Innovative High Performance Machining Technologies for a Green and Digital Environment

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ABSTRACT

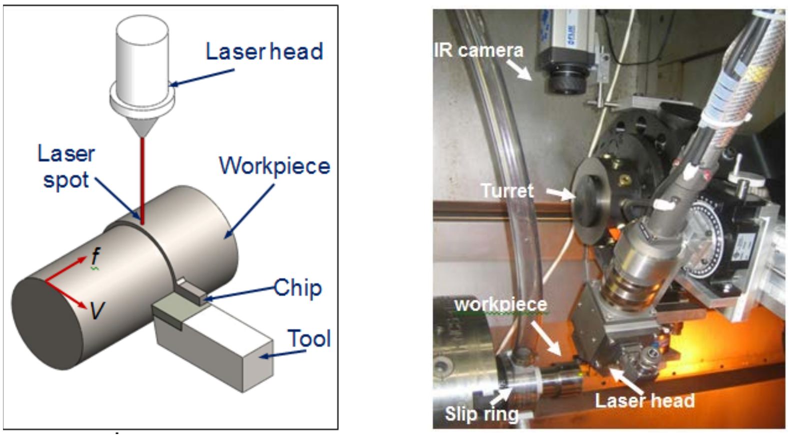
Although machining is a well-established process, new developments are required to help the industry keep a competitive edge by increasing productivity, reducing lead time, and ensuring a low impact on the environment. This paper focuses on the state-of-the-art technologies for high-performance machining that are aligned with higher digital inter-connectivity and greener environment. The key areas that are focused on are the following: (1) High performance and hybrid machining: To deal with the low machinability of difficult-to-cut metals such as Inconel and ceramics (aluminium oxide, silicon nitride), new technologies have evolved including heat-assisted machining, super-abrasive grinding. (2) Environmentally friendly technologies: There are many environmental challenges in machining with respect to the cutting fluid management and the waste materials. Some of the promising technologies are cryogenic machining, minimum quantity lubrication, and dry machining. (3) Virtual machining: The development of high fidelity models of machining processes is one of the key research activities to reduce the lead time and waste and to ensure an optimum selection of the process conditions.

1.0 HIGH PERFORMANCE AND HYBRID MACHINING

High performance machining refers to the strategies to machine parts with high productivity, high quality, and overall low cost. It is usually applied in the machining of difficult-to-cut materials such as super-alloys, ceramics, and composites. The high performance can be achieved through each individual component of the overall machining system, e.g. high performance machine tools, high performance cutting tools, and so on. Hybrid machining integrates conventional machining processes with other technologies to further improve the machining performance. As examples of hybrid machining and high performance machining, laser assisted machining and super-abrasive are presented in this section.

1.1 Laser Assisted Machining

Laser-assisted machining (LAM) is a hybrid process that uses a high power laser beam to locally preheat the workpiece prior to cutting, as shown in Figure 1(a). By softening the material with a laser beam, it was found that the cutting forces were reduced by 20–40% for turning of Inconel 718 [1], by 30–50% for Ti6Al4V, and by 10–40% for steel 100Cr6 [2]. The tool life was increased by 180% for laser-assisted turning of the titanium metal matrix composites [3], and the material removal rate was increased by 30% for Inconel 718 [4]. It was also observed that LAM improved the surface finish and surface integrity for Inconel 718 [5]. A good surface finish less than 0.3 μm was produced in LAM of transmission shafts of AISI 4130 [6]. Since it is controllable, economic, and environmentally friendly, LAM was considered as an alternative process for machining of difficult-to-cut materials such as nickel alloys [1, 4, 8], metal matrix composites [3] and hardened steel. It was also considered as a replacement of the currently used hard turning and grinding operations [7].



(a) LAM principle

(b) Laser assisted turning setup

Figure 1: Laser assisted turning system.

In the LAM process, the high preheating temperature associated with large plastic deformation may promote undesirable microstructural change on machined surfaces, such as the formation of a white layer [9]. Therefore, the preheating temperature in LAM must be well controlled below the austenitization start temperature in order to avoid workpiece subsurface damage, and at the same time to achieve the maximum benefits of reduced cutting force, reduced tool wear and good surface finish [10]. To achieve this goal, Shi et al developed a moving heat source model incorporating microstructure evaluation model to optimize LAM preheating temperature [1, 11, 12]. A laser assisted turning system was also developed at the Aerospace Manufacturing Laboratory (AML) at the National Research Council of Canada (NRC) for machining of Ni-alloys and Ti-alloys, as shown in Figure 1(b). It was shown that the machining forces were reduced by up to 40% in comparison with conventional cutting.

As shown in open literature, all of the researchers were focusing on the effects of LAM on cutting forces, tool wear, and surface finish. The influence of laser heating on the residual stresses of the machined surface has not been reported. It has been know that compressive residual stresses can improve part service life. How to control the LAM to create compressive stresses on the machinedsurface is a significant research direction in the future. Currently, LAM technology is mainly used in tuning and single direction milling processes. Application of LAM in 3 or 5-axis milling processes is also becoming an important research direction.

