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ORIGINAL PAPER

Surface conditioning in machining: optimizing component performance through advanced process modeling and control

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Abstract
This Special Issue showcases a broad spectrum of fundamental research targeting the in-line measurement and assessment of surface conditions in machining operations. It presents and discusses various measurement approaches, including those based on acoustic emission, micromagnetic fields, the Seebeck effect, and other techniques. These methods are explored for their effectiveness in assessing and ensuring the quality of machined surfaces. The collected research delves into surface modeling techniques and investigates diverse strategies for predicting the effects of process parameters on surface integrity. It also focuses on the strategic selection of these parameters to enhance final component performance. There is a significant emphasis on the evolution of in-process control methods, which are crucial for elevating the quality and functionality of machined surfaces and facilitating unmanned manufacturing. These advancements are instrumental in improving manufacturing efficiency and augmenting the quality of the final products.

Keywords Surface integrity · Surface engineering · Surface conditioning · Soft sensor · Process control

1 Introduction

The functional performance of manufactured components is significantly influenced by their process chain, especially by their finishing or semi-finishing machining processes. The surface layer experiences a series of transformations during these machining processes, which directly impact its mechanical properties. These properties, essential to a component's overall attributes, stem from a confluence of the component's geometric design, the inherent qualities of the bulk material, and the alterations within the surface layer induced by manufacturing processes. Functional properties are thus discernible through precision functional testing. The seminal work of Field and Kahles in 1964 introduced the concept of "surface integrity" to underscore the significance of material characteristics, especially those of the modified surface layer, in influencing functional properties. They conceptualized surface integrity as the natural or improved state of a surface following machining or similar surface-generating processes, and provided a comprehensive catalog of modifiable surface layer characteristics. This concept has become a cornerstone in understanding and optimizing the performance of machined components. [1]

This surface layer is pivotal in defining a component's performance under conditions such as cyclic stresses, influencing its tribological properties and corrosion resistance, among others. The emphasis on Surface Integrity is essential for grasping the connection between the physical properties of machined components and their functional performance, as highlighted by Jawahir et al. on surface integrity [2]. Predictive modeling becomes instrumental in guiding the modification of machining process parameters, like feed rate and cutting speed, to achieve specific thermo-mechanical load distributions. These models integrate known and measurable disturbance factors, including tool wear and variations in workpiece initial state.

The implementation of adaptive control systems allows for real-time adjustments of process variables in response to measured or estimated disturbances, as discussed in Stampfer et al. on surface conditioning in machining [3]. The shift towards function-oriented and unmanned manufacturing marks a significant transformation in traditional manufacturing practices. Smart machinery is diminishing the dependence on highly skilled manual labor while

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facilitating the production of components with superior mechanical properties, thereby enhancing the sustainability of the manufacturing process and the component itself. This requires a shift in the mindset and culture among manufacturing professionals, encouraging them to adopt investigative methodologies typical of material science fields. Such an approach is vital for advancing precision in machining processes and optimizing component performance.

2 DFG Priority Programme Surface Conditioning (SPP2086)

In the present special issue, the majority of contributions originate from German production technology institutes involved in the DFG Priority Programme 2086 "Surface Conditioning in Machining," coordinated by the authors. This programme integrates approaches from machining, metrology, material science, and simulation. All of these are dedicated to the stated goal: optimizing the surface layer state after machining to improve component properties. This involves a process control that specifically targets the surface layer properties in machining processes based on a soft sensor. This soft sensor predicts process parameters and surface layer states during and after machining through a combination of in-process measurements and approaches based on both physical and data-driven models. The soft sensors can identify surface layer properties that are not immediately accessible in the process and can compensate for disturbances caused by material, tool, or process factors. This ensures that the surface layer properties, and thus functional properties such as fatigue strength or tribological characteristics, are maintained. The control loop of DFG priority programme 2086 "Surface Conditioning" is depicted in Fig. 1.

2.1 In-process measurement of Surface Layer States

Typically, surface characteristics are assessed through indirect measurement principles, which are suitable for surface control without the need for feedback. These principles facilitate non-contact and non-destructive evaluation of surface topography, as well as microstructural and mechanical properties. Tactile measurements are commonly used for assessing surface topography, but they have limitations like prolonged measurement times and the requirement for slow relative velocities between sensor and workpiece, complicating their integration with on-machine processes. Optical devices, such as confocal light microscopes, offer non-contact topography measurements, though they demand stable ambient light conditions and are sensitive to vibrations and the presence of metalworking fluids on the workpiece [4]. Scatter light methods present another viable option for non-contact surface measurement, with coherent light sources providing spatially resolved roughness data and incoherent light sources offering mean roughness information, the latter being easier to integrate and evaluate on-machine [5]. For microstructural and mechanical surface characteristics, traditional measurement techniques like electron microscopy, x-ray diffraction, and electron backscatter diffraction are often costly, time-consuming, and inherently destructive [6]. Consequently, the non-destructive, indirect measurement of these characteristics via micromagnetic testing, such us Eddy current tests or Barkhausen noise, has become prevalent in manufacturing [7]. Despite these advancements, surface control without feedback remains challenging due to complex mechanisms and the presence of both known and unknown disturbance variables. Continuous measurement of target surface characteristics with appropriate cycle time is essential. To this end, the integration of measurement techniques directly into the manufacturing process is preferred for continuous surface control. Figure 2 depicts various options for integrating these measurement techniques into the process, highlighting the strategic incorporation of surface characterization into manufacturing workflows.

