

A Method for Real-Time Milling Monitoring Based on Tool Engagement Analysis in Hybrid Micro-Manufacturing

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Research Article

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A Method for Real-Time Milling Monitoring Based on Tool Engagement Analysis in Hybrid Micro-Manufacturing

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Abstract

Hybrid manufacturing technologies that combine additive and subtractive processes have emerged as a leading trend in recent years. However, surfaces produced by additive manufacturing are typically characterized by poor surface quality and frequently contain defects such as cracks. This insufficient surface integrity complicates accurate workpiece positioning, resulting in unstable tool engagement and variable cutting conditions during a single machining operation. This paper presents a method for estimating the degree of tool engagement, enabling both the detection of surface cracks and the monitoring of the radial depth of cut. The proposed approach does not require complex calibration procedures, and the derived indicator directly corresponds to the physical working conditions of the cutting tool. The method was experimentally validated using material discontinuities of varying widths, including a naturally delaminated surface, and for different values of radial depth of cut. Owing to its computational simplicity, the method is particularly suitable for real-time implementation and supports the concept of in-process quality control in hybrid manufacturing.

Keywords

Hybrid manufacturing; tool engagement; radial depth of cut; surface discontinuities; real-time monitoring; micro-machining

1. Introduction

Hybrid manufacturing technologies are becoming increasingly significant in modern industry [1]. These approaches enable the combination of advantages offered by both additive and subtractive manufacturing technique [2]. Additive processes allow for the fabrication of lightweight structures with complex internal geometries, while subtractive methods ensure high dimensional accuracy and superior surface quality in functionally critical regions interacting with other machine components [3].

The most widely used additive techniques in the context of hybrid manufacturing can be categorized into two main groups: powder-based methods, such as Selective Laser Melting (SLM) and Laser Direct Metal Deposition (LDMD), and wire-based methods, primarily Wire Arc Additive Manufacturing (WAAM) [4]. Powder-based techniques are characterized by thinner layer deposition, resulting in higher dimensional and geometric accuracy [5], whereas WAAM offers significantly higher volumetric deposition rates [6]. Among these approaches, Direct Energy Deposition (DED) methods,

including WAAM and LDMD, are particularly suitable for integration within a single manufacturing system. This is due to the fact that they do not require filling the entire working chamber with powder, but instead deliver material locally, directly to the region where energy is applied [7].

Despite their advantages, additive manufacturing technologies are inherently associated with poor surface quality [8], the presence of surface defects [9], and limited dimensional and geometrical accuracy [10]. Therefore, proper planning of the additive process is a critical step to ensure stable subsequent subtractive machining [11]. However, even with optimization of the additive process, the subtractive step of hybrid manufacturing is inevitably associated with fluctuating cutting conditions, particularly pronounced in micromachining [12]. Four key aspects of additively manufactured surfaces significantly influence the stability of subsequent machining processes: dimensional accuracy, surface defects, surface deformation, and the layered structure of the material.

The layered nature of the surface leads to cyclic variations in the depth of cut. In conventional machining with tools exceeding 1–2 mm in diameter, this effect is typically negligible. However, in micromachining with tool diameters below 1 mm, it results in noticeable force fluctuations [12]. Moreover, such a surface structure complicates the precise definition of technological datum, as the physical definition of a reference plane becomes ambiguous [13]. In addition, limited dimensional accuracy, resulting from the mechanics of external wall formation, and surface deformation caused by residual stresses affect not only tool positioning accuracy but also lead to real-time variations in radial depth of cut during machining [14]. For small radial depths of cut and micro-scale tool diameters, this may even result in a complete loss of contact between the tool and the workpiece (air milling). Finally, machining across surface defects, such as cracks, not only adversely affects cutting conditions but may also indicate the need for part regeneration or rejection [15], [16].

Due to the numerous sources of deformation and defects inherent to additively manufactured components, process monitoring techniques for additive manufacturing have been rapidly developing. Kanonenko et al. [17] proposed a method for crack detection during the additive process based on acoustic emission signals. However, more widely adopted approaches rely on image-based analysis [18]. For instance, Charalampous et al. [19] developed a system capable of real-time evaluation of dimensional accuracy during additive manufacturing process, which is consistent with the principles of in-process quality control approaches [20].

Nevertheless, in an integrated manufacturing environment, any undetected defects, as well as dimensional and geometrical deviations, are propagated to the subsequent subtractive stage. To mitigate this issue, intermediate quality control procedures are typically employed [21]. However, in integrated hybrid manufacturing systems, interrupting the process for quality control contradicts the fundamental concept of process integration. Therefore, an effective alternative is the implementation of in-situ machining process monitoring systems, which enable in-process evaluation without disrupting the hybrid manufacturing process [22].

In machining process monitoring, the most commonly developed systems focus on tool wear detection [23], [24] and surface roughness evaluation [25], [26]. Cutting forces [27] and vibration signals [28] are the most frequently utilized data sources in such approaches. Nevertheless, several studies in the literature address the problem of cutting depth monitoring.

Prickett et al. [29] proposed a system for measuring depth of cut based on ultrasonic distance sensors. Lee et al. [30] developed a method in which both depth of cut and tool runout are determined through frequency-domain analysis of cutting torque. Liao et al. [31] introduced an approach for monitoring chip formation and depth of cut using acoustic emission signals. Additionally, recent studies have explored the application of neural networks for analysing cutting forces in order to assess the degree of tool engagement [32], [33].

