool geometries and turning processes. Research work on alternative carbides also shows promising results. In the machining of hardened steel (53 HRC) it was shown that the new NbC (Niobium Carbide) tools had significantly higher wear resistance compared to WC tools, both in an uncoated condition, see Fig. 3.2. This could also be verified in milling operations and is a topic of ongoing research at the BAM and IWF in the TU Berlin, Germany.
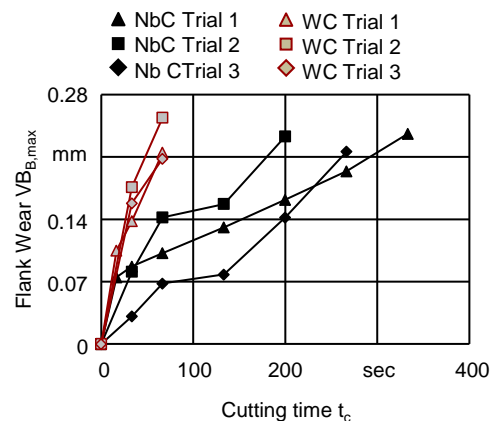

Fig. 3.2. Comparison of WC-Co and NbC-Co cutting tools in machining of hardened steel

Work Materials

The typology of materials processed by cutting continues to expand, as does the number of variants of each material type. The recent CIRP keynote by M'Saoubi et al. [6] is indicative of this for aerospace materials and presented a typology with some of the more recent materials introduced for aero-structure and aero-engine parts. The common drivers include a reduction in total mass / weight, improvements in fuel efficiency and carbon footprint, as codified in the FLIGHTPATH 050 guidelines. The increasing use of composite materials is indicative, now accounting for over 50 % of the weight of recent aircraft models such as the Airbus A350 XWB at 52 %.

Similarly, there are common drivers in all high-end sectors to introduce so called "difficult-to-cut (DTC)" materials for improved functional design purposes. For example, the automotive sector is introducing gamma titanium aluminide brake discs.

More recently, the challenges in cutting of biomedical materials has led to more research into the fundamental mechanisms. For example, there are few publications on cutting of Co-Cr-Mo alloys used for orthopaedic implants where bio-compatibility is a pre-requisite combined with high wear resistance in-vivo and strength. New research has shown that much higher specific cutting forces were obtained in orthogonal cutting compared with titanium Ti-6Al-4V [7].

Additive Manufacturing, as a direct digital manufacturing technology, will impact on material inputs directly through part finishing. The challenges in cutting additive manufactured parts are not only due to fundamentally different material micro-structures and properties, but also the potential for varying the composition, micro-structure and properties within a part by functional grading (4D printing).

4. The Manufacturing System

A manufacturing system comprises processes, procedures and controls that convert raw materials into physical products. Manufacturing presently occurs in an environment with fragmented communications protocols and automation practices. Advances in materials (tools, coolants, workpieces), higher levels of process flexibility (batch size of one), and the ever present need to reduce costs will continue to drive the need for predictive tools to eliminate trial and error approaches at all stages of process development.

The ultimate goal of the factory-of-the-future is to interconnect every step of the manufacturing process. This will involve an unprecedented level of technical integration of systems across domains, hierarchy, geographic boundaries, value chains and life cycle phases. This integration will only be a success if the technology is supported by global consensus-based standards [8].

Manufacturing as a sector generates more data than any other and this offers significant potential to increase competitiveness and efficiency through the appropriate use of information technology and data analytics [9]. Benefits can be obtained at all levels in an organization from strategic planning across the supply chain down to operations on the shop floor.
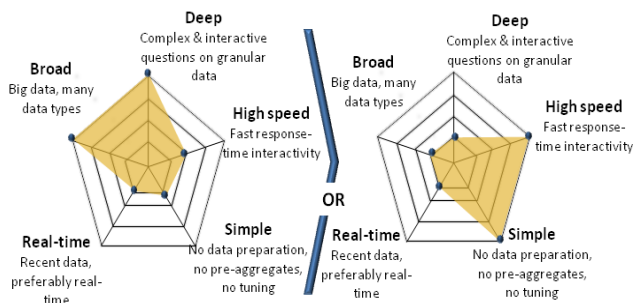

Fig. 4.1. Alternative approaches to data analysis [9]

Vast quantities of data are generated and stored and can be used to generate real-time information on product quality, production output, overall equipment effectiveness (OEE), machine availability and maintenance. The extraction of value from the vast amount of stored data available requires an infrastructure and expertise appropriate to large data sets so that specific patterns can be identified. Data can be analyzed deeply and broadly, but not quickly at the same time as depicted in Fig.4.1. Recent data analytics capabilities include event stream processing (ESP) and complex event processing (CEP). In this way direct working with data from events, as they happen, allows for faster reaction times – enabling a response to a developing situation within a process.

