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IN-SITU MEASUREMENT AND DIMENSIONAL ERROR MODELING: A CASE STUDY IN A MACHINE TOOL MANUFACTURER

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Abstract. *Quality assurance in manufacturing processes is an issue that will require new strategies to follow the evolution guided by Industry 4.0. Thus, considering the data relevance for this new revolution, it is crucial to understand how inspection and measurement techniques can make the most of the process's information to make quality more manageable and avoid rework. In this sense, based on data-driven strategies, the present study aimed to improve the dimensional accuracy of clamp levers and grippers manufactured by milling. To achieve this purpose, a case study was stated on the multinational machine tool manufacturer responsible for 42 CrMo4 steel clamp levers and grippers production. Starting with a root causes mapping, it was possible to identify critical internal operations for dimensional accuracy variations in the products that require some enhancements. Hence, machined clamp levers and grippers' critical dimensions measured with a coordinate measuring machine (CMM) used in the quality department were compared to those measured with an in-situ measurement probe to improve the online equipment accuracy. Regarding the systematic error evaluation for two critical dimensions in the products, this approach found about 0.019 mm and 0.009 mm absolute corrections to enhance the measurement probe method. Also, cutting tool wear experiments contributed to identifying tool wear values higher than the maximum tolerances near the tool life limit. As a result, a proposed tool wear modeling supported a compensation approach for this phenomenon during machining, according to the number of manufactured components within the tool life. It defined ways to use manufacturing operations data, which were experimentally and statistically analyzed, allowing new opportunities to meet the tight tolerances of the clamp levers and grippers, and facilitating the assembling stage, considering possible adjustments in the machining programming. Finally, the proposed human-based data-driven methodologies contribute to defining the first step of measurement and inspection evolutions through the 4.0 Industry structure in an entire manufacturing system.*

Keywords: *metrology; machining; in-situ measurement; error modeling; dimensional accuracy; tool wear.*

1. INTRODUCTION

The rapid development of new technologies experienced in the last decades has brought the conception of the 4.0 Industry. Emerging as a German initiative, 4.0 Industry aims to integrate state-of-the-art technologies to define a resilient production based on cyber-physical systems (Lasi et al., 2014; Klingenberg, Borges and Antunes Jr., 2019). Beyond the technological advent that allows the consolidation of this concept, data acquisition, interpretation, application, and storage are crucial for the proper functioning of the 4.0 Industry (Klingenberg, Borges and Antunes Jr., 2019).

Data-driven strategies are a central starting point for the 4.0 Industry applications, considering that each operation involved in a production process has intrinsic limitations (Albertazzi and Sousa, 2008). Klingenberg, Borges and Antunes Jr. (2019) showed an extensive systematic literature review that reinforced the need to develop skills for data-based value generation in practical implementations of the 4.0 Industry. In this context, all operations involved in a manufacturing system will need to adequate their data collection and analysis capabilities.

Processing data usage can also benefit the metrology and quality tools in the 4.0 Industry. In this sense, it is crucial to understand how quality tools can take advantage of data, like go/no-go gauges, coordinate measuring machines (CMM), and in-situ measurement probes/sensors used to analyze dimensional accuracy regarding the design tolerances (Horst, Hedberg and Barnard, 2019). Thus, identifying potential causes of failure and dimensional variations and guaranteeing a robust process control could be more accessible in the 4.0 Industry.

Although in-situ probes can benefit effective production (Davis et al. 2006; Horst, Hedberg and Barnard, 2019), these measurement systems require reliability to fulfill their role in quality management. In this sense, these in-situ measurement probes or other high-complexity inspection techniques can be compared with conventional offline methods, such as CMM, as an alternative for robustness evaluation (Schmitt and Niggemann, 2010; Zanini et al., 2021). Zanini et al. (2021) proposed strategies for X-ray computed tomography (CT) inspection of additively manufactured lattices using the substitution method based on references analyzed with a coordinate measuring machine. As a result, it was possible to state the uncertainties related to the CT inspection based on the conventional CMM, bringing new insights into its implementation as a measurement tool (Zanini et al., 2021). Similarly, other metrology approaches may be compared to CMM according to a structured methodology to improve its effective quality control capability.