Such systems would enable compensation for workpiece clamping errors arising from the poor surface quality of additively manufactured parts. Currently, misalignment of the workpiece leads to variations in tool engagement. By actively monitoring the degree of engagement, it becomes possible to compensate the toolpath accordingly. Furthermore, such a system would allow for the detection of surface deformations, which in extreme cases may result in air milling. Additionally, it could facilitate the detection of surface defects during the subtractive stage, effectively complementing and reinforcing quality control procedures applied in the additive manufacturing process.

This study presents a method for determining tool engagement during the cutting process. Furthermore, the proposed solution is specifically designed for real-time operation while maintaining low computational requirements. The proposed method enables monitoring of both the radial depth of cut and the presence and geometry of surface discontinuities.

2. Methodology

The method proposed in this study is intended to detect and describe discontinuities in the machined material and determine the parameter of radial depth of cut basing on force signal. The method is based on definition of the level of active cutting-edge engagement in the cutting process. The approach relies on the analysis of cutting force signals with a distinction between the feed direction and the direction normal to the feed. Furthermore, the method is based on the decomposition of tool kinematics into the motions of individual cutting edges within the active half-rotation of the tool.

The method is designed for real-time applications, particularly in machining process monitoring systems and in-process quality control solutions for hybrid manufacturing processes. Using the proposed approach, it becomes possible to detect cracks in the manufactured component during the subtractive machining stage and compensation of errors arising from inaccurate datum definition on additive manufactured surface. The following sections describe the main principle of the method, the mathematical framework, and its geometrical interpretation. The outline of the proposed solution is presented in Figure 1a.

107 This subsection outlines the main assumptions of the proposed method as well as the simplifications
 108 adopted during its development. All algorithms presented in this work were designed for implementation
 109 in real-time machining monitoring systems. This objective was achieved by simplifying the
 110 mathematical framework as much as possible and by eliminating force transformations.

111 The method is based on the analysis of cutting forces with a distinction between the feed
 112 direction (X) and the direction normal to the feed (Y). Forces recorded in the axial direction (Z) are not
 113 considered due to their relatively low magnitude and high susceptibility to noise. All forces are measured
 114 in the dynamometer reference frame, which is mounted on the workpiece side. No transformation of
 115 forces to the rotating tool coordinate system is performed, as such a transformation would require
 116 identification of the angular position of the tool at time t . It is assumed that the dominant contribution
 117 to the measured forces originates from the main cutting force F_c , which is related to the uncut chip
 118 thickness. Additionally, it is assumed that even at zero uncut chip thickness, non-zero forces may be
 119 recorded due to measurement noise. The procedure used to filter the influence of noise is described in
 120 the following sections.

121 The presented method is valid only for a two-flute cutting tool, and all considerations in this
 122 work are conducted under this assumption. This follows from the fact that, during slot milling, a two-
 123 flute tool always has exactly one active cutting edge at a given moment. Consequently, the equations
 124 presented in this work do not include the variable Z_{EFF} representing the number of effective cutting
 125 edges, as they are formulated in a reduced form corresponding to $Z_{EFF} = 2$.

126 Another assumption related to tool geometry concerns the helix angle λ . It is assumed that the
 127 cutting edge is not inclined, i.e., $\lambda = 0$. This assumption follows from the method used to determine the
 128 tool engagement angle φ_{en} . In the case of slot milling, this angle is assumed to be equal to π . If the helix
 129 angle is non-zero ($\lambda \neq 0$), there exists a moment t at which both cutting edges are simultaneously
 130 engaged in the cutting process (Fig. 1b).

131 The proposed method is not sensitive to changes in the axial depth of cut a_p , as it does not rely
 132 on the magnitude of the measured forces but only on the time intervals during which the forces are non-
 133 zero. A change in the axial depth of cut a_p affects the height of the uncut chip layer but does not influence
 134 its width h . It is therefore assumed that the occurrence of a zero chip cross-section results from a
 135 reduction in chip width h rather than from a reduction in its height a_p (Fig. 1c).