1.2 Super-abrasive Grinding

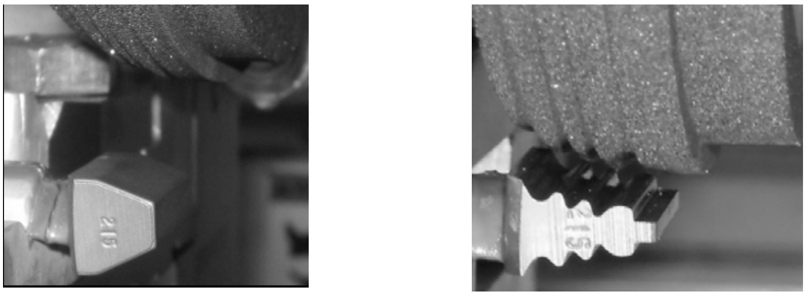
Super-abrasive materials include diamond and cubic boron nitride (CBN). Diamond is the hardest material known so far and CBN is the second hardest. As an abrasive in grinding, diamond is mainly used on grinding materials for ceramics, granites, carbides, and composites, while CBN is more suitable for grinding ferrous materials and non-ferrous high strength alloys. As with conventional abrasive wheels, super-abrasive wheels are also made in various sizes, shapes, and bonds. Different from conventional abrasive wheels, however, super-abrasive wheels can be made with a single layer of abrasives by electroplating or brazing abrasive grains on precisely machined wheel cores. Such wheels possess unique advantages over conventional abrasive wheels for profile grinding and for running at high peripheral velocity. Super-abrasive grinding is applied for extending wheel life, dealing with difficult-to-grind materials, and/or improving productivity due to the extreme wear resistance of the abrasives. For the past 14 years, the AML-NRC has been working in development and optimizing of new super-abrasive grinding technologies.

Wheel life is closely related to wheel wear. For dressable wheels, e. g. vitrified CBN wheels, wheel wear resistance is expressed by grinding ratio, or G-ratio, which is the material removed per unit volume of wheel wear. The wheel life is usually expressed in terms of parts ground between wheel re-dressing operations. In a study in high speed grinding of hardened steel with vitrified CBN wheels, a G-ratio of 4,300 was reported [13], which is about 100 times of that obtained with conventional abrasive wheels. Higher G-ratio helps reduce wheel consumptions and the machine downtime for wheel changing. Unlike dressable wheels, single layer super-abrasive wheels are not periodically dressed. Grinding performance in terms of grinding forces, power, and surface roughness of such wheels is characterized by progressive changes [14]. This characteristic should be considered and it presents challenge in selecting grinding parameters to ensure that the required ground surface qualities are achieved through the wheel life.

An example of applying vitrified CBN in grinding fir-tree root forms of actual turbine blades is presented in Figure 2 [15]. The measured results for surface roughness and radial wheel wear are presented in Figure 3, in which the surface roughness was normalized to the targeted part roughness and the radial wheel wear was normalized to the part dimensional tolerance. The number of parts ground was also normalized to a predetermined targeted number. The lines for the normalized values of 1.0 representing the targeted surface roughness and wheel wear, respectively, are also included in the figures. It can be seen from Figure 3 that both the surface roughness and radial wheel wear increased progressively with continued grinding. For the targeted number of parts, the surface roughness was about 75% of the targeted value. The surface roughness was just slightly higher than the targeted value when twice of the targeted number of parts were ground. The radial wheel wear limit, however, was reached at the targeted number of parts. This indicates that the wheel wear was the only constraint for extending wheel life beyond the targeted value. It should be noted the total number of good parts ground between dressings could be increased if wheel radius compensation had been applied to correct the effect of wheel wear on part dimensions.

The capability of super-abrasive grinding to grind difficult-to-cut materials and grind profiled surfaces can be illustrated by the deep slot grinding with electroplated CBN wheels on a newly developed nickel alloy [16]. Machining of the slots by broaching did not work due to excessive tool wear. The slot geometry is illustrated in Figure 4. The depth and widths at the slot bottom and the top were 19.25, 5.08, and 21.28

