Journal of Machine Engineering, 2022, Vol. 22, No. 2, 99–107
ISSN 1895-7595 (Print)   ISSN 2391-8071 (Online)

Received: *31 January 2022* / Accepted: *04 May 2022* / Published online: *16 May 2022*

condition monitoring,
deburring,
feature generation

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PRIMARY TESTING OF AN INSTRUMENTED TOOL HOLDER FOR BRUSH DEBURRING OF MILLED WORKPIECES

Brush deburring requires consistent contact pressure between brush and workpiece. Automating adjustments to control contact pressure has proven difficult, as the sensors available in machine tools are usually not suitable to observe the small amplitude signals caused by this low force process. Additionally, both the power consumption and the vibration signal caused by the process strongly depend on the workpiece surface features. This paper describes a test setup using an instrumented tool holder and presents the corresponding measurement results, aiming to quantify the axial feed of the brush. It also discusses the interpretation of different signal components and provides an outlook on the utilization of the data for tool wear estimation.

1. INTRODUCTION

Monitoring, supervising and controlling production processes and adapting parameters autonomously are major goals in fields of Industry 4.0 development [1]. Modern machine tools are often well equipped with options to sense and evaluate their condition [2] and even tool wear [3]. During deburring, heavy-duty machinery may often be underutilized in terms of mechanical load and power consumption respectively. Sensors integrated in the spindle or other parts of the machine tool need to cover the full range of machine's capabilities. Therefore, integrated sensors and surveillance systems are typically not well suited to process monitoring for low force deburring operations and often struggle to yield useful process information under these conditions. However, purpose built sensors [4], piezoelectric force measurement [5–7], and several other sensory machine tool components [8] are used to integrate further sensing functionality into machine tools. In many application scenarios, acoustic emissions can be used for process monitoring [9], as well.

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The aim of supervising processes is not only monitoring and data collection, but also creating control loops and enabling autonomous and self-optimising process control [10, 11]. The Institute of Production Engineering and Photonic Technologies (IFT) and its business partners have developed a measurement and control system based on an Instrumented Tool Holder (ITH) [12]. This modified tool holder detects acceleration for in-process monitoring and the wirelessly transmitted data can be utilized for real-time process evaluation or control. Setting countermeasures by adapting cutting parameters or sending feedback to higher level monitoring systems is possible so far [13]. So even networks with decentral data processing or cloud services can be addressed [14] to enable data-based process optimization [15].

Besides the system's applications for drilling and milling operations, further development shows the potential for using the ITH in filigree and delicate processes. Discussing the topics of sensorization and process control, this paper shows the ability of an ITH-system to monitor brush deburring.

2. EXPERIMENT AND SIGNAL PROCESSING

Apart from many other possibilities of avoiding or removing burr, brush deburring remains a simple and inexpensive method [16]. In this work a generic setup without material or tool-specific considerations was chosen.

2.1. TEST SETUP

The test series was carried out in a DMU 75 monoBlock CNC machining center by deburring with a disk brush (as in Fig. 1b and 1c). The aluminum (EN AW-7075 AlZnMgCu1,5) workpiece had generic pockets (as in Fig. 1a) to imitate workpieces such as cylinder heads. Burrs were repeatedly created, after each deburring cycle, by face milling the upper surface (260×180 mm). Considering that many process parameters effect the burr caused by milling [17, 18], all data was gained under the same condition regarding burr. After milling deburring was accomplished first in clockwise then in counter-clockwise orientation following the same path (see also in Fig. 1a). Process parameters are listed in Table 1. In this setup coolant was used for milling, but not for deburring. However, the residual coolant was not removed after milling.

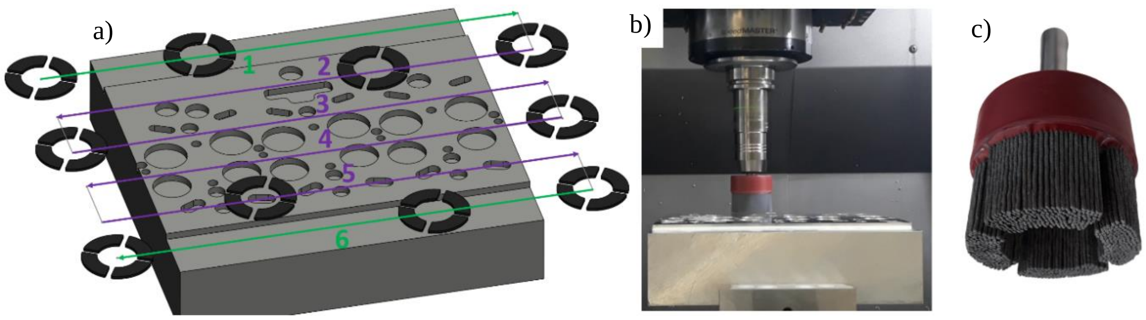

Fig. 1. Experimental setup: (a) path of movement, (b) setup with ITH, (c) used brush in detail