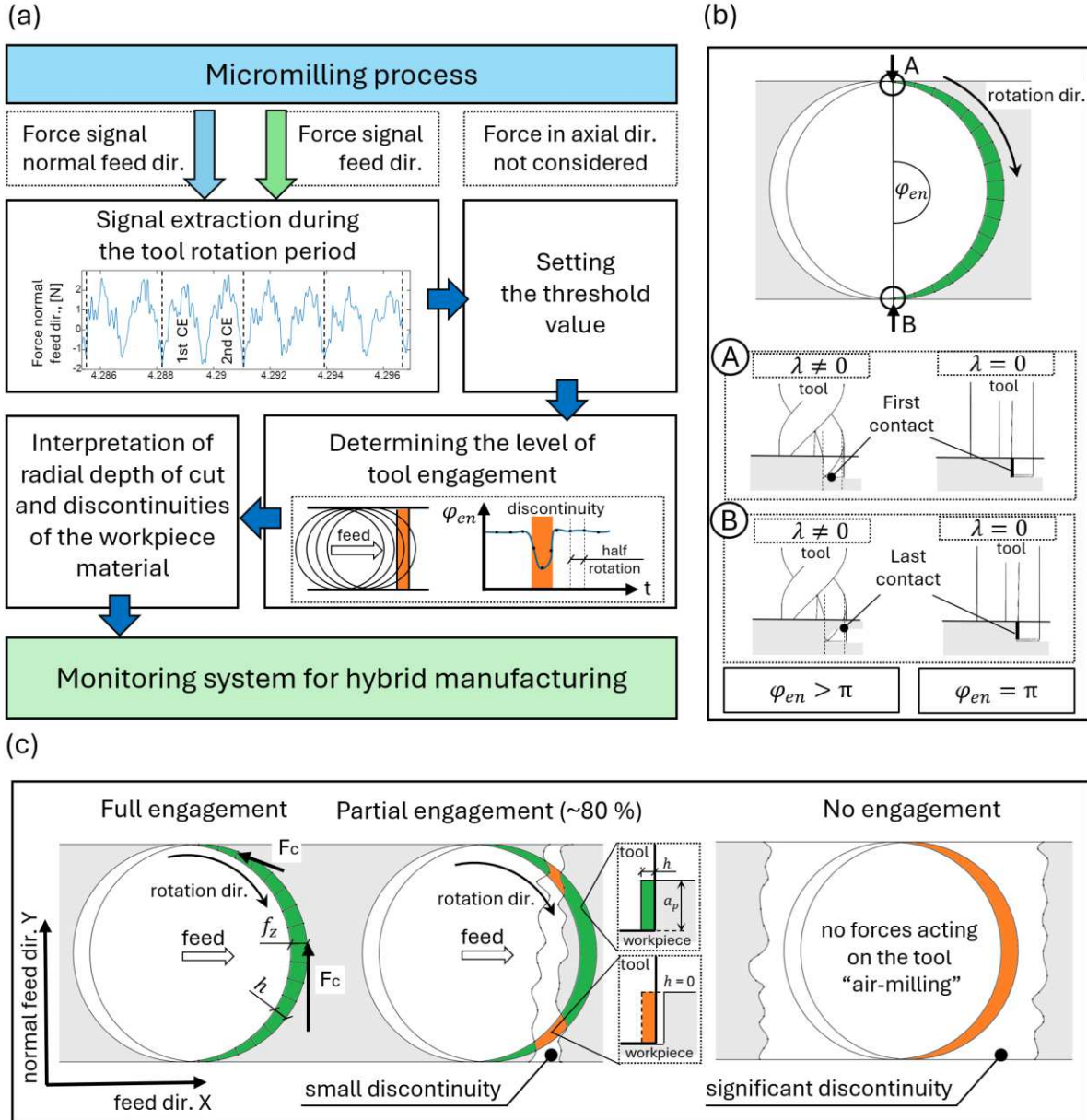


Fig. 1 (a) Outline of proposed approach; (b) helix inclination angle impact on tool engagement; (c) Percentage of tool engagement in discontinuity milling

2.2. Mathematical framework

First, the theoretical engagement time of the active cutting edge t_{en} must be determined. For a two-flute tool, this time corresponds to half of the tool rotation period (1). It is also necessary to determine the sampling period of the measurement system T_{dyn} (2). The value of T_{dyn} is calculated based on the sampling frequency f_{dyn} . The sampling period T_{dyn} is then used to determine the actual engagement time of a single cutting edge in the cutting process, denoted as t_{rel} .

$$t_{en} = \frac{30}{n} \cdot \frac{\varphi_{en}}{\pi} \quad (1)$$

$$T_{dyn} = \frac{1}{f_{dyn}} \quad (2)$$

Next, the threshold value of the cutting force F_{th} must be defined. In groove milling, the tool remains continuously engaged in the material (Fig. 2a). However, in side milling (Fig. 2b) or when machining discontinuous material (Fig. 2c), there are regions where cutting forces are not present. In theory, at a moment t when the tool is not engaged in cutting, the forces recorded by the dynamometer should be equal to zero. In practice, this is not the case due to the presence of noise and disturbances in the measurement system. Therefore, a threshold value F_{th} is introduced. When the measured force F_{reg} at time t does not exceed the threshold F_{th} , it is assumed that cutting does not occur and the uncut chip thickness h is equal to zero (3).

$$|F_{reg}(t)| < F_{th} \Rightarrow h(t) = 0 \quad (3)$$

It should be noted that the threshold value should be determined individually for each measurement setup. In this study, the threshold value was defined empirically based on the author's experience. The same threshold value was used for both the X and Y axes, $F_{th} = 0.2$ N. Additionally, force signals must be filtered according to condition (3) simultaneously in both axes. This means that if a sample is rejected in the X direction, it should also be rejected in the Y direction, and vice versa. This approach ensures that the number of samples remains consistent in both signals. Consequently, condition (3) should be reformulated as condition (4), where forces recorded in axes X and Y are denoted as F_{Xreg} and F_{Yreg} , respectively.

$$|F_{Xreg}(t)| < F_{th} \vee |F_{Yreg}(t)| < F_{th} \Rightarrow h(t) = 0 \quad (4)$$

Additionally, a dynamic reference level should be introduced, determined based on the mean value of the measured forces (5). This is related to the inherent tendency of piezoelectric sensors to exhibit force drift. The mean force values within a single buffer are denoted as $\bar{F}_{Xreg}$ and $\bar{F}_{Yreg}$, respectively.