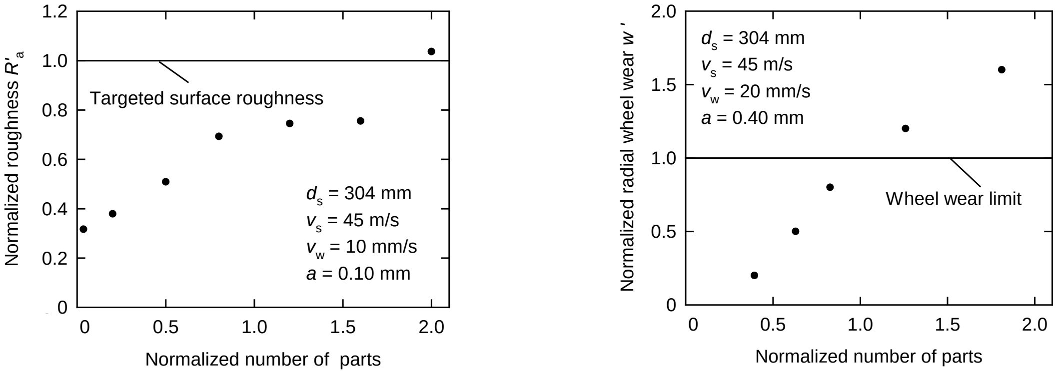
mm, respectively. Pictures of the actual disk before and after grinding all the slots are given in Figure 5 along with a close-up picture showing the details of the slot geometry. A total of 48 slots including those in the disk and 4 slots in a disk segment were ground with this wheel. There were no signs of burning, and chatters. Microscopic examinations of the wheel surface indicated that the wheel was still in its good condition after grinding these slots. There were no signs of wheel surface loading and bonding wear, which implied that the wheel was able to be used for grinding more slots. It can also be seen from this example that the grinding operation here is used mainly for large volume of material removal, not used for finishing the parts.



(a) Blank of fir-tree root form

(b) Ground fir-tree root form

Figure 2: Grinding of fir-tree root form.



(a) Normalized surface roughness

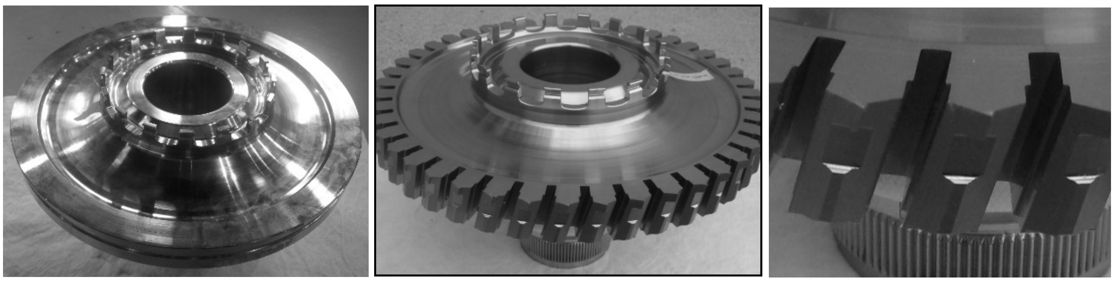
(b) Normalized radial wheel wear

Figure 3: Surface roughness and radial wheel wear.

(a) Illustration

(b) Setup

Figure 4: Illustration and setup of deep profiled slot grinding.



(a) (b) (c)

Figure 5: Prototyping in an actual disk: (a) before slotting (b) after slotting (c) close-up of slots.

2.0 ENVIRONMENTALLY FRIENDLY TECHNOLOGYES

The demand for greener manufacturing has been the primary drive for research on technologies that reduce cutting fluid consumption. New manufacturing paradigms involve more dependence on green manufacturing techniques. The assessment of the environmental performance of machining processes has become an essential aspect of process characterization and optimization [17]. Metal cutting processes are among the highest category of energy consumption in manufacturing processes [18]. The conventional method of heat disposal in machining with flood cooling/lubrication is becoming increasingly unacceptable, as it represents an economical and environmental burden. In addition to being a health hazard, it is estimated that the price of conventional cooling makes up to 17% of manufacturing costs, much higher than the cost of tooling, which is estimated as 4% [19]. Dry machining or near-dry machining along with the optimization of cutting tool design to fit specific operations has been employed as a solution to eliminate the need for cutting fluids.

2.1 Minimum Quantity Lubrication (MQL)

Minimum Quantity Lubrication (MQL) of machining processes has gained significant interest, as an emerging technology to replace the conventional flood cooling in conventional and high speed machining of metallic and composite components for automotive, aerospace and die and mould industries [20–27]. The use of this technique results in considerable reductions in the quantity of lubricant used, thereby reducing manufacturing costs, as well as the impact of the process on the environment [28]. MQL machining involves a cutting fluid delivery method where the fluid, typically a straight biodegradable oil, is fed to the cutting zone in quantities between 0.2 and 30 ml/min [29], which is much less than conventional flood cooling where the flow rates usually range between $4x10^3$ and $4x10^4$ ml/min [30]. The fluid is fed either in the form of a rapid succession of droplets, or with the assistance of a transporting medium, i.e. air, as an aerosol spray [31]. The delivery of the MQL aerosol in machining can be done either externally, using one or more nozzles directed to the cutting zone or internally, via built-in channels in the tool through the spindle. Two systems of MQL can be found; single channel, where the mixture of the gas and atomized fluid (aerosol) is formed and supplied prior to the nozzles, or a two channels system, in which the mixing of oil and air occurs directly ahead of the tool using an atomizer nozzle (Figure 6).