Table 1. Process parameters

tool	axial feed (mm)	rotational speed (rpm)	feed rate (mm/min)
face mill: D = 80 mm, 6 cutting edges	0.2	2000	1800
disk brush	0.2, 0.4 and 0.6	1500 (in both directions)	1000

The brush's geometry (as in Fig. 1c) is specified in Table 2. Depending on the radius, within one rotation approximately 40 to 100 bristles passed the workpiece. Tool wear of the brush results in decreasing length of the bristles accordingly. However, the individual bristles vary in length statistically. The length of the overall tool and therefore shortening of the overall tool can be identified by probing and scratching the surface of the workpiece with the tool.

Table 2. Disk brush parameters

outer diameter (mm)	inner diameter (mm)	diameter of bristles (mm)	length of bristles (mm)	number of segments
50	28	1.2	24	4

2.2. INSTRUMENTED TOOL HOLDER SYSTEM

The ITH uses hydraulic expansion technology to clamp the tool and the spindle interface is HSK. The hydraulic tool holder is unchanged in its outer contour and has battery, MEMS-Sensor and transceiver unit for wireless communication integrated within the body. This setup is equivalent to the version described by Bleicher et al. in [12] with one exception. The sensitivity of the tool holder was modified to cover ±50 g of acceleration using 16-bit sampling at a 9.5 kHz of sample rate instead of the former ±100 g. This important adaptation is required for delicate processes with small vibration to provided increased resolution and decreased noise.

2.3. TIME DOMAIN ANALYSIS

Figure 2 shows the signal while deburring with different axial feed. The stepped shape of the individual traces clearly indicates when the brush contacts the workpiece during a deburring cycle. Furthermore, the amplitude seems to increase on the paths 2, 3, 4 and 5 in comparison to paths 1 and 6. Regarding latter, the contact zone is only 6mm wide as shown in green in Fig 1a.

At smaller axial feeds, the signal amplitude is reduced. The systems requirement for lowest possible measurement noise of the measurement chain becomes very clear, as well, otherwise brushing might not be detected properly.

Moreover, there is a difference in signal strength depending in the rotation direction. The reason might be a slight bending of the bristles in their neutral position resulting in less excitation when using the brush in clockwise orientated rotation. This effect seems to outweigh the existence of burrs, because the majority of them gets removed during deburring in clockwise direction.

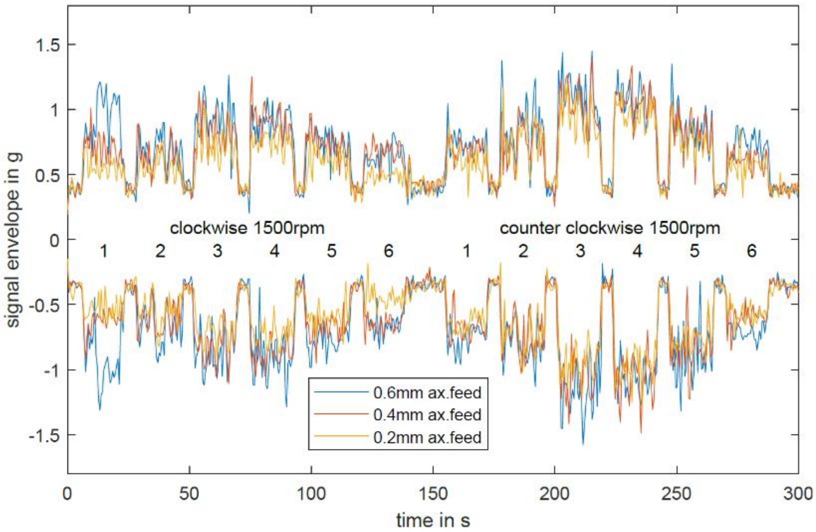

Fig. 2. Vibration signal measured with an ITH while deburring with different values of axial feed