$$\begin{aligned} & \left(F_{Xreg}(t) < \bar{F}_{Xreg} + F_{th} \wedge F_{Xreg}(t) > \bar{F}_{Xreg} - F_{th} \right) \vee \\ & \vee \left(F_{Yreg}(t) < \bar{F}_{Yreg} + F_{th} \wedge F_{Yreg}(t) > \bar{F}_{Yreg} - F_{th} \right) \Rightarrow h(t) = 0 \end{aligned} \quad (5)$$

Knowing the sampling frequency of the measurement system f_{dyn} , it is possible to determine the number of samples that should be contained in a buffer with a duration of t_{en} . This number is denoted as n_{dyn} and is calculated using Eq. (6). This relationship should be equivalent to the formulation given in Eq. (7). After applying the threshold filter, n_{th} samples remain in the buffer. Knowing the sampling period of a single measurement T_{dyn} , the actual time during which cutting occurs can be determined. This time is denoted as t_{real} and is calculated using Eq. (8).

$$n_{dyn} = f_{dyn} \cdot t_{en} \quad (6)$$

$$t_{en} = n_{dyn} \cdot T_{dyn} \quad (7)$$

$$t_{real} = n_{th} \cdot T_{dyn} \quad (8)$$

170 The share of cutting-edge engagement time, denoted as p_{real} , can be determined as the ratio of the actual
 171 engagement time t_{real} to the theoretical engagement time t_{en} (9). By substituting Eqs. (7) and (8) into
 172 Eq. (9), the sampling period T_{dyn} can be eliminated from the expression, resulting in the simplified form
 173 given in Eq. (10).

$$p_{real} = \frac{t_{real}}{t_{en}} \quad (9)$$

$$p_{real} = \frac{n_{th}}{n_{dyn}} \quad (10)$$

174 The buffer used to calculate the value of p_{real} has a duration equal to the theoretical engagement time
 175 of the active cutting edge t_{en} and contains n_{dyn} samples. The proposed algorithm is not sensitive to
 176 phase shifts of the buffer. Regardless of the tool rotational phase, the interpretation of p_{real} should
 177 remain the same.

178 In practice, a slight variation in the value of p_{real} may occur depending on the phase shift;
 179 however, each buffer always contains samples corresponding to one half-rotation of the tool. In a
 180 particular case, this half-rotation may be realized by only a single cutting edge. In the presented model,
 181 radial runout is not considered; therefore, it is assumed that the time t_{en} corresponds to the operation of
 182 two perfectly identical cutting edges. The phase shift problem is illustrated in Figure 2d.