The MQL technology appears to have a niche of applications, where it would prove beneficial in terms of quality and savings, in addition to the environmental benefits [29]. Several work has focused on the application of MQL in machining operations, such as milling [32-37], turning [38-43] and drilling operations [44-47]. However, the application of MQL in machining processes requires special considerations of the jet characteristics to ensure that the cutting fluid adequately covers and penetrate to the cutting zone area, mainly, the tool–chip and tool–work interfaces. This requires the droplet size of the spray to be small enough to penetrate the cutting zone [29], but greater than 5-10 µm, otherwise they become airborne fluid particles that cause health problems if inhaled [48].

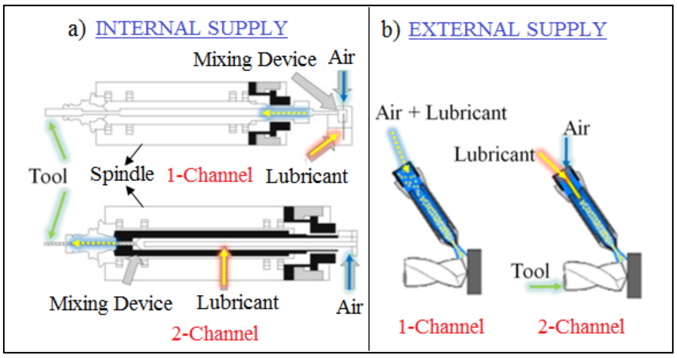


Figure 6: Different MQL systems and delivery.

In the machining process, a good understanding of the lubrication and cooling effects at the cutting zone will lead to efficient and economic machining [49]. Youssef et al. [50] investigated the different flow regimes of MQL, and the effect of different MQL parameters; namely, the air flow rate (AFR), the oil flow rate (OFR), and the distance (L) from nozzle exit to the cutting zone on the jet flow characteristics through flow visualization and its effects on the machining performance of CFRP, in order to select the optimum jet for machining. It was found that optimum MQL spray was achieved with high AFR and low OFR. This combination provided good atomization represented by large number of small droplets at high axial velocity with less vortex formation that gives better penetration into the cutting zone, as shown in (Figure 7). This was translated in the reduction of tool wear using MQL by 30% as compared to pressurized air and 22% as compared to dry and conventional flood coolant (Figure 8).

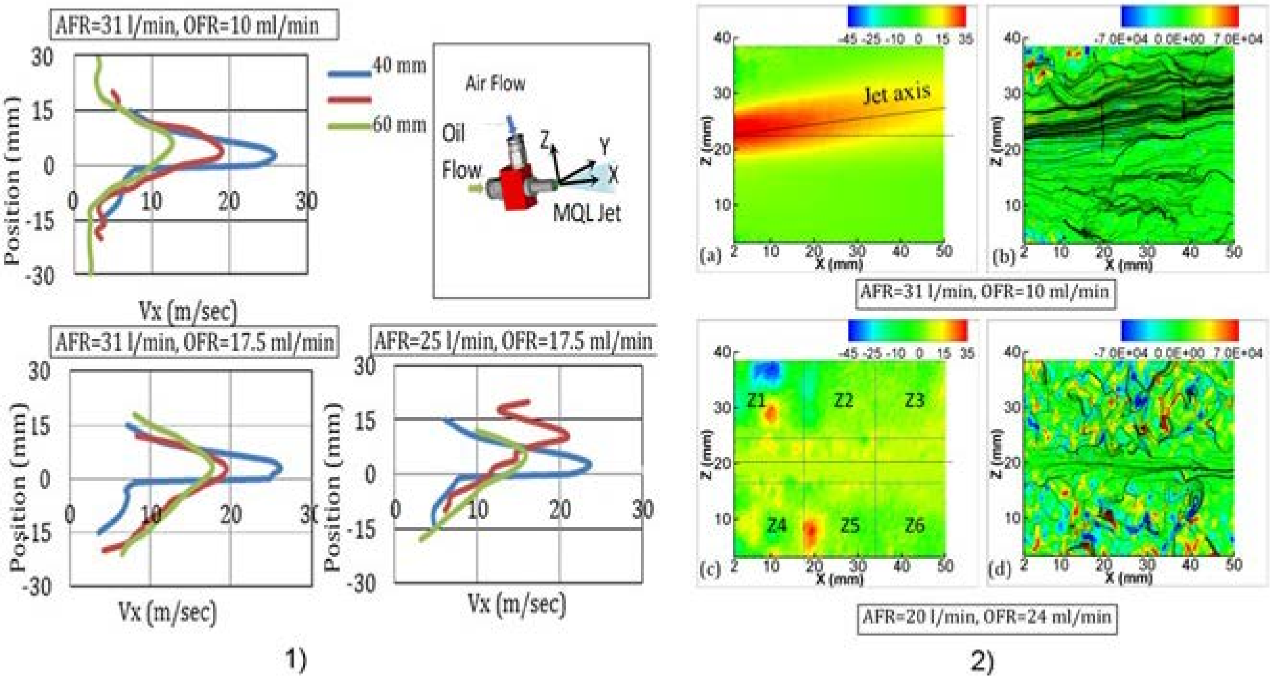


Figure 7: Effect of MQL parameters (AFR and OFR) on the 1) average axial velocity and 2) stream velocity field (a,c) and vorticity field (b,d).

