Paradigm Shift Towards Integrated Sustainability and High Performance Machining

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Abstract The environmental impact of machining is presented in terms of the damage to human health, ecosystem quality, and resources. To reconcile the conflicting requirements of economic growth and environmental protection, a paradigm shift towards integrated sustainability and high performance machining is discussed in the light of the new industrial revolution I5.0. Implementation of the sustainability strategy showed that the use of innovative and eco-friendly cooling/ lubrication methods in machining can significantly reduce the environmental impact and improve productivity, part quality, and process economics at the same time. Implementation of the resilience strategy, through a cyber-physical adaptive control system, showed up to 50% and 35% of combined reduction in the production cycle time and cost, respectively, as well as extending the tool life and eliminating the part damage.
Keywords: paradigm shift, sustainability, machining, cyber-physical system, adaptive control

1. Introduction

Machining is the largest class of manufacturing activities, and the final step in the process chain, providing dimensional accuracy, surface quality and other quality attributes. It claims up to 65% of all manufacturing processes, and the cost associated with it can exceed 65% of the product cost. Industry continuously pursues high speed machining to increase productivity and reduce cost [1]. This, however, leads to rapid tool wear, which is responsible for up to 20% of the total machine down time. In addition to energy and material consumption, machining is a source of emission of harmful substances that affect the environment and human health.

2. Environmental Impact of Machining

Machining has a direct effect on the environment and workers' health, as demonstrated by the harmful effect of cutting fluids, for example [2]. Oil-based cutting fluids consume oil resources, and generate toxic emissions during their production, leading to air pollution. Other hazards include environmental pollution due to chemical breakdown of the cutting fluid at high cutting temperatures, energy consumption to operate auxiliary systems, and water pollution and soil contamination during the final disposal. Many cutting fluids contain chlorinated paraffin, which is transformed into dioxin, which is toxic and carcinogenic. Skin exposure to cutting fluids is responsible for approx. 80% of all occupational hazards caused by skin contact with fluids [3].

3. Paradigm Shift Towards Sustainable Machining

3.1. Framework of the Paradigm Shift

The emerging industrial revolution I5.0 can set the ground for the framework of sustainability and high performance machining since it reinforces the role of industry to the society and the wellbeing of the workers [4]. The main strategies of the paradigm shift are the three pillars of I5.0, namely, sustainability, resilience, and human-centricity.

I- The sustainability strategy:

This strategy is based on the principles of comprehensive environmental sustainability, energy, and materials conservation, and linking the process development to the product life cycle management. With this mindset, the following key technologies need to be developed further and implemented in an industrial setting:

1- Reducing the use of cutting fluids to reduce hazardous mist produced during cutting and the waste in landfills. Optimized minimum quantity lubrication (MQL) and cryogenic machining (CM) were shown to improve the process performance, part quality, and reduce the cutting energy and the environmental impact [5,6]. The boundary film for(Leidenfrost effect) and its effect on enhancing liquid nitrogen (LN2) lubricity and reducing its cooling capacity is not well understood and needs further investigation. A physics-based simulation of the fluid-structure interaction using FE and CFD analyses also needs to be developed to design delivery systems of LN2 in confined space and through rotating tools, as in milling and deep hole drilling. Presently there is no commercial tooling concept for such applications. This simulation capability will allow assessing the product life cycle performance by designing the machining process to control the induced residual stresses, and micro-structure evolution to enhance the functional performance of the part, e.g., fatigue strength, as well as reducing production cost.

2- Another enabling technology that needs further development is the integration of additive and subtractive manufacturing (ASM) processes for near net-shape (NNS) manufacturing. Such a technology can significantly reduce energy and material consumption.

II- The resilience strategy

This strategy requires the development of interdisciplinary technologies that support creating cognitive cyber-physical systems (CCPS) to blend physical components and computing devices and to enable artificial intelligence (AI) based solutions. This strategy should ensure that each component in the CCPS is independent in making its own decision and has cognitive skills for perception, communication, and collaboration [7], building on advancement in generative artificial intelligence, and quantum computing. Other technologies to be developed specifically for machining include:

1- Real-time process and tool condition monitoring (TCM); wear and sudden tool pre-failure detection using advanced AI and deep machine learning techniques [8] and wireless sensor-based smart tooling. The data-driven training of the TCM system needs to advance to account for the variability of the signal features due to the physical phenomena that take place during the cutting of various classes of materials, e.g., metal matrix composites, biomaterials, and additively manufactured parts.