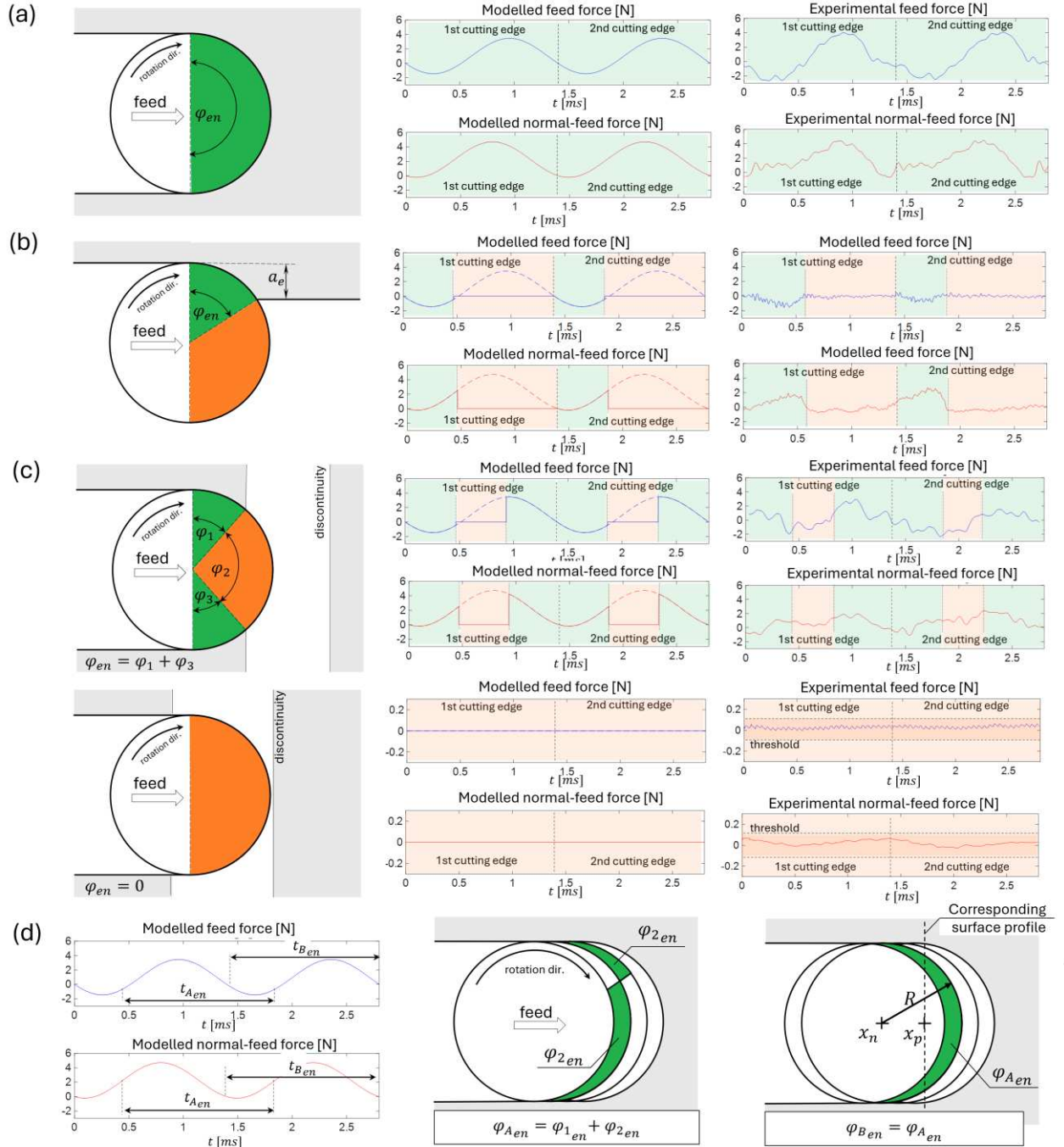


Fig. 2 Engagement of cutting edge while (a) groove milling, (b) radial immersion milling, (c) discontinuity milling; (d) the phase shift problem

2.3. Geometrical Interpretation

A single buffer, corresponding to the operating time of one active cutting edge, contains n_{dyn} samples. From each buffer, a single value of p_{real} is determined, representing the level of tool engagement in the cutting process. Assuming that the buffer starts at time t_{start} and ends at time t_{end} , the value of p_{real} obtained from the n -th buffer is assigned to time t_n , defined by Eq. (11). The determined value of p_{real} corresponds to the physical cross-section of the machined workpiece; therefore, it is necessary to

transform the analysis into the spatial domain expressed in length units. The position along the feed axis, x_n , at time t_n is calculated using Eq. (12), where the feed per tooth is denoted as f_z .

$$t_n = \frac{t_{end} - t_{start}}{2} \quad (11)$$

$$x_n = f_z \cdot n \cdot t_n \quad (12)$$

The determined value of x_n represents the position of the tool axis. The presented analysis is based on force signals acquired over one half-rotation of the tool. The trajectory of the active cutting edge follows a trochoidal path, whereas the cross-sectional profile of the machined material is linear. Therefore, it is assumed that the determined value of p_{real} corresponds to the surface profile that contains the geometric centroid of the theoretical uncut chip area (Fig. 2d). The centroid of the determined cross-sectional area is located at point x_p , whose distance from the axis of rotation can be calculated using Eq. (13), where A_t denotes the uncut chip area defined by Eq. (14).

It should be noted that the difference between points x_p and x_n does not affect the geometric interpretation of the width of the discontinuity, as it represents only a relative shift. This shift becomes relevant only when determining the position of discontinuity with respect to a reference point.

$$|x_p - x_n| = \frac{f_z \cdot (\pi \cdot R^2 - A_t)}{A_t} \quad (13)$$

$$A_t = \pi \cdot R^2 - 2R^2 \arccos\left(\frac{f_z}{2R}\right) - \frac{f_z \cdot \sqrt{4R^2 - f_z^2}}{2} \quad (14)$$

3. Experimental setup

All cutting experiments were conducted on a custom-built SNTM-CM-ZUT-1 machine. In all trials, a 1.5 mm diameter solid carbide end mill with an NXT coating was used. The helix angle was $\lambda = 46^\circ$, while the measured corner radius was $r_\epsilon = 28 \mu m$. The workpieces were manufactured using additive manufacturing technology from aluminium alloy 6061. The machining process was performed with a feed per tooth of $f_z = 10 \mu m$ and a spindle speed of $n = 21,000$ rpm. The axial depth of cut was set to $a_p = 100 \mu m$. Experiments were conducted across five categories corresponding to different tool engagement conditions. A summary of all machining cases is provided in Table 1.

During the experiments, cutting forces were measured using a Kistler MiniDyn Type 9256C piezoelectric dynamometer. The sampling frequency was $f_{dyn} = 204,800$ Hz. Surface topography measurements were performed using a Mitutoyo Quick Vision WLI optical measurement system, with an XY scanning resolution of $0.2 \mu m$.

Category	Description	Theoretical engagement φ_{en}/π
I. Slot milling	Slot milling, continuous undamaged surface	1.00
II. Radial immersion milling	Up-milling, undamaged surface, radial depth of cut: a) 0.30 mm b) 0.75 mm c) 1.05 mm	a) 0.29 b) 0.50 c) 0.63
III. Artificial discontinuity milling	Slot milling, artificially damaged surface; discontinuity length: a) 0.25 mm b) 0.50 mm c) 0.75 mm d) 1.00 mm e) 1.25 mm f) 1.50 mm g) 1.75 mm	a) 1.00 – 0.47 b) 1.00 – 0.22 c-g) 1.00 – 0.00
IV. Natural discontinuity milling	Slot milling on a naturally discontinuous surface (delamination from AM process); discontinuity length ~1.8 mm	1.00 – 0.00
V. Variable radial depth of cut	Up-milling, undamaged surface, variation of radial depth of cut in range: 0.75 mm – 0.30 mm	0.50 – 0.29

4. Results and discussion

The analysis of the results presented in this section is divided into three parts. The first part focuses on evaluating the proposed method for determining the engagement of the active cutting edge in the cutting process. The second part addresses the application of the method into real-time process monitoring systems. The third part provides a comparison of the proposed approach with other existing methods. Such a structure enables a comprehensive assessment of both the kinematic aspects of the cutting process and the capabilities of machining monitoring, as well as the competitiveness of the proposed method.