Similar approach was used by Damir et al. [41, 42] in using flow visualization capabilities to select the optimum MQL conditions in order to optimize the jet cooling and lubrication capabilities for machining performance in milling of Ti alloys (Figure 9). The performance of optimum MQL configuration was compared to dry and flood coolant in terms of cutting forces, surface roughness, and cutting temperature.

Additionally, they performed Life cycle analysis using the Eco-indicator method to quantify the environmental impact of each process. The optimum MQL jet showed better machining performance as compared to dry cutting, with 36% reduction in the cutting forces, 50% decrease in roughness and 60% decrease in tool temperature, as shown in (Figure 10). It showed even comparable results with flood coolant. The life cycle analysis showed that the MQL machining had the lowest total score (0.13), which is significantly lower than the flood machining (4.54) and slightly less than the dry machining (0.14). This indicated that MQL machining can provide a sustainable alternative to flood machining that can significantly improve the environmental and machining performance of the process.

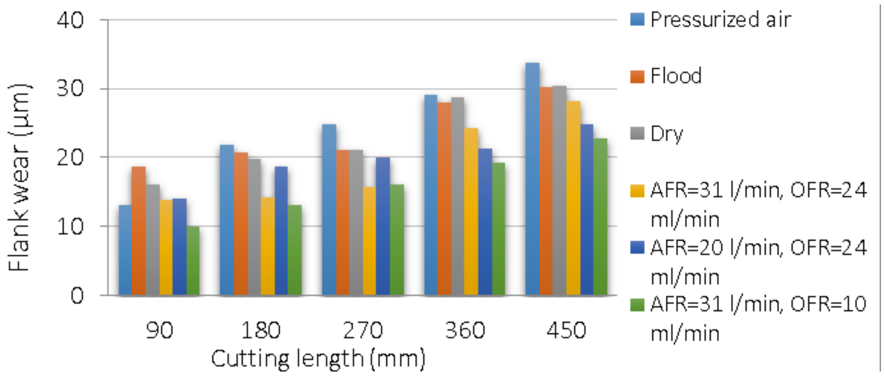


Figure 8: Effect of MQL parameters and cooling modes on progressive tool wear [50]

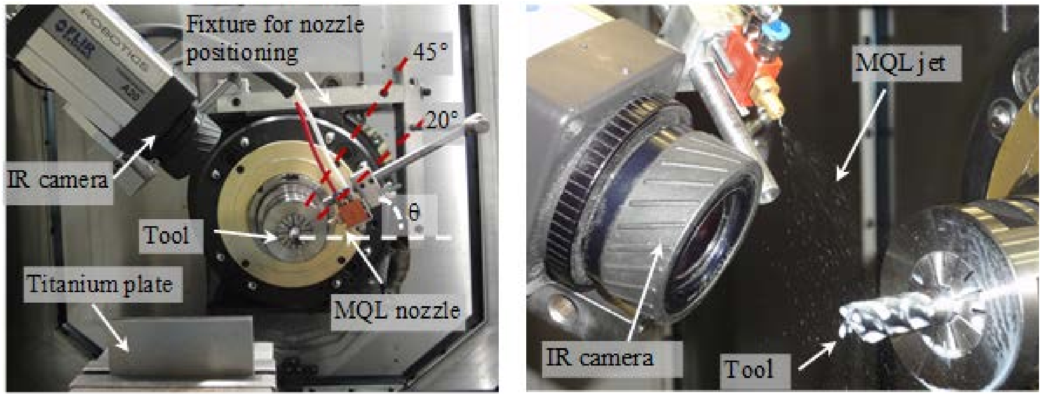


Figure 9: MQL setup in machining of Ti alloy [51]

