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Micromilling force prediction through Digital Twins

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Abstract

The digital twin concept is defined and applied to the case of force prediction in micromilling where it could have a strong impact as experimental and analytical approaches are complicated by the intrinsic physical phenomena taking place in micro chip removal processes. A first assessment is presented in this paper regarding the capability of a commercial software (VERICUT®) to simulate not only the CNC machines in terms of geometry, kinematics and control, but also the milling force. Typical micromilling conditions have been experimentally tested and compared with the corresponding simulated conditions in terms of force components in the time domain. Results point out how the prediction performance is not acceptable where micro chip removal phenomena as minimum chip thickness take place, but promising improvements are foreseen in case of the implementation of micromilling specific models in the software.

Keywords: Micromilling, Force, Digital Twin, Vericut.

1. Introduction

The precursor to what will come to be known as digital twins (DT) was the mirror environment which engineers at NASA developed during the disastrous Apollo 13 mission in an attempt, proven successful, to recreate a remote real system in order to determine the correct approach to recreate an air purifier [1]. Over the years the interest and investment into digital twins has grown considerably [1] and is predicted to reach a global market value of $16 billion by the year 2023 [2]. The increased interest in DTs is due to the opportunities they afford for accelerating product and process development, performance optimization and enabling predictive maintenance.

These characteristics will allow manufacturers to reduce costs and build better products [2, 3]. However, it is still quite difficult to find a universal definition of what a digital twin is since this varies somewhat depending on their key aspects. However, it is possible to give a universal description of what a digital twin must be able to do to be considered as such.

“A digital twin […] continuously predicts future statuses (e.g., defects, damages, failures), and allows simulating and testing novel configurations, in order to preventively apply maintenance operations. More specifically, the twinning process is allowed by the continuous interaction, communication, and synchronization (closed-loop optimization) between the DT, its physical twin and the external, surrounding environment. […] Finally, the digital twin provides modelling and simulation applications for representing, in a realistic and natural way, both the current status of the physical twin, and different “what-if"' scenarios” [1]. Barricelli et al. [1] claim that digital twins should aspire to closed-loop optimization whereby there is a constant stream of back-and forth-information between the digital and the real machines with the former learning from the latter and optimizing it by predicting future states and choosing the one which provides the best outcome.

The climate of volatility created by the COVID-19 pandemic [4] has recently forced companies to think of its long-term effects and how supply chains and product processes will change. To withstand current and future storms, heavy investments in making resiliency and in hiring talent for digitalization should be made [4]. This can in short considerably assist companies in manufacturing products by allowing nonessential workers to work from home and boost SMEs in acquiring data digitally which has been characteristically done by hand up to this point [4].

Given this brief overview of digital twins, it is appropriate to address why a software like VERICUT® (CGTech) can thought as a digital twin. These considerations are necessary since some of the notions written above are in contradiction with how VERICUT® works. The biggest point of contention is the seamless and continuous flow of data which is required between the digital twin and its physical counterpart. The software does not do this automatically. Sensors can collect information which then has to be manually inserted in the software. For example, the Lego Group used sensors to measure exactly the layouts of all their machines and then reproduced them within VERICUT® to achieve the most accurate results [5]. Special software solutions can be developed for big companies to facilitate the interdepartmental communication surrounding the various features of VERICUT® such as simulation, verification, inspection and optimization with data being made available as soon as it is produced and also creating an historical record of past productions [5-7]. Furthermore, the kind of instantaneous communication between worlds, which many advocate for in literature, these authors argue is unfeasible for the kind of application VERICUT® is intended for. What use would it be to update a CNC simulation, inspection, and optimization software during the execution of a job? Even if in process corrections could be adopted, this would result in an uneven finished product or batch with irregular quality or characteristics. It makes sense to collect data throughout the entire job or test run and then update the software with the relevant data collected by the adopted sensors and/or use historical data from other jobs. Lastly, VERICUT® does employ all the major standards used for developing digital twins. The software is capable of reading and implementing STEP files, uses ISO 13399 compliant information deriving from tool manufacturers such as being able to read and process .GTC and .DXF files. VERICUT® can also interact with MTConnect derived data as proven by Vijayaraghavan et al. [8] who used a cloud of points representing real positions occupied by the cutter and compared them to the digitally machined part in order to identify which portions of the real part were different from the required solid model. In fact, such integration with the MTConnect protocol will be fully supported by VERICUT® in the near future being provided directly within the software allowing for a direct and continuous contact between the digital twin and the real machine.

This paper in particular wants to explore the application of digital twins (specifically using the software VERICUT®) to the manufacturing process of micromilling. This first assessment is based on the cutting force simulation capability of a DT implemented in VERICUT®.