4.1 Cutting edge engagement analysis

The analysis presented in this section focuses on the kinematics of the cutting process, specifically on determining tool engagement. The method is based on the analysis of force signals recorded along the feed direction and the direction normal to the feed. To determine the degree of tool engagement using the proposed approach, only calibration of the threshold value is required. Unlike conventional approaches, no extensive calibration involving force characterization under various cutting conditions

is necessary. The threshold value can be determined based on the range of recorded forces when the rotating tool is not engaged in cutting. However, it should be noted that the proposed method does not allow for the determination of the axial depth of cut a_p .

The method enables identification of the machining strategy through the determination of the radial depth of cut a_e . Figure 3a presents the tool engagement ratio p_{real} as a function of tool position for groove milling. Values close to the theoretical full engagement (1.00) can be observed, with an average value of 0.83 calculated over a 5 mm segment. Figure 3b shows the values of p_{real} for radial immersion milling ($a_e = 300 \mu\text{m}$, $750 \mu\text{m}$, $1050 \mu\text{m}$). The average values of p_{real} were 0.35, 0.45, and 0.55, respectively, compared to the theoretical values of 0.29, 0.50, and 0.63.

The discrepancies between the engagement values determined from cutting forces and those obtained theoretically result from changes in the direction of the cutting force. For small values of a_e , the feed force sense remains constant. However, with increasing radial depth of cut, the feed force orientation changes and may cross the predefined threshold band. In such cases, the corresponding samples are incorrectly classified as non-cutting. As a result, underestimated values of p_{real} are observed for higher values of a_e , as seen for full slot milling and radial immersion milling at $a_e = 750 \mu\text{m}$ and $a_e = 1050 \mu\text{m}$. In these cases, the mean absolute error reached 0.13. For lower radial depths of cut ($a_e = 300 \mu\text{m}$ and $750 \mu\text{m}$), the agreement with theoretical values is significantly better, with a mean absolute error of 0.06.

Variations in the tool engagement value p_{real} are also observed during machining across surface discontinuities, which manifest as a sudden drop in p_{real} value (Fig. 3c). The length of this drop corresponds to the width of the discontinuity. Table 2 compares the determined and actual discontinuity width, with a mean relative error of 11.14 %.

It should be noted that the proposed method is not suitable for detecting very small discontinuities. A discontinuity with a length of $L = 0.25 \text{ mm}$ was not detected, as no significant drop in p_{real} value was observed. This limitation results from the system dynamics. The tool does not have sufficient time to return to its undeformed state, and consequently, the recorded forces do not fall within the predefined threshold band. In this case, the tool engagement p_{real} decreased to 0.47 and returned to 1.00 within $t_p = 0.0071 \text{ s}$, resulting in a rate of change p_{real}/t_p equal to 0.1493 ms^{-1} , which was too high for the system to register the discontinuity. For comparison, the rate of change for a discontinuity of $L = 1.50 \text{ mm}$ (tool diameter) was 0.0466 ms^{-1} .

Increasing the threshold value to $F_{th} = 1.0 \text{ N}$ for $L = 0.25 \text{ mm}$ enabled detection of the discontinuity (Fig. 3c). However, this resulted in a significant reduction of p_{real} for continuous surface machining, with the value dropping to 0.41, corresponding to an absolute error of 0.59.

Discontinuity width [mm]	Determined discontinuity width [mm]	Relative error [%]	p_{real}/t_p [ms ⁻¹]
0.25	0.00 (not detected) (0.32 for $F_{th} = 1.0$ N)	- (28.0)	0.1493
0.50	0.41	18.0	0.1091
0.75	0.68	9.3	0.0935
1.00	0.90	10.0	0.0699
1.25	1.12	10.4	0.0560
1.50	1.38	8.0	0.0466

4.2 Application in process monitoring systems

The proposed method has two main potential application areas in machining process monitoring systems for hybrid manufacturing technologies. The first is the detection of cracks, which are a typical type of surface defect in additive manufacturing. The method can be applied in in-process quality control systems to assess whether the machined surface contains defects such as cracks.

Figure 3d presents the surface topography of a workpiece with a natural crack formed during the additive manufacturing process. The crack has an approximate width of 1.8 mm and consists of two regions of layer separation, forming an island-like structure in the central part. The tool engagement profile determined using the proposed method closely corresponds to the actual surface condition. Distinct regions can be identified: areas of proper machining with full tool engagement (regions A and E), two delamination zones with a significant drop in p_{real} value (regions B and D), and a porous region between the separated layers (region C). The proposed method not only enables detection of real cracks but also provides insight into their structural characteristics.