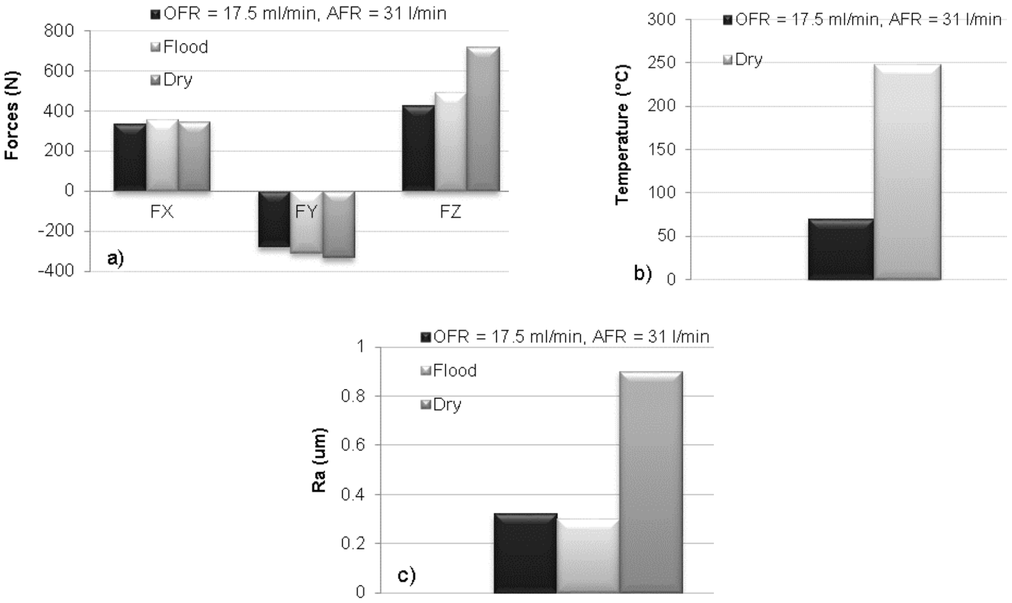


Figure 10: MQL Comparison of MQL, flood and dry cutting in machining performance in terms of a) cutting forces, b) Temperature and c) surface roughness [51].

3.0 VIRTUAL MACHINING

In recent years, with the rapid development of high-performance computers, virtual system has many applications in manufacturing fields, such as Virtual Machine Tool (VRT), Virtual Machining (VMach), Virtual Assembly (VA), Virtual Tooling (VTo), and Virtual Prototyping (VP) [53]. This section focuses on the virtual machining, and provides a comprehensive review, the key factors and typical applications of the VMach technology.

3.1 Key Factors in Modelling of Machining Processes

The object of virtual machining is to understand the cutting process through computer modelling and simulations prior to physical machining on the shop floor, in order to reduce the lead time and waste, and to determine optimum cutting conditions. The cutting process can be modelled as a function of workpiece material, tool geometry and material, and cutting conditions.

Finite Element Analysis (FEA) has been considered as a powerful virtual tool and is widely used to simulate complex machining processes. However, the key bottle neck is to model the flow stress of the workpiece material as a function of the high strain, high strain rate, and temperature experienced in cutting processes [54], which is referred as the material constitutive law. The unique features encountered in the cutting process include the severe deformation (high strains, up to 500%) that takes place at high temperatures (up to 1000 ℃) and high strain rates (up to 10^6 s^{-1}) in very small deformation zones [55], including the primary and the secondary shear zones as shown in Figure 11. This causes the mechanical behaviour of the workpiece material during the cutting process to be far different from that observed in conventional material tests. It has been demonstrated that the orthogonal cutting tests at room and high temperature in conjunction with the Distributed Primary Zone Deformation (DPZD) model can generate a wide range of constitutive data (strain, strain rate and temperature) encountered in machining [56,57]. Based on the constitutive data and the evaluation criteria of the constitutive law formulation, more reliable and accurate constitutive laws can be identified. A couple of material constitutive laws have been successfully identified using this methodology, such as Ni-alloy, Ti-alloys, Al-alloys and TiMM composites [58, 59].

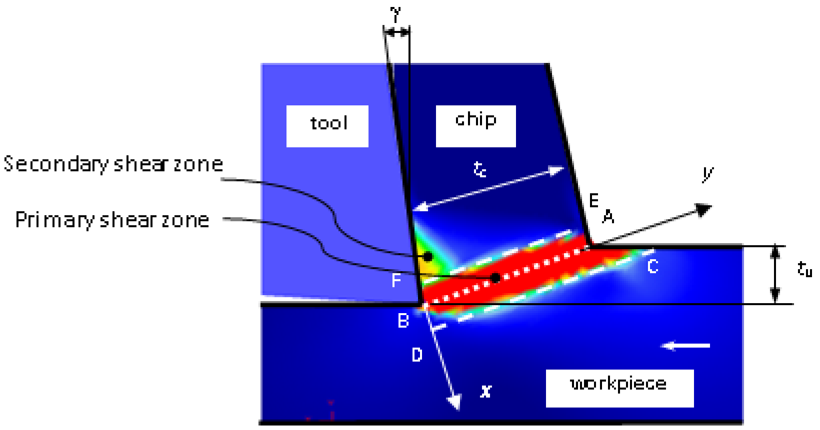


Figure 11: Primary and secondary shear zones in the orthogonal cutting process from FEM [55] (V- cutting speed, t_u- uncut chip thickness, t_c- chip thickness, γ- rake angle).