2. Micromilling characteristics

Whilst micromilling shares most of the problems and complexities of traditional milling it also possesses some unique challenges, these are mainly due to the fact that when tools become smaller the tool edge radius re cannot be considered infinitely small and assumes finite values. The tool edge radius becomes therefore comparable in size to the chip thickness. Furthermore, at the microscale, an intermittent chip formation process can be observed when chip thickness is lower than the minimum one throughout the engaged arc. In this case, several non-cutting tooth passes take place (ploughing) before material removal can be observed [9]. Moreover, the nominal rake angle provided by the manufacturer is no longer sufficient to describe the tool-material interaction, but the so-called partial effective rake angle [10] should be applied at the edger rounding when the uncut chip thickness is below 0.4*re and highly negative rake angles take place with or without the formation of a "dead metal cap" in front of the cutter [11]. Micromilling is therefore a complex process, difficult to monitor since measuring cutting forces is extremely complex and requires state of the art setups difficult to reproduce in an industrial scenario and inspecting parts during or after the process is a complex operations requiring expensive and often lab grade equipment such as SEM microscopes [12]. The ability to simulate the entire micromilling process, detect collisions, near misses, inspect the component at predetermined lines of code and possibly also the cutting forces poses therefore a considerable advantage from an industrial standpoint.

3. Mechanistic models in Micromilling

In order to gain more generality, semi-empirical or mechanistic models have been introduced both for the macro and the microscale [9, 10, 13, 14] to predict cutting forces by means of relationships containing empirically determined cutting coefficients and chip geometrical parameters that, in turn, are analytically obtained from the process kinematics. The empirical cutting coefficients allow considering the cutting phenomena that can be neither analytically modeled nor measured during the experimental tests.

A relevant group of mechanistic models includes models whose coefficients are determined by milling tests for each given cutter geometry and tool–workpiece material combination [9, 10, 14].

One of these models has been selected from the macro- and micromilling literature for the aims of this study as it is able to accurately capture the micromilling phenomena [9]. This model is based on cutting-condition-independent coefficients and partial effective rake angle. Moreover, it has been demonstrated by the authors that it is a good tool for predicting forces in micromilling with a low calibration experimental effort [10].

Force®, the module of VERICUT® able to predict forces in milling, is based on a mechanistic model considering a whole host of parameters associated to workpiece and cutting tool materials, detailed cutting edge and tool geometry [15]. Force® is capable of analyzing in real time forces, feed rates and chip thicknesses, for every line of NC code to which they are dynamically linked, as they are encountered by the cutting tool, thus leading to easily identify critical conditions such as high cutting forces, excessive volume removal rates and tool deflections. The objective is to adjust feed rates and/or spindle speeds in order to improve the cutting quality, prolong tool life by decreasing wear and reduce production times [16].

Force® therefore is capable of producing an optimal feed rate, for a given cutting condition, via the evaluation of 4 key factors:

- Force acting upon the cutter
- Maximum Chip Thickness
- Spindle Power
- Maximum allowable feed rate

The software is capable of recognizing instances like chip thinning and adjusts feed rates accordingly to keep the cutting forces profile as constant as possible throughout the whole process and reduce tool wear all the time remaining under the user-specified limits in terms of maximum forces applied.

Force® does not rely on finite element results, which, while accurate, remain by their nature theoretical, but uses specific material characteristics based upon physical cutting trials in laboratory conditions executed via a DoE campaign. This is done in the search to provide the most accurate cutting force estimates possible evaluating cutting conditions for which the effects of temperature, friction and shear stress are also considered [15, 17].

4. Materials and Methods

4.1. Machine tool and force acquisition system

For the experimental campaign of this study, a Kern Evo machine tool (Table 1) has been equipped with a Kistler 9317B dynamometer and a force compensation approach has been applied to remove unwanted dynamic effects and, at the same time, preserve harmonic components located at higher frequencies than the nominal dynamometer bandwidth [10].

4.2. Specimens and Tools

The design of the workpiece was made for guaranteeing two levels of radial depth of cut ae. The choice of machining 4 independent shoulders was

based on the necessity of keeping the number of workpieces low when compared to the number of runs. The Aluminum 6082-T6 specimen geometry is represented in Fig. 1, together with its setup on board of the dynamometer.
The TiAlN coated hard metal Dormer S150.5 mill (Dc = 0.5 mm; Z = 2; re = 4 um; rake angle = 0 deg; helix angle = 30 deg) has been selected for the present study.