2- Robotized machining: Manual finishing operations, e.g., polishing, cause repetitive stress injury (RSI) of the worker. Robotized machining can eliminate these ergonomic hazards and improve the consistency of the part quality. This technology has the potential to perform rough machining operations, if reliable multi-body numerical dynamic models are developed to integrate the robot and the process dynamics to simulate the system behaviour along optimized cutting path. Robotized machining can be augmented with cryogenic cooling to reduce cutting forces and improve the system dynamic stability. The use of other collaborating robots to perform hybrid processes, such as drilling/riveting, can satisfy two or even the three I5.0-based strategies at the same time.

3- Offline-online optimization and adaptive machining can improve productivity, part quality and tool life. This technology can easily be incorporated in a cyber-physical system CPS platform, which was shown to improve productivity by up to 45%, and when integrated with a TCM, the production cost can be reduced by up to 25% [9].

4- Physics-based constitutive models for anisotropic, and graded materials need to be developed and combined with artificial intelligence (AI) and swarm intelligent (SI) techniques to improve CCPS' adaptability, and scalability.

III- The human-centric strategy

This strategy ensures the transition away from a digital-driven paradigm towards a more society-centric approach. Enabling technologies that supports this strategy include collaborative robots that work together with humans, and brain-machine interface (BMI) technology that enables the worker to control an external device using brain signals. These technologies have unlimited impact on the realization of sustainable manufacturing.

3.2. Effect of the Sustainability and Resilience Strategies on Machining Performance

This section presents the current research work carried out by the author and the research team at the NRC Canada and McGill University, demonstrating the effect of sustainability and the resilience strategies on machining.

3.2.1. Sustainability Strategy in Machining

SimaPro software was used to carry out a life cycle impact assessment (LCIA), in terms of three damage categories: human health, eco-system quality, and resources. The analysis produces a single-valued indicator 'EI-99' [10]. The higher the EI-99 value, the worse is the environmental impact. The case of machining 10 kg of Al-6061 using three lubrication/cooling methods of flood, MQL, and dry cutting was investigated. The MQL and flood cooling flow rates were 10 mL/h and 6 L/min, respectively. The lubricant used was triglyceride and propylene glycol ester solution. For waste treatment, the Al-6061 material and the cutting fluid were assumed to be 100% recycled.

The assembly network and the single score result 'EI-99' of the LCIA analysis for various cooling methods are shown in Fig. 1. While flood cooling generates an EI-99 score of 12.40, MQL and dry cutting generate a score of EI ~ 0.58, i.e., more than 20 folds smaller. The effect of the cooling method on the damage category of human health, for example, showed that the damage caused by flood cooling is more than two orders of magnitude greater than MQL and dry cutting. Although dry cutting and MQL showed similar environmental impact, the thermal softening of work piece material in dry machining causes considerable increase in energy consumption, higher tool wear, and poor surface quality. The milling tests that were carried out on Al-6061 using carbide milling cutters showed that the tool could not support the temperature rise in dry machining at a f= 0.15 mm/rev, and cutting speed V= 160 m/min. In this case, the material melted down and stuck to the tool and the workpiece and parts of the tool was broken. The temperature reached 800^{o}C at the failure point. In comparison, MQL showed insignificant tool wear at a much higher speed, V= 400 m/min (150% increase in material removal rate MRR). The MQL reduced the temperature at the cutting edge by approx. 75%.

The effect of combining LN2 cryogenic cooling and MQL in cutting Ti-Al6-4V was recently examined [11]. Figure 2(a) shows that using this hybrid cooling method increased tool life by a factor of 2.8 and 2, and 1.12, compared to flood, cryogenic cooling, and HPC, respectively. The inserts used in flood and cryogenic cooling experienced sudden tool fracture, causing damage to the part. Figure 2(b) shows that LN2 and hybrid cooling produced surface compressive residual stresses of approx. −100 MPa. This state of stress improves the part fatigue strength under dynamic loading. Flood cooling, on the other hand, created unfavorable surface tensile stress of around +100 MPa.