This study aimed to develop data-driven strategies to improve the dimensional accuracy of clamp levers and grippers manufactured by milling. Thus, comparing machined clamp levers and grippers' critical dimensions measured with CMM and an in-situ measurement probe (ISM) based on systematic errors could be used to improve the ISM accuracy. Additionally, experimentally estimating the cutting tool wear also contributed to developing a model to offset this phenomena effect on dimensional variation during machining. Mapping dimensional deviation sources during processing steps facilitates the identification of different operations contributions to the final product dimensional variation using a data-based approach. Thus, the proposed human-based data-driven methodologies favor achieving the first step for the 4.0 Industry implementation, demonstrating how to incorporate data-based decisions in manufacturing processes.

2. MATERIALS AND METHODS

The case study was developed in a multinational machine tool manufacturer branch located in the metropolitan region of São Paulo, Brazil. The proposed investigation aimed to revise the machining conditions of 42 CrMo4 steel clamp levers and grippers (Fig. 1) to identify strategies to improve these components' dimensional accuracy by avoiding rework.

The produced clamp levers and grippers are applied in tool magazines to hold the mandrels. These components are made in batches with ten components per machining cycle of about 45 minutes, running along two regular shifts daily. After manufacturing, grippers are heat treated with induction hardening and returned for jointing with the clamp levers. This assembling operation is conducted manually, and each clamp lever and gripper must have a compatible fitting system to meet the application requirements. However, some processing-induced dimensional errors can affect the fitting during the set assembling, requiring reworking and impacting the cycle time.

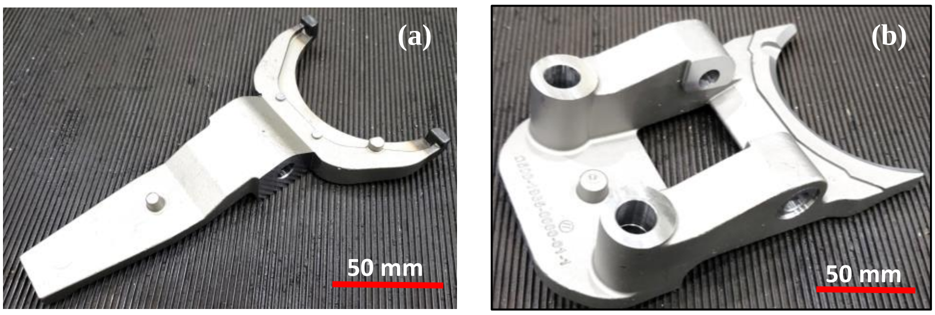

Figure 1. 42 CrMo4 steel (a) clamp levers and (b) grippers.

Even under rigorous quality control, grippers-clamp lever set manufacturing involves many activities that can introduce dimensional errors. Thus, a root causes mapping could support the main error sources recognition for developing action plans, as further detailed in Section 3. As a starting phase for this analysis, a technical visit was carried out to the fabrication cell during a typical working shift to accompany each procedure during the manufacturing process. Then, action plans could be proposed for improving the dimensional accuracy of clamp levers and grippers based on the evaluated activities, as detailed in Sections 2.1 and 2.2.

2.1 In-situ measurement planning

A horizontal five-axis G550 machining center (GROB-WERKE GmbH & Co. KG, Mindelheim, Germany) performed the milling operations of the clamp levers and grippers. This machine operates with a high-pressure cooling lubricant pumped at about 2.3 MPa (GROB-WERKE GmbH & Co, 2021). The machine uses a tool magazine to manufacture near-net-shape clamp levers and grippers without multiple setups.