Table 1
Experimental setup and acquisition system

Equipment	Description
Machine tool	Kern EVO CNC ultraprecision five-axis machining centre (spindle speed up to 50.000 rev/min, nominal positioning tolerance ±1 um, precision on the workpiece ± 2 um)
Dynamometer	Piezo-electric triaxial dynamometer Kistler 9317B
Charge amplifiers	Kistler 9015A
Acquisition board	NI 9234; sampling frequency (fs) = 25,600 Hz; anti-aliasing filter cutoff frequency = 11,500 Hz
Data filtering	Fifth order Butterworth low-pass filter cut-off frequency = 6000 Hz

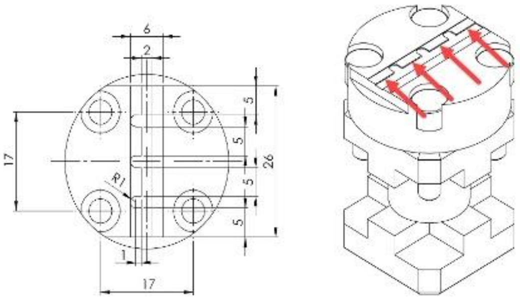

Fig. 1. Workpiece design as seen mounted on the Kistler 9317B Force Link, in red the four shoulders machined during the experiments are shown. Workpiece material: Aluminum 6082-T6.

4.3. Machine tool implementation in VERICUT®

The Kern EVO was digitalized by initially analyzing the entirety of its kinematic relationships and implementing them within the software, associating each degree of freedom of the machine with the correspondent CAD models capable of performing

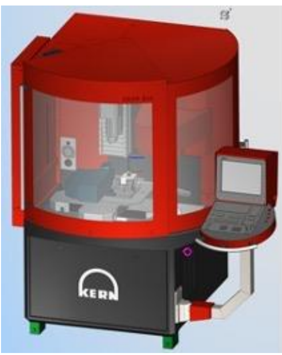

Fig. 2. Kern Evo implemented in VERICUT®

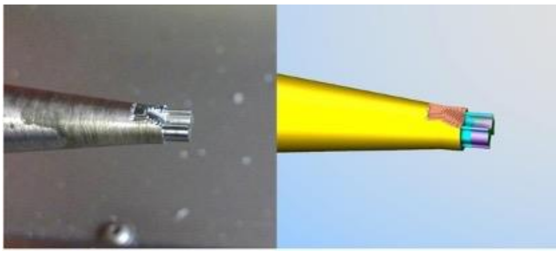

Fig. 3. Digital twin validation part.

such a movement. Thus, a complete Project Tree was integrated also featuring the machine control (Heidenhain 530), travel limits associated to the specific machine present in the university's laboratories and a tool library where the toolholders and tools used for the machining operations are stored (Fig. 2). Collision checking parameters were also identified and implemented.

Once the machine was completely implemented in VERICUT®, validation of the Digital Twin took place by simulating complex NC programs which had in the past already been run through the real machine. Amongst these was the extruder pictured in Fig. 3 where face validation took place between images acquired during the program simulation and photos taken of the workpiece at the time of machining.

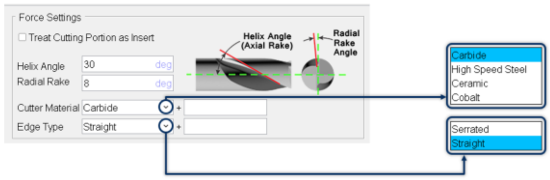

Fig. 4. Force® Settings window present for every tool created in the VERICUT® Tool Library.

In order to predict forces in VERICUT® it is necessary to supply the software with information concerning the helix and rake angle, the type of cutter material and edge as seen in Fig. 4, and workpiece material.

4.4. Experimental plan

The carried out experimental plan has been inspired by [9]. The tests performed by Lee et al. proved accurate enough to calibrate their own model and correctly estimate cutting forces. Compared to what used by Lee et al. [9], it was decided to slightly reduce the number of revolutions as a function of the

Test Number	ap [mm]	ae [mm]	n [rpm]	Vf [mm/min]	fz [mm/tooth*rev]	Vc [m/min]	Cutting Time [s]	Error [%]
1	0,05	0,25	9900	9,9	0,0005	15,80	30,30	-92%
2	0,05	0,25	9900	19,8	0,0010	15,80	15,15	-82%
3	0,05	0,25	9900	39,6	0,0020	15,80	7,58	-80%
4	0,05	0,25	9900	59,4	0,0030	15,80	5,05	-75%
5	0,10	0,25	9900	19,8	0,0010	15,80	15,15	-83%
6	0,10	0,25	9900	39,6	0,0020	15,80	7,58	25%
7	0,10	0,25	9900	59,4	0,0030	15,80	5,05	42%
8	0,10	0,50	19800	79,2	0,0020	31,60	3,79	25%
9	0,10	0,50	30000	120	0,0020	47,88	2,50	10%
10	0,05	0,50	39900	159,6	0,0020	63,68	1,88	57%
11	0,10	0,50	39900	159,6	0,0020	63,68	1,88	400%

Fig. 5. Experimental plan. (color legend: red: big errors; yellow: middle errors; green: small errors). Error [%] = (Sim. – Meas.)/Meas. The table reports the maximum error between X and Y component.

fundamental frequencies constituting the force signals (Fig. 5).