3.2.2. Resilience Strategy in Machining

A cyber-physical adaptive control system (CPACS) was developed and tested for the challenging process of drilling a stack of 3 layers (L1 and L3: CFRP composite, and L2: Al-7075) [12]. This system integrated the following: (a) an adaptive control system (ACS), (b) a real-time tool condition monitoring system (TCMS) to detect the tool wear level, (c) a generalized force and damage prediction model, (d) an offline model-based tool life optimization module, and (e) a techno-economic for decision making. Figure 3 shows the layout of the CPACS. The generalized drilling model (Box 3) predicts the cutting and axial forces F_c and F_z in the stack layers. By comparing F_z to a pre-defined force limit F_{cr} for each layer in the feedrate optimization (Loop 1), a decision is made to either keep or change the feedrate $f_{J,L}$. The optimized feedrate for each layer $f_{O,L}$ is then communicated to the CNC controller (Box 1). During cutting, *VB* is detected (Box 2) at each hole through feature extraction from the spindle power feedback signal. The actual feed and spindle speed, and the detected *VB* are transferred to the online ACS (Box 3) to adjust the feedrate to the highest allowable level (Loop 1). The decision-making module (Box 4) determines whether to maintain or modify the feedrate *f*, and if it is economical to reduce *f* or change the tool. Figure 4 shows the system performance in controlling the feedrate in layer L3 to maximize the tool life, without exceeding F_{cr}. A total of 740 holes with acceptable hole quality were produced using a single tool. The figure depicts the validated case of acceptable delamination level ($\phi < 0.05$) when *VB*= 135 µm and the feedrate was reduced by the ACS to 0.05 mm/rev. In the absence of the ACS, considerable delamination, $\phi = 0.53$, was observed at *VB*= 135 µm and $f = 0.075$ mm/rev. The figure also shows that the tool wear *VB* predicted by the TCMS was in good agreement with measured values. The CPACS performance was compared to four drilling strategies (S1 to S4) that produced the same number of holes. In strategy S1, the tool change was not allowed, and *f* was kept constant ($f = 0.042$ mm/rev) for all stack layers to keep *VB* < 200 µm. In strategy S2, a single tool change was allowed and the initial feedrate, before off-line optimization, $f = 0.075$ mm/rev was maintained for all stack layers. Strategy S3 was similar to S2, but two premature tool changes were allowed to simulate the commonly followed practice. Strategy S4 used the off-line optimum cutting conditions ($f = 0.147$ mm/rev for the CFRPs, and $f = 0.075$ mm/rev for Al-7075) and allowed multiple tool changes. Compared to strategies S1 to S4, the activation of the CPACS reduced the cycle time by 13%, 49%, 10% and 1%, respectively. The corresponding reduction in cost was estimated to be 51%, 34%, 35% and 77%, respectively. This shows the high performance machining associated with the CPACS implementation. Additionally, CPACS doubled the tool life and eliminated the part damage observed with conventional machining.

4. Concluding Remarks

The framework for a paradigm shift towards integrated sustainability and high performance machining, based on I5.0, was presented. Implementation of the sustainability strategy showed that the use of innovative and eco-friendly cooling/lubrication methods can reduce the environmental impact by more than 20 folds, while improving productivity, part quality, and process economics. Implementation of the resilience strategy, through a CPAC system, showed up to the 50% and 35% of combined reduction in the production cycle time and cost, respectively, as well as doubling tool life and eliminating the part damage observed in conventional machining.

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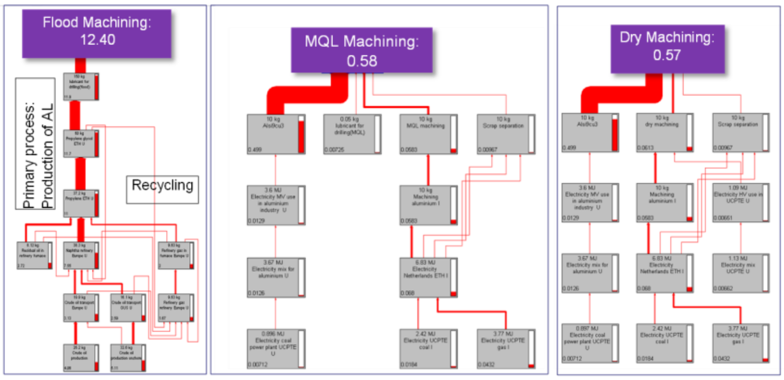