In the future, greater integration of manufacturing technology with information technology will see a move from current reactive approaches that address problem issues as they arise to a proactive and predictive approach that prevents such problems arising in the first instance. This enables autonomous decision-making resulting in the development of self-awareness at the machine level as shown in Fig. 4.2 [10]. More open machine communication systems pose cybersecurity risks and frameworks need to be developed to identify and to mitigate against such threats [11].
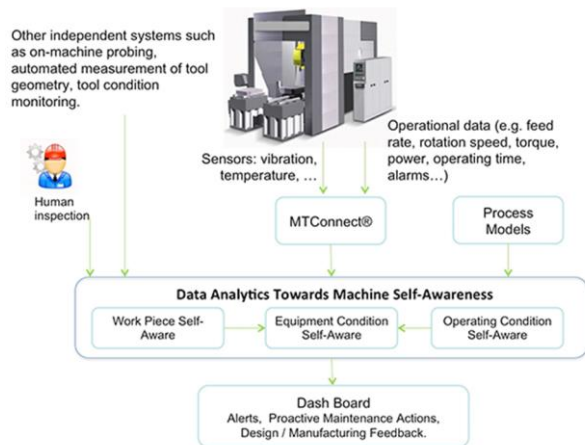

Fig. 4.2. The self-aware machine tool [10]

The relationships between the workforce and technology must also evolve. Human-factory and human-machine interactions will become more flexible. Workers will be expected to have a wider and more flexible skillset but in return will have greater control over their work and personal schedules. Collaborative working involving the sharing of knowledge across platforms will be enhanced and learning cycles will be shortened due to data storage, semantic technologies and the ability of the worker to merge and analyse the company's experiences with his/her own experiences for the creation of new ideas [8].

Greater process integration is another trend as additive, subtractive processes and metrology functions are incorporated into a single machine tool [13].

5. Performance Evaluation

Performance evaluation has the potential for disruptive change with the increase in digitization in manufacturing. Process monitoring is arguably one of the first cyber-physical technologies and is a well established technology in industry in particular in automotive and aerospace manufacturing. Research in process monitoring has constantly been pushing technological barriers with the development of new sensors and sensorless systems, multisensory input, sensor fusion, use of artificial intelligence, adaptive control and automated decision making [14]. One of the barriers to implementation was the lack of sophistication and integration of platforms that can access and process the data. The emergence of INDUSTRY 4.0 and the Industrial Internet of Things is one of the key enablers together with a number of technology specific enablers based on digitisation that are combining to

provide the potential disruption including open access, increased sensorisation, cloud hosted analytics and wider technology acceptance by operators.

At a process level developments towards increases in process sensorisation are becoming more prevalent. One example is through use of novel wireless passive sensor systems reported by Stoney et al. [15] based on use of surface acoustic wave strain sensors. Similarly it is becoming more realistic to consider great multisensory data sets using measurable phenomena such as spindle power correlated with tool engagement. Figure 5.1 shows the power data mapped onto the surface of medical implant during grinding [16].
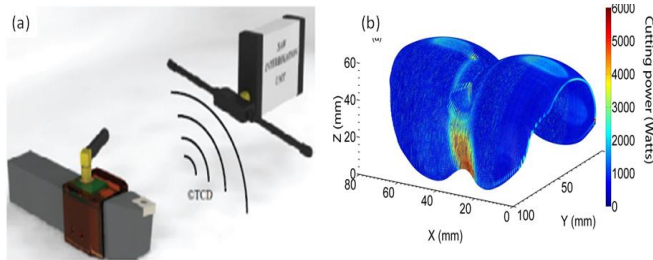

Fig. 5.1. Example of (a) wireless sensing of strain during turning [15] and (b) power mapping to freeform surfaces [16]

The concept that every executed line of G-code is an experiment as postulated by Park et al. [17] shows how process data is becoming more visible and useable. Quantification of other factors that impact directly on cutting processes is also becoming more feasible with new sensor technology such as monitoring of coolant quality inline [18].

Recent CIRP initiatives on energy and resource efficiency have been a considerable source of knowledge in quantifying energy and environmental aspects of processes. which has been largely enabled through the increase in digitization in manufacturing. The ability to undertake detailed measurement of energy and resource consumption has enabled fundamental insight into sustainability aspects in cutting processes [19,20].

Therefore it can be envisaged that the multiphenomena ranging from specific process information, machine condition information and energy information can be accessed in a manner not foreseen prior to the enhanced digitization and therefore provides a much more homogeneous quantification of performance. The emergence of new metrology tools that can be used within the process in real time provides the potential to fully close the loop around the process.

Already new standard communication channels such as MTConnect to couple multiple sensor systems on multiple machine types are emerging, as well as new approaches and architectures for cloud based monitoring [21,22].