The second application area of the method is the detection of shape deviations in workpieces manufactured using additive technologies. Typical geometric inaccuracies result from deformation of thin-walled structures caused by residual stress. In machining, such shape deviations manifest as changes in tool engagement during side (radial immersion) milling.

Figure 3e shows the variation of the p_{real} indicator corresponding to a change in radial depth of cut in the range of 0.75–0.30 mm (theoretical p_{real} range: 0.50–0.29). A change in the average value from 0.45 to 0.35 can be observed. While the theoretical variation equals 0.21, the observed change is only 0.10. This discrepancy results from the mechanism of feed force direction change described in Section 4.1.

In the initial phase of machining for $a_e = 750$ μ m, the values of p_{real} are underestimated due to changes in the direction of the feed force. This underestimation reduces the sensitivity of the method under these cutting conditions and therefore constitutes a limitation of the approach. The change in force direction for the analysed conditions occurs at the angular position of the cutting edge $\varphi_{ex} = 1.17$, which corresponds to a radial depth of cut $a_e = 457$ μ m and a tool engagement ratio $p_{real} = 0.37$. This value

therefore represents a variability threshold beyond which the method becomes insensitive to changes in radial tool engagement. This threshold defines a limit that should not be exceeded either from below or above. However, relative variations in the value of p_{real} may still serve as an indicator of changes in tool engagement both above and below this threshold. The proposed method can be successfully applied in machining process monitoring systems for hybrid manufacturing, particularly for estimating radial tool engagement in regions where the direction of the feed force remains constant.

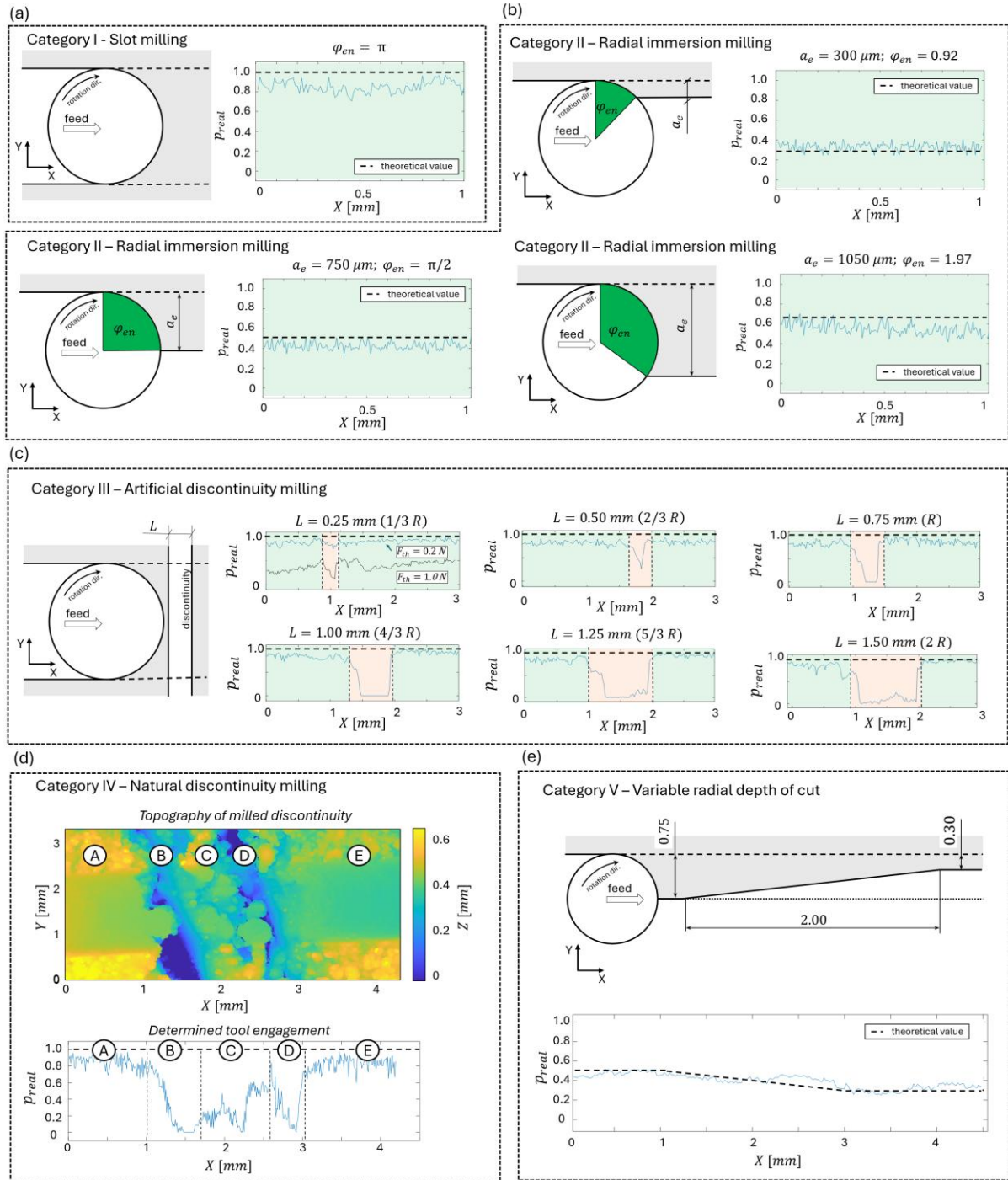


Fig. 3 Tool engagement for (a) groove milling, (b) radial immersion milling, (c) discontinuous surface milling, (d) natural damaged surface, (e) variable radial depth of cut.