2.4. FREQUENCY DOMAIN ANALYSIS

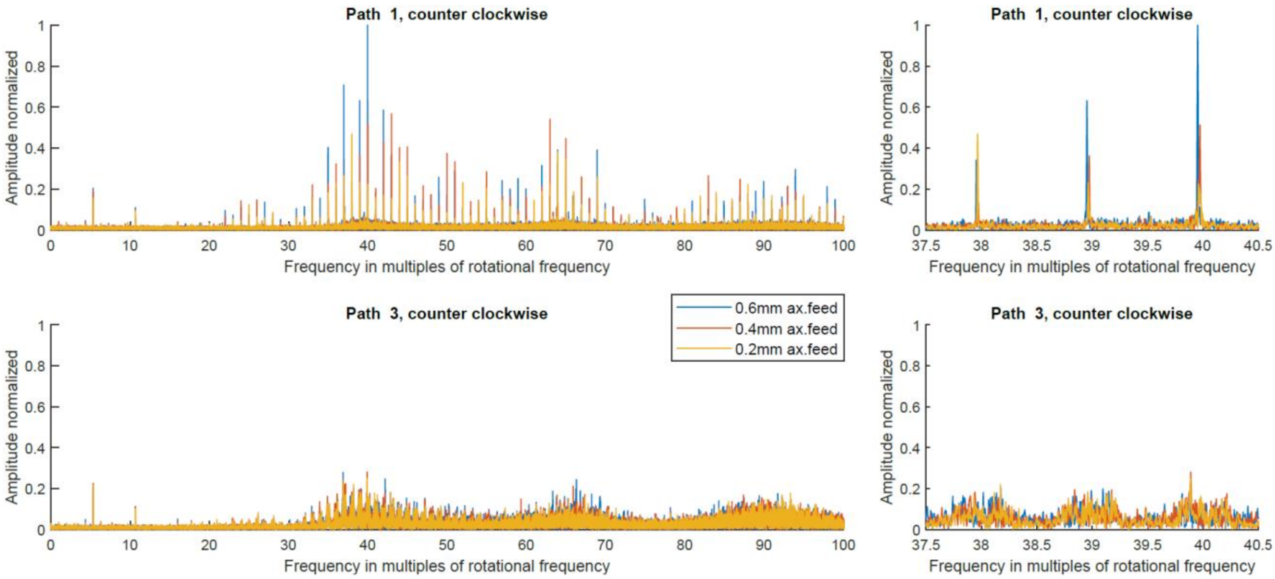

Fig. 3. Amplitudes of ITH signal of different axial feeds and paths, (detail view in the right column)

In order to obtain a dependable frequency domain representation, a discrete Fourier transform (DFT) was calculated using a 10 second sample of the signals measured form each path's center section and a Hamming window was applied. As can be observed in Fig. 3, deburring with small contact area like in paths 1 and 6 caused separated spectral lines at multiples of the rotational frequency. The strongest components have been observed around the 40th multiple. The explanation is in the number of bristles passing a certain point during one rotation.

Deburring like in paths 2 up to 5 results in a wider distribution around the whole-numbered multiples of the rotational frequency. Mostly the rather irregular structures along the path in combination with the full contact width cause the ITH's signal not to be as canonically structured as before. Similarly, in real-world processes regularity of the work-piece's structure cannot be assumed. In general both cases need to be considered.

2.5. ANTICIPATED PARAMETERS OF INFLUENCE

Constant milling parameters lead to the assumption of constant occurrence of burr in quality and quantity throughout the test series. Therefore, it is obvious from the data that the following parameters effect the measured signals significantly:

- tool's axial feed as a result of z-offset and superposed shortening of the bristles caused by tool wear,
- the rotational direction of the tool,
- generic pockets as workpiece characteristics along the path of the tool center point (TCP) and contact width.

Especially latter causes both paths 3 and 4 to be the most intensive with a significant difference in the frequency domain compared to paths 1 and 6. The data shows the need for advanced signal assessment to distinguish these effects clearly.

3. SUPERVIZED DEBURRING

In machine learning, key features must be identified to train the machine learning algorithm. The features can be extracted from time domain signals or via transformation into frequency domain as summarized by Teti et al. in [19]. In this case, the extracted features should show the difference between the different axial feeds from the small data set. Because it is important to generate as many independent features as possible to automatically identify process changes in machine (and deep) learning scenarios, the “best” features must be identified using limited computing time. Indicators are developed and applied here to achieve a robust method that correlates the brush's length offset or axial feed to radial acceleration measurement from the ITH.