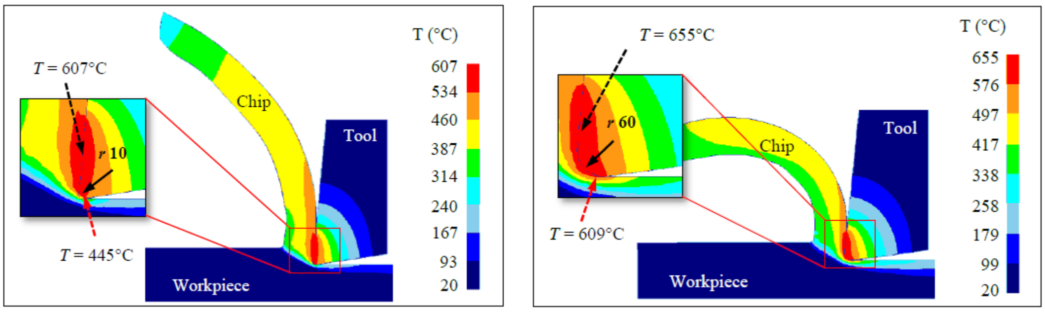
In addition to the material constitutive laws, the friction mechanism and thermal interaction at the chip-tool interface under the severe operating conditions is also very complex and needs special attention. It has great impacts on the simulation results. Two basic friction models, the Coulomb friction model and the shear friction model with a uniform frictional coefficient or shear friction factor were commonly applied in the simulations of the cutting process [60, 61]. However, these simplified friction models cannot explain the experimental results measured from the cutting test using the split tool technique [62, 63]. The experimental results show that the frictional stress approximately sustains a uniform value in the region close to the tool tip and then decreases to zero at the tool-chip separation point. Based on this experimental observation, a friction model with variable coefficients was proposed by Shirakashi and Usui [64]. Experimental results have shown that the Usui's friction model with the thermal-constriction based heat transfer model can more accurately model the thermal and tribological interaction between the tool and the chip during machining [59].

To simulate the cutting process with segmental chip formation, the material fracture/damage model should be carefully selected [64, 65]. Also, the material microstructure evolution model should be considered, which has potential influence on the cutting process, chip formation, residual stress and surface when the cutting temperature exceeds the material phase transformation start temperature [64, 67, 68].

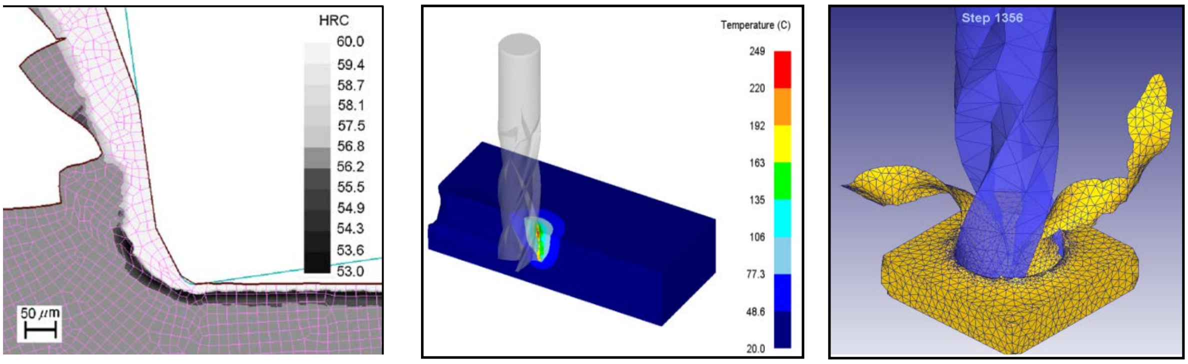
3.2 Virtual Machining Applications

In AML-NRC, virtual machining technology has been applied in many aspects, such as predictions of machining forces, chip formation, residual stresses and tool wear, simulation of tool coating and tool geometry effects. It is also applied in simulation of hybrid machining processes, such as laser-assisted machining process (LAM) [53, 63] and vibration-assisted machining (VAM), in order to optimize the process parameters including the laser power and spot size, as well the vibration amplitude and frequency. Figure 12 shows some examples of these applications.

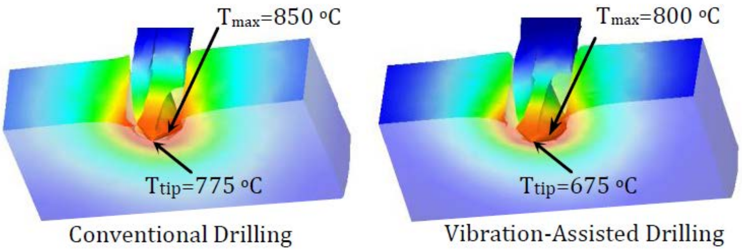
Recently, Carbon Fiber Reinforced Polymer (CFRP) composites are extensively used in aerospace applications due to their light weight and special strength. The CFRP composite has multi-ply structures with anisotropic thermal and mechanical properties. These unique features are very different from metals, which make modelling of CFRP machining very difficult and challenging. The AML-NRC team developed a hybrid analytical-FEM based model to simulate drilling of CFRPs. Based on the predicted forces and temperature fields, the material delamination and thermal damage, which are the major defects in drilling of CFRPs, were accurately evaluated [71, 72], as illustrated in Figure 13