The G550 machining center contained an OMP60 probe (Renishaw, Wotton-under-Edge, England) responsible for on-machine measurement of critical products' dimensions. This device was named ISM in the present study. The ISM measures are commonly considered for manual compensations inputs by the operator if necessary to avoid scrap. However, these adjustments needed a procedure based on the equipment response capabilities in terms of accuracy to avoid introducing dimensional variations in the manufactured components. As a prior work package, the ISM accuracy was evaluated regarding the grippers' critical dimensions in the machining center. So, nine identified grippers had their critical dimensions, named C1 and C2 (Tab. 1), measured with the ISM using a 175 mm/min feed and later measured with a Global Advantage Hexagon (Stockholm, Sweden) tactile coordinate measuring machine (CMM). Each dimension was evaluated for the milling reference coordinates' positive and negative symmetric sides.

Table 1. Main critical dimensions for the gripper-clamp lever assembly.

Critical dimension	Description	Nominal value (mm)	Tolerances (mm)
C1	Define the value between the gripper's zero position and a Ø12 hole centered in the symmetry axis.	140	0/+0.01
C2	Define the diameter of lateral holes in the grippers used in a pin fitting during assembling.	Ø10	+0.029/+0.044

The CMM measurements were taken as the calibrated reference due to the expectation of lesser prone-to-error results [4]. Thus, the evaluation of the on-machine method performance used an adaptation of the substitution method regarding CMM calibrations [6, 7]. Therefore, the uncertainty of the ISM (U_{ISM}) used Eq. (1) (ISO, 2009; Schmitt and Niggemann, 2010; Zanini et al., 2021):

$$U_{ISM} = k_c\sqrt{u_{cal}^2 + u_{dft}^2 + u_{proc}^2 + u_{pc}^2 + u_b^2} \quad (1)$$

in which u_{cal} refers to the CMM standard uncertainty; u_{dft} is the uncertainty attributed to workpiece shape variations between the inspection techniques; u_{proc} defines the standard deviation of the reference measurements; u_{pc} considers the uncertainty related to differences between the measured parts in actual working shifts and the ones used for the experiments; u_b is the portion of systematic errors of the ISM measurements, which refers to regular errors that can be managed (Albertazzi and Sousa, 2008); and k_c is a constant that defines the coverage factor (Schmitt and Niggemann, 2010; Zanini et al., 2021).

The CMM standard uncertainties would be 0.0019 mm for C1 and 0.0015 mm for C2 because of the machine accuracy of (1.5+L/333) μm, where L corresponds to the length in millimeters. Also, CMM measurements standard deviation (u_{proc}) and the systematic errors attributed to the ISM measurements (u_b) were determined with nine replications (Albertazzi and Sousa, 2008, Zanini et al., 2021). The covered factor k_c was stated as 2, considering the associated confidence interval of 0.95 (Schmitt and Niggemann, 2010; Zanini et al., 2021). Finally, the ISM uncertainty determination disregarded the u_{dft} term, considering that CMM and ISM measurements were conducted just in sequence (Zanini et al., 2021), and the u_{pc} source, taking into account the workpieces used for the measurement evaluation, were real grippers under regular working shifts.

2.2 Tool wear evaluation plan

While machining the most critical geometry in grippers, an arc with beveled edges, the tool wear was also evaluated as a second work package. The experiments were performed with the actual processing conditions, considering the cutting parameters of rotations (n) of 4600 rpm, feed (F) equal to 1380 mm/min, and cutting speed (v_c) of 250 m/min for two tools used for the arc machining. In this scenario, the production rate is of 1.43 parts/minute.

The tools are made up of 16MnCr5 steel. Both milling tools have a similar non-conventional geometry, as illustrated in Fig. 2a, 2b, and 2c. Hence, the tool wear evaluation considered the four critical points of the tool's cutting edge, taking the relative distances between the tool lengths and the preset references located in the cutting edges P1, P2, P3, and P4 (Fig. 2d). The measures were named Z-P_, considering the last digit as the preset identification number. The nominal values of each preset are shown in Tab. 2.