3.1. FEATURE IDENTIFICAION

It is obvious that the extracted features need not consider the significant changes in frequency content due to changes in contact width. Besides statistical standard features [19] three others were developed, compressing the data of each path of Fig. 2 into one index:

- Feature 1: Aiming to evaluate the time signal directly, a threshold can be set. If the level of, for example, 0.55 g is exceeded, adequate deburring can be concluded. As depicted in Fig 2. Air cutting between the paths with contact also leads to a certain signal amplitude (here around 0.40 g). The threshold (i.e. 0.55 g) can be set based on the measured data sets with known axial feed.
- Feature 2: Here the original signal is modified using a band-pass filter with 900 Hz and 2250 Hz cutoff frequencies. These frequencies correspond to the 36th and 90th multiple of the rotational frequency. Within one rotation, around 36 up to 90 bristles pass a certain location, depending on the exact position. Thus, the filtering brings a focus to the effects directly related with the spinning tool. Then the power of the filtered signal is processed. For reasons of comparability, the feature was scaled by its maximum. This feature for sure depends on the exact filter and chosen cutoff frequencies. In frequency domain, the definition can be written like

$$feature2 = \int_{f\,=\,900\,Hz}^{f\,=\,2250\,Hz} |signal(f)|^2 \text{ df}$$

where: *f – frequency in Hz, Signal(f) – signal in frequency domain.*
- Feature 3: The rectified value of the time domain signal was processed. Thus this feature is defined as the average of the signals absolute value.

$$feature3 = \frac{1}{10\ s}\int_{t\,=0\ s}^{t\,=\,10\,s} |signal(t)| \text{ dt}$$

where: *t – time from zero to ten in seconds, signal(t) – signal in time domain;*
This includes all frequency content and gives a more general description of feature 1. For instance for a time interval of 10 seconds (while the brush is supposed to have contact to the workpiece), all amplitudes are considered with positive sign and are averaged. Thus, single spikes or drops do not affect the logics outcome heavily (i.e. by exceeding a threshold of feature 1), because the overall signal of 10 seconds is considered.

Figure 4 compares feature 2 and 3 with the following observations. When dealing with measured data, noise is present. The noise threshold is found by reference air cutting. In this context, signal artefacts from the rotating spindle without the brush having contact with the workpiece are considered as noise. Here, all paths, even those with smallest contact width and little axial feed, are clearly distinguishable from the condition of no contact.

The deviation of the individual paths is related to the generic pockets along the way of the brush. Some of these causing more vibration result in overall higher feature values.

In addition, a high spread between samples along the same path but with different axial feed is seen. 11 out of 12 sets for each feature show the desired monotonic behaviour, thus the features' output increase with increasing axial feed. The lowest value at 11 of 12 paths refers to 0.2 mm of axial feed, whilst the highest value refers to 0.6 mm feed. The three chosen setups of feed can be used for calibration.

On the one hand, feature 2 provides larger gaps due to changes in axial feed at most of the paths allowing the determination of axial feed of a new set of data based on the chosen feature. At most paths, feature 2 offers a wider span than feature 3. On the other hand, feature 3 provides less path-based discrepancy than feature 2, for instance the overall range of distribution is smaller. Furthermore, the difference in rotational direction seems to be less evident.

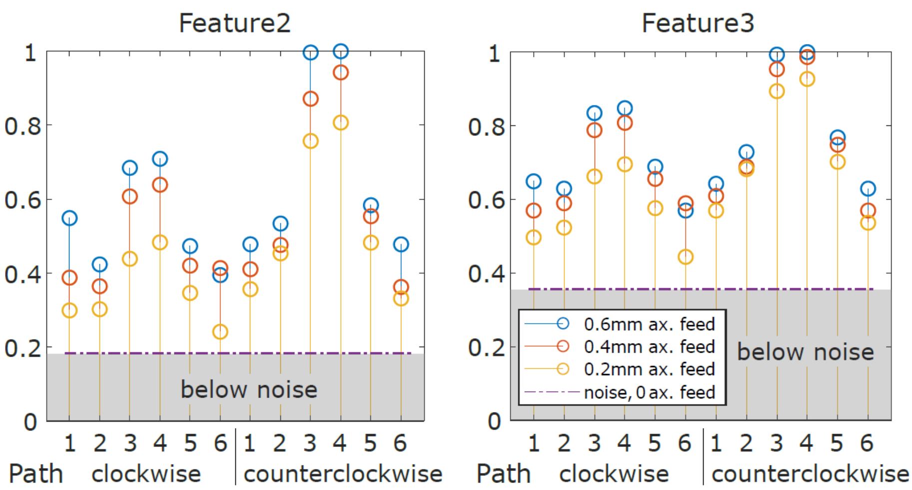

Fig. 4. Features generated for deburring with different feed

3.2. FEATURE UTILIZATION

For control by supervising the deburring process, two efficient approaches of evaluation are possible: 1) gathering information along all paths of one workpiece and concluding the actual axial feed out of this rather large set, or 2) deducing the tool wear by comparing data measured always along the same path under similar conditions. A quantification of the present process needs to consider the specific amplitudes along the individual paths. Using the features' span around the intended axial feed allows knowledge to be gained about present tool wear from the latest process data, as depicted in Fig. 5. To decrease misinterpretation and to find an expedient solution for making decisions, relying on more than one feature or evaluation of large sets of data can be advantageous.