6. Modeling and Simulation

Predictive capabilities will remain a critical component of the HPC technology roadmap. Modeling and simulation of machining operations either focus on the fundamentals of chip formation and material removal to predict process forces and temperatures, or consider the larger machining environment (tool, workpiece and the machine tool) to predict process times and optimize tool paths. Neither modeling approach has yet reached its full potential. A recent review paper [23] highlights advances and challenges in modeling tool-workpiece interactions.
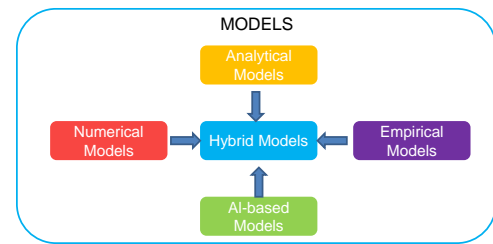

Fig. 6.1. Four basic modeling approaches. Hybrid models, combining approaches, will improve speed and quality of model predictions [23]

There still is a need for cheap, easy to implement models providing industrially relevant outputs. Scientifically fundamental models by definition provide fundamental outputs such as tool temperatures, stresses, or tool-chip friction values, however these outputs have limited application on the workshop floor. Model outputs of most interest to industry include items such as; tool wear, achievable finishes, burr formation, geometric part accuracy etc. Predictive tools using physical model outputs as inputs to produce industrially relevant outputs are in demand. Hybrid models combining more than one modelling approach, i.e. analytical and numerical or empirical and numerical, to shorten computational times and improve accuracy must also be developed as illustrated in Fig. 6.1. Increases in computational efficiency will enable the realization of full 3D models which are currently lacking. To date, modelling has not kept pace with the introduction of new tooling (geometries and coatings), and coolant innovations (MQL, cryogenic approaches). Key to expediting their incorporation into models is establishing key relevant material properties. Sensor development, enhanced connectivity and further development in AI could foreseeably realize the rapid development of process specific empirical based models.

System level simulations, including workpiece CAD/CAM data, cutting parameters and machine tool dynamics, have gone beyond collision detection and kinematic verification of the tool path. Sophisticated virtual machining models are now incorporating cutting force models to optimize feed rates along the cutting path and to avoid machining states that are detrimental to final surface quality and part geometric accuracy, e.g. chatter. A paper by Altinas et al. [24] outlines the most recent developments and challenges facing the next generation of machining optimization models. Increased demand for high precision freeform surfaces will test tool path optimization strategies. The continuous changes in tool feed rates required to accommodate nonlinear tool trajectories means continuously varying tool velocities and accelerations must be considered along the entire tool path. Machining precision components with high aspect ratio geometries will require models to adapt to variations in the relative dynamic stiffness between the workpiece and the machine tool. This will be necessary to avoid unfavorable chatter stability lobes. As in any modeling or simulation approach faster computational times are still desired to accommodate higher degrees of complexity and shorten solution convergence.

Ideally outputs from local physical based tool-workpiece models, especially regarding cutting forces (tool and workpiece dependent), will need to be combined with the larger system level models to increase prediction accuracy.

7. Conclusions

The objective of this paper is to highlight some of the issues around the development of a new roadmap for cutting processes as related to the work of the Scientific Technical Committee "Cutting" (STC C) of The International Academy for Production Engineering (CIRP). It is evident that there are numerous aspects associated with cutting processes where we still have rather limited knowledge and capabilities despite decades of intensive research and development. The recent novel work of Brinksmeier et al. [25] on process signatures provides evidence of this. The new era of digitisation opens up an entirely new environment with powerful new capabilities to achieve the economic production of surfaces to the demanded qualities through cutting processes. There are truly outstanding opportunities for innovation in the new era of digitalisation. As the leading global manufacturing research community, we are well positioned in CIRP to navigate the future direction and to identify new and potentially lucrative digital tools for High Performance Cutting in the 2020+ scenario. This means thinking outside of our conventional box and being open to flexible approaches and structures in our CIRP community.
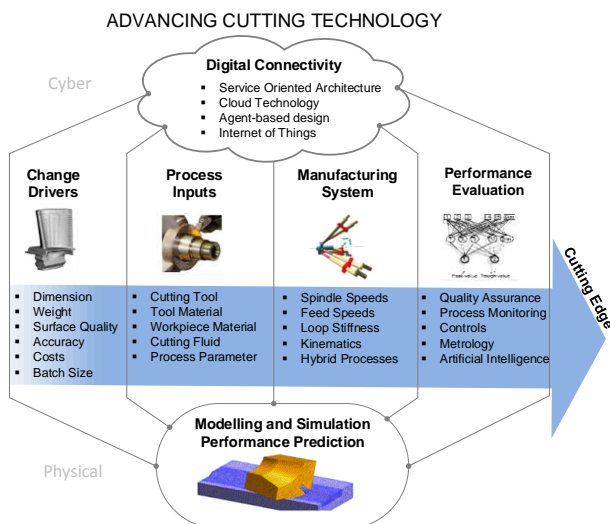

Fig. 7.1. Cloud contextualized roadmap- a starting point for STC C

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