4.3 Comparative analysis

The method presented in this study is inherently designed for real-time applications. Its computational complexity is low and does not require significant processing resources. For this reason, it is necessary to position the proposed approach relative to other existing methods.

To this end, two reference methods were selected for comparison. The first is based on statistical analysis of a selected indicator (standard deviation), while the second method commonly used in process monitoring systems is based on artificial neural networks.

The main common feature of all three methods is their applicability to real-time systems and their potential for adaptation to the estimation of tool engagement. However, each method requires a different approach to result interpretation as well as system calibration. The key characteristics of the three compared methods are summarized in Table 3.

The primary advantage of the proposed system is the absence of a complex calibration procedure. Only a simple threshold calibration is required, based on the measurement system response with the spindle running under no-load conditions (i.e., without cutting forces). In contrast, the remaining methods require more sophisticated calibration and training procedures, which involve the preparation of datasets for various cutting conditions. In many practical cases, particularly in single-piece or small-batch production, such data acquisition is not feasible.

Another important advantage is the possibility of direct physical interpretation of the indicator. The p_{real} parameter directly represents the degree of tool engagement in the cutting process, and its variations enable effective monitoring of machining conditions. In statistical approaches, the indicator does not inherently describe the physical cutting conditions; only after calibration can it be related to process parameters. Neural network-based systems also allow for a physical interpretation of the output; however, this requires dedicated training, and even then, the computation time is approximately an order of magnitude higher.

The main limitation of the proposed system is its relatively low sensitivity. The method is not capable of detecting cracks smaller than 0.5 mm (for a tool with a radius of 0.75 mm), whereas the other methods can detect discontinuities below 0.25 mm. Furthermore, a reduction in sensitivity is observed when monitoring radial tool engagement in regions where the direction of the feed force changes. In contrast, both statistical and neural network-based methods exhibit stable sensitivity across the entire operating range.

Aspect	Proposed method	Statistical approach	Neural network-based approach
Description	Counting the number of samples within a buffer and identifying samples outside the threshold band	Determination of signal standard deviation within a buffer and analysis of its variation across consecutive buffers	Three-layer regression-based neural network
System calibration	Only threshold band calibration based on measurement system noise	Calibration of indicator values required for different cutting conditions	Requires large training dataset and time-consuming training process
Complexity	Very low; simple counting of samples outside the threshold band	Low; typically implemented using Welford's algorithm	High; number of input neurons corresponds to buffer size
Computation time (*)	~1.8 ms	~2.9 ms	~20.0 ms
Sensitivity (**) - crack detection	Up to 0.5 mm	Below 0.25 mm	Below 0.25 mm
Sensitivity (**) - radial immersion	Reduced sensitivity when feed force direction changes	Stable sensitivity across full range	Stable sensitivity across full range
Physical interpretability	Direct physical interpretation; indicator reflects actual tool engagement	No direct physical interpretation	Possible physical interpretation depending on output definition
Crack detection mechanism	Sudden drop of indicator from theoretical level; absolute value indicates tool engagement	Decrease in indicator value; absolute value does not directly indicate discontinuity	Indicator represents probability of machining a discontinuous surface
Radial immersion estimation	Indicator directly corresponds to tool engagement; under conventional strategies, it directly reflects radial immersion	Requires precise calibration; neither absolute nor relative value directly reflects engagement	Output can be defined to directly represent radial immersion

(*) Computations performed on Intel Core i7-14700 CPU (2.1 GHz) with 64 GB RAM

(**) For a tool radius $R = 0.75$ mm

5. Conclusions

A novel approach to process monitoring dedicated to hybrid micromanufacturing systems is presented in this study. The proposed method enables the determination of tool engagement, which can be utilized both for the identification of radial immersion and the detection of material discontinuities. Consequently, the method can be applied in in-process quality control systems for detecting surface defects and geometric deviations of the workpiece.

The key aspects of the proposed approach can be summarized as follows:

- The method does not require a complex calibration procedure; only a simple threshold calibration based on measurement system noise is necessary, eliminating the need for extensive training datasets.
- The indicator p_{real} directly represents the physical degree of tool engagement, without the need for additional interpretation or mapping procedures.
- The main limitations include the inability to monitor axial depth of cut and limited sensitivity to small discontinuities. Furthermore, the method loses sensitivity when the feed force changes its direction.
- The computational cost of the method is very low, as it is based on simple sample counting. The absence of force transformation into the tool coordinate system significantly reduces computational complexity, enabling very short computation times suitable for real-time applications.

Despite its advantages, further research is required to evaluate the method for tools with a wider range of diameters. It is also necessary to investigate the sensitivity of the method as a function of threshold band width in order to establish a universal calibration procedure. Future work should additionally focus on improving the detection of small natural cracks and extending the method to other types of surface defects characteristic of various additive manufacturing processes.

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Competing interests

The author declares no competing interests.

Author Contribution

Marcin Gołaszewski contributed to the study by performing conceptualization, data curation, formal analysis, investigation, methodology development, software development, validation, visualization, and writing.

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