To display the system's utilization an illustrative example of sensed data is presented in Figure 5. Based on the measurements shown in prior, a new set of data can be categorized and quantified. A linear interpolation at all 12 paths (6 clockwise and 6 counter clockwise) shall be computed based on feature 2. This is possible in 11 of 12 cases, with the monotonic behaviour of the prior measurement. Only at the 6th path in clockwise direction, an estimation of the brush's current length is not reasonable due to the weak correlation. Taking the full production process of brushing over the complete workpiece into account averages variance and deviation on single paths. Whilst individual paths like the first or fifth would lead to feature values corresponding to the interval of 0.4 mm and 0.6 mm, other paths indicate to the interval of 0.2 mm up to 0.4 mm of tool length. Deducting the actual state from more than one path increases reliability. Based on the average value gained by linear interpolation of Feature 2 along all paths and the nominal axial feed chosen in the NC-program, a forecast of tool wear becomes possible.

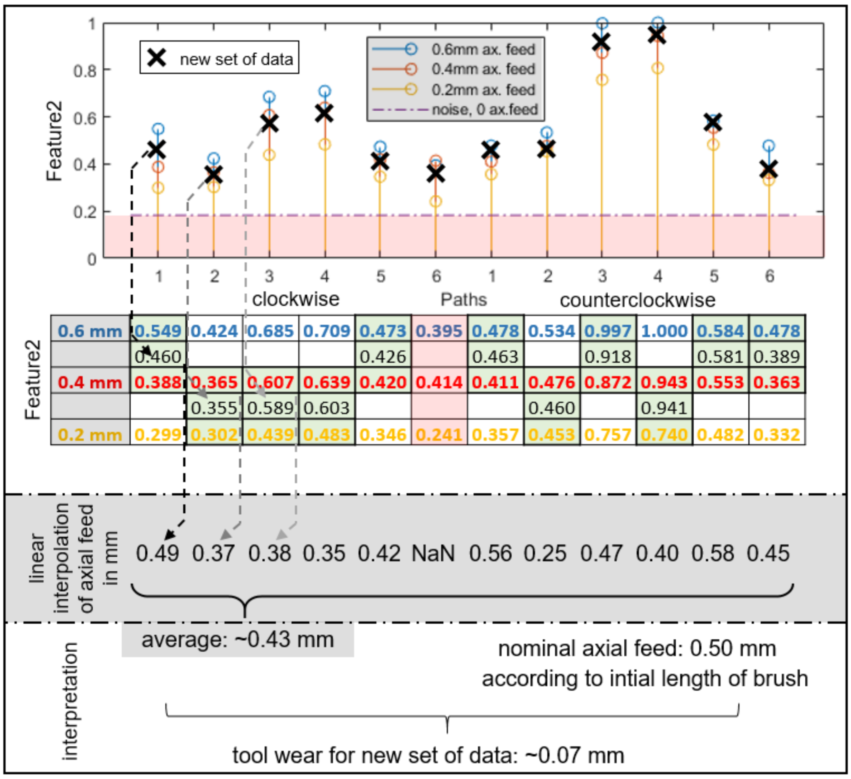

Fig. 5. Feature 2 utilized for tool wear estimation (illustrative example)

4. CONCLUSION AND OUTLOOK

This paper shows the ability of an acceleration-sensitive instrumented tool holder (ITH) to monitor deburring, a low-force process. The required constant surface pressure not only affects the quality of the deburring process, but also the service life of the deburring brushes. Due to tool wear and subsequent shortening of the bristles, contact pressure and deburring effectiveness are decreased if no counter measures are taken.

As these research findings show, rotational direction can have an impact even when using a tool that ought to be invariant to rotation direction. With further use of the ITH-system by industrial partners, it should be possible to generate a large amount of data and deduce the impact parameters and dependencies by machine learning, or data-driven, approaches.

For future work, the exact geometrical property of the brush shall be considered with statistical aspects on the bristles and their individual length. Moreover, a larger set of data is required to cover the overall wear status of the tool with statistical wear estimation over the complete tool lifetime.

ACKNOWLEDGEMENTS

The authors also want to express appreciation and thanks to the Austrian Marshall Plan Foundation for supporting the research work and strengthening the academic exchange between TU Wien and US universities. Special thanks are due to the Machine Tool Technologies Research Foundation (MTTRF) for supporting the infrastructure on TU Wien, utilized for this research work.

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