The comparison between simulated and acquired forces was performed by analyzing the measured force graphs against the one generated by the simulation with VERICUT®. The envelope of the force peaks during the cutting operations has been compared for each experimental condition. Fig. 5 reports the Error values and Fig. 6 reports an example of the analyzed graphs.

4. Results and Discussion

The first apparent conclusion is that the prediction model used by VERICUT® is incapable of considering ploughing and rubbing. The first 4 tests (Fig. 5) in fact show how significantly the software underestimates forces at play with the worst-case scenario being the

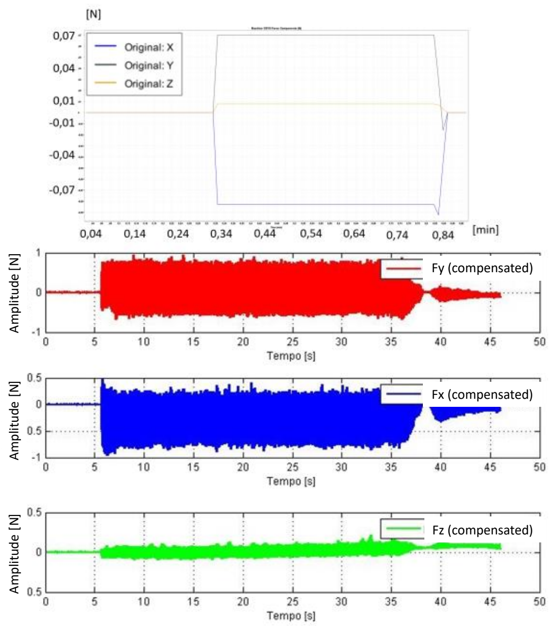

Fig. 6. Predicted (top) and measured (bottom) forces (test 1: ap = 0.05 mm, ae = 0.25 mm, n = 9900 rpm, Vf = 9.9 mm/min)

lowest feed per tooth coupled with the lowest axial cutting depth. As one might expect, the discrepancies decrease as the feed per tooth increases but remain significant throughout all of the tests carried out with the lowest axial depth of cut. This is not surprising and confirms what was expected, as Lee et al. [9] specifically noted. The first four tests which they also used to calibrate their model are designed to ensure ploughing and rubbing occur between the cutter and the workpiece. Test 5 is interesting since the VERICUT® prediction model also significantly underestimates forces here as well. The best explanation for this is that whilst the depth of cut is now 0.10 mm, the feed per tooth is still low and therefore phenomena like ploughing and rubbing are still present.

Quite all subsequent experiments feature a 0.10 mm axial depth of cut and a 0.002 feed per tooth (or more). The prediction capabilities improve dramatically yielding far closer estimates. Considering test 6 and 7, it is possible to see how the model fits far closer than before, with errors of 25% and 42% respectively.

However, these values should not induce much confidence given the complexities of predicting forces in micromilling and the fact that in all probability the Force® model has been calibrated on the macro scale. This fact probably prevents predicting ploughing and rubbing phenomena.

The increase in overshoot in test 7 compared to test 6 could be ascribed to material softening. This overshooting effect seems, however, to disappear once the radial depth of cut is widened to include the entire diameter of the tool passing from a 90° contact angle to 180° (tests 8 and 9). This could be because of the balance among higher Vc, slightly higher Vf and increased ae playing a role on the capability to dissipate heat. Increasing further Vc and Vf, the overestimation of the model continues to increase reaching very high values (tests 10 and 11). Whilst acquisitions at these tooth passing frequencies are extremely complex and can be difficult to obtain since few higher order frequencies can be correctly acquired before dynamic amplification sets in, these last two measurements seem to indicate the recurrence of thermal softening in a similar transition seen between tests 6 and 7.

5. Conclusions

A preliminary evaluation of the force prediction capability of a digital twin implemented in VERICUT® has been carried out. The used software can correctly represent machine tool, tool, fixturing system and specimen. Moreover, it simulates the machine kinematics and control, so complete cutting operations can be simulated together with the cutting forces. Some discrepancies have been highlighted between simulated and measured forces, especially when ploughing, rubbing and thermal softening take place, but improvements can be foreseen by applying specific micromilling force models in the software. This would give a powerful tool to researchers and companies working in the micromilling field. The authors suggest and intend to conduct further research by developing proprietary algorithms in order to improve the prediction capabilities of commercial software such as VERICUT® when dealing with complex micromilling operations dominated by ploughing and rubbing phenomena. The goal will be to augment the existing software whilst maintaining user friendly interfaces thus providing a significant contribution to I4.0 preparedness even to companies operating in very complicated machining sectors.

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