Figure 1. LCIA assembly network for machining Al-6061using three cooling/lubrication methods

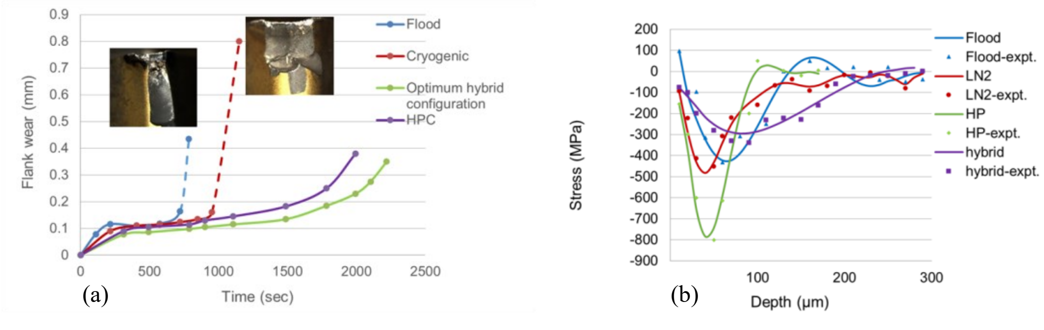

Figure 2. (a) progressive tool wear, and (b) residual stresses in the surface and subsurface layer for the tested cooling methods (turning at 56 m/min cutting speed, 0.2 mm/rev feed rate and 1.5 mm radial depth of cut) [11]

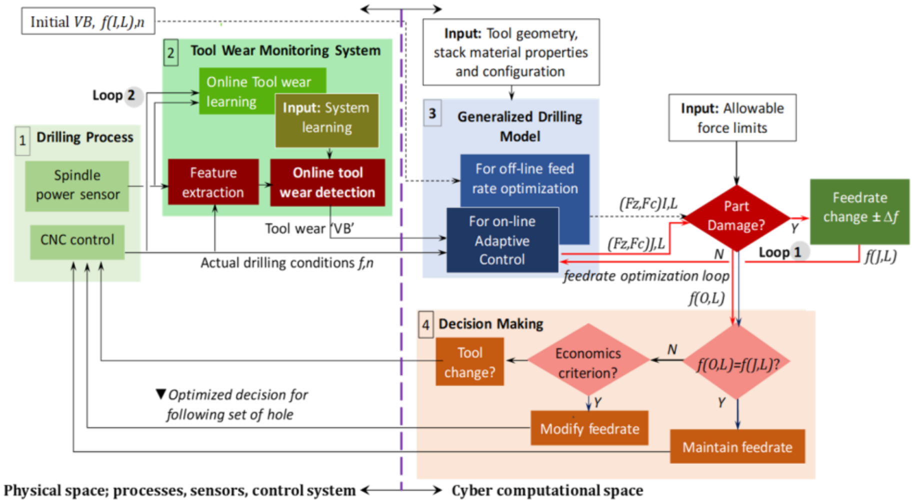

Figure 3. Layout of a new CPAC system approach [12]

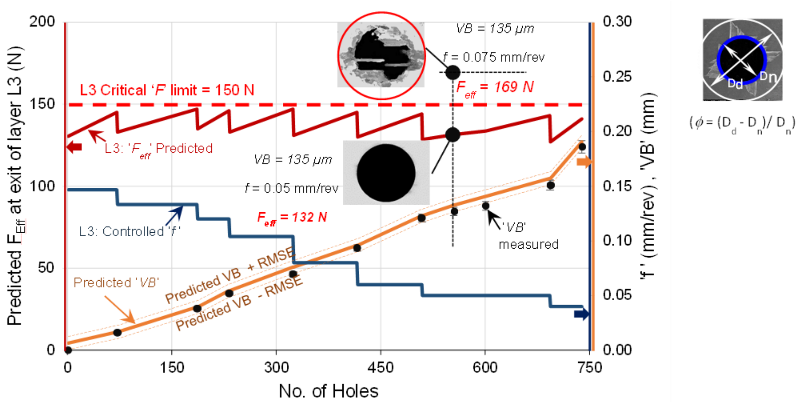

Figure 4. CPAC system performance curve with experimental validation of VB and delamination predictions at the exit plane of L3-CFRP [12]

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