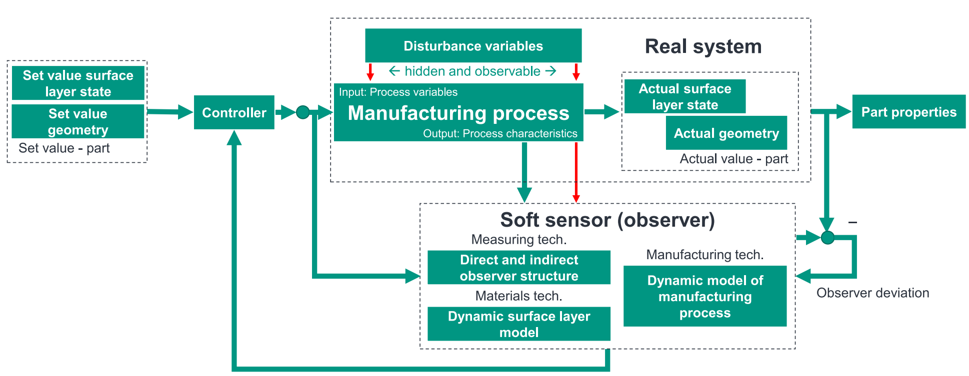

Fig. 1 Process control loop of the DFG Priority Programme 2086. Generic scheme of a surface focused process control [3]

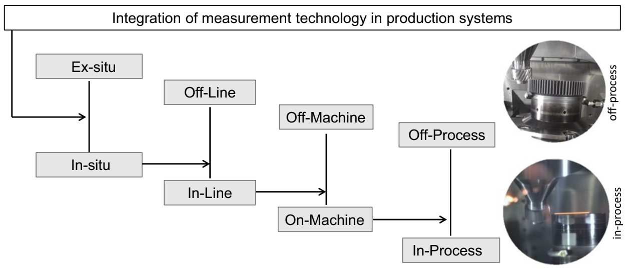

Fig. 2 Nomenclature for measurement integration in production systems, adapted from [8]

The measurement methods featured in this special issue are detailed in Table 1.

2.2 Process control for targeted setting of surface layer states

The recent trend in manufacturing aims to develop intelligent, self-adjusting, and unattended machining systems to enhance productivity. This shift has significantly advanced methodologies beyond traditional empirical approaches, which primarily focus on establishing correlations between machine tool behavior, process parameters, and potential disturbances to influence the resultant geometry and surface quality. State-of-the-art applications now include tool failure detection and adaptive process control. These innovations modify feed drive or spindle speed by utilizing measurements of spindle power, process forces and torque, showcasing the potential of process control through soft sensors and representing an evolution in machining technology [9]. A step further, the concepts of controlled functional properties and engineered surfaces pivot on a mechanism-based hypothesis. This hypothesis claims that the intrinsic thermal and mechanical loads exerted by the machining process are decisive in determining the state of the surface layer. This conceptualization is augmented by the integration of available sensors and computational models, including the previously mentioned soft-sensors. These tools facilitate the in-process acquisition of real-time data regarding the current state of the surface layer. A significant challenge that remains is the ability to respond to deviations detected during the machining process and to actively modulate the process to ensure specific surface layer characteristics, thereby guaranteeing the desired functional properties of the machined component. Figure 3 illustrates a control schema adopted by numerous contributions in this special issue. These research efforts employ the previously described measurement methodologies for in-situ measurement and utilize process information as input for soft sensor models capable of assessing the current state of surface integrity of the component and forecasting the necessary adjustments of process parameters to achieve optimal surface layer conditions, aiming for the unmanned manufacturing of engineered surfaces.

Table 1 Classification of measuring techniques in this special issue

Thin-film-system	Tool-integrated thin-film sensor system for measurement of cutting forces and temperatures during machining
3MA system	Soft sensor for in-line quality control of turning processes based on non-destructive testing techniques and advanced data fusion
Acoustic emission	Classification of the machine state in turning processes by using the acoustic emission
Barkhausen noise	Subsurface conditioning in BTA deep hole drilling for improved component performance
	Towards developing a control of grinding processes using a combination of grinding power evaluation and Barkhausen noise analysis
Scattered light	Control concept for the regulation of the surface properties using consecutive cuts in cryogenic hard turning of AISI 52100
Eddy current	A process-reliable tailoring of subsurface properties during cryogenic turning using dynamic process control
Temperature and acceleration	In-process approach for editing the subsurface properties during single-lip deep hole drilling using a sensor-integrated tool
Seebeck effect	Methodology for soft-sensor design and in-process surface conditioning in turning of aluminum alloys
High-speed imaging	Digital process twins: a modular approach for surface conditioning and process optimization
Diffractometer	3D residual stress modeling in turning of AISI 4140 steel
	Data-driven prediction of the surface layer state in hard-turning for optimization of component quality
Force	Surface conditioning of zirconia ceramic by enhanced ultrasonic vibration-assisted burnishing

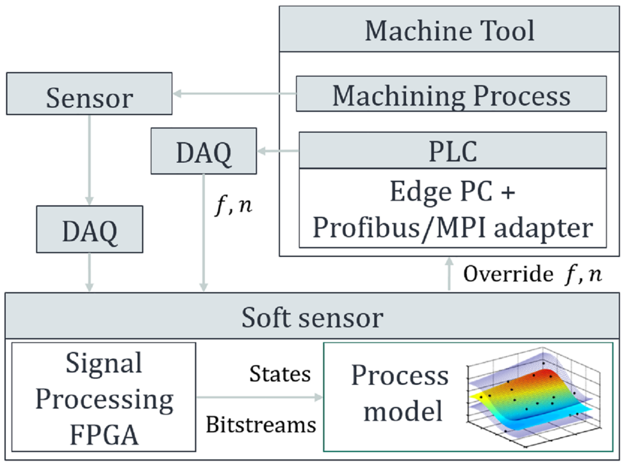

Fig. 3 Adaptive control scheme for surface engineering

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Data availibility No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The Authors declare that they have no conflict of interest.

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