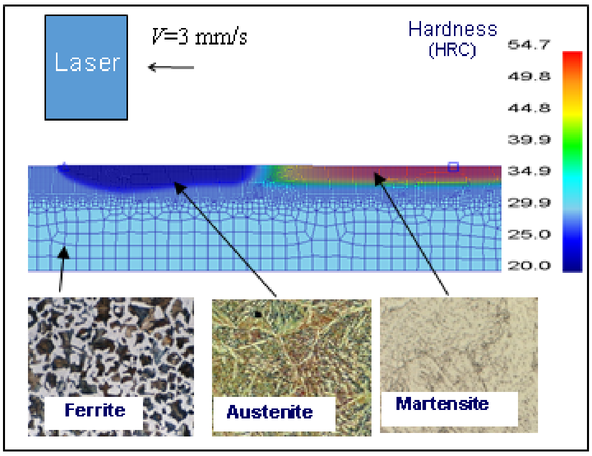
(a) Cutting edge effect on temperature field [60]



(b) Simulation of segmental chip with microstructural changes [VM15], as well milling and drilling processes

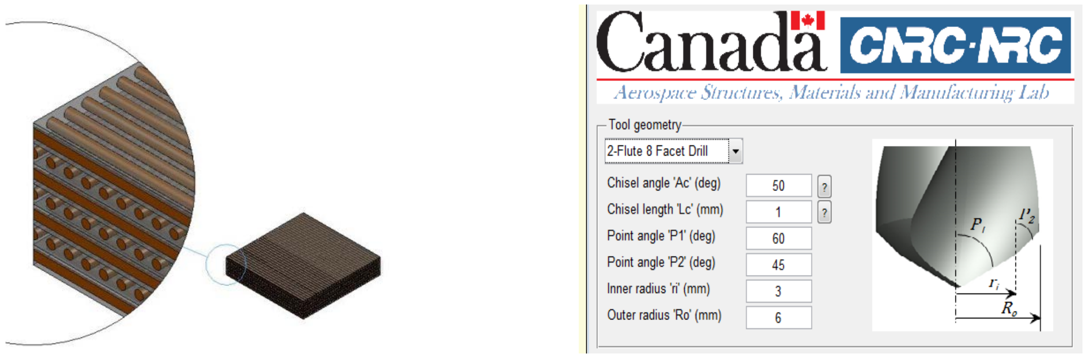


(c) Simulation of vibration-assisted drilling (VAD)



(d) Modellin of microstructure evolution inr laer heating process

Figure 12: Virtual machining applications



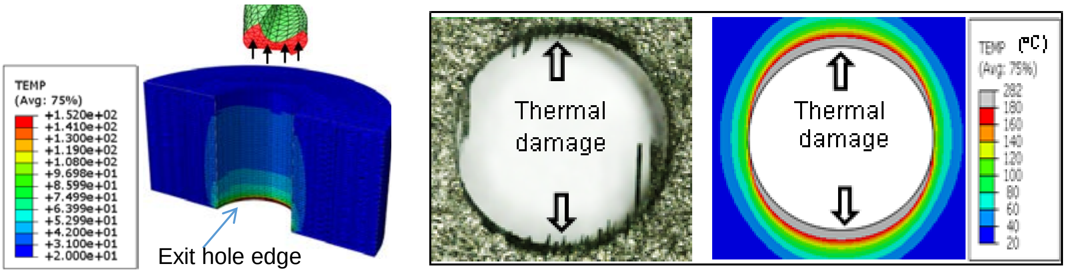
Tool geometry

2-Flute 8 Facet Drill

Chisel angle 'Ac' (deg) 50
Chisel length 'Lc' (mm) 1
Point angle 'P1' (deg) 60
Point angle 'P2' (deg) 45
Inner radius 'ri' (mm) 3
Outer radius 'Ro' (mm) 6

(a) Multi-ply structure of CFRP

(b) Virtual system interface



(c) Prediction of temperature field

(d) Comparison of prediction with test result

Figure 13: Simulation of drilling of CFRP composites [72]

CONCLUSION

The paper presents an overview of the recent developments in the area of machining that contributes to the increase in productivity while respecting the environment. To increase productivity, two technologies were discussed namely the Laser-assisted machining and super-abrasive grinding. Minimum quantity lubrication was presented given its low impact on the environment and the potential to improve the tool performance and part quality. Finally, it was essential to show some of the advances in virtual machining to closely represent the process environment thus allowing proper optimization and process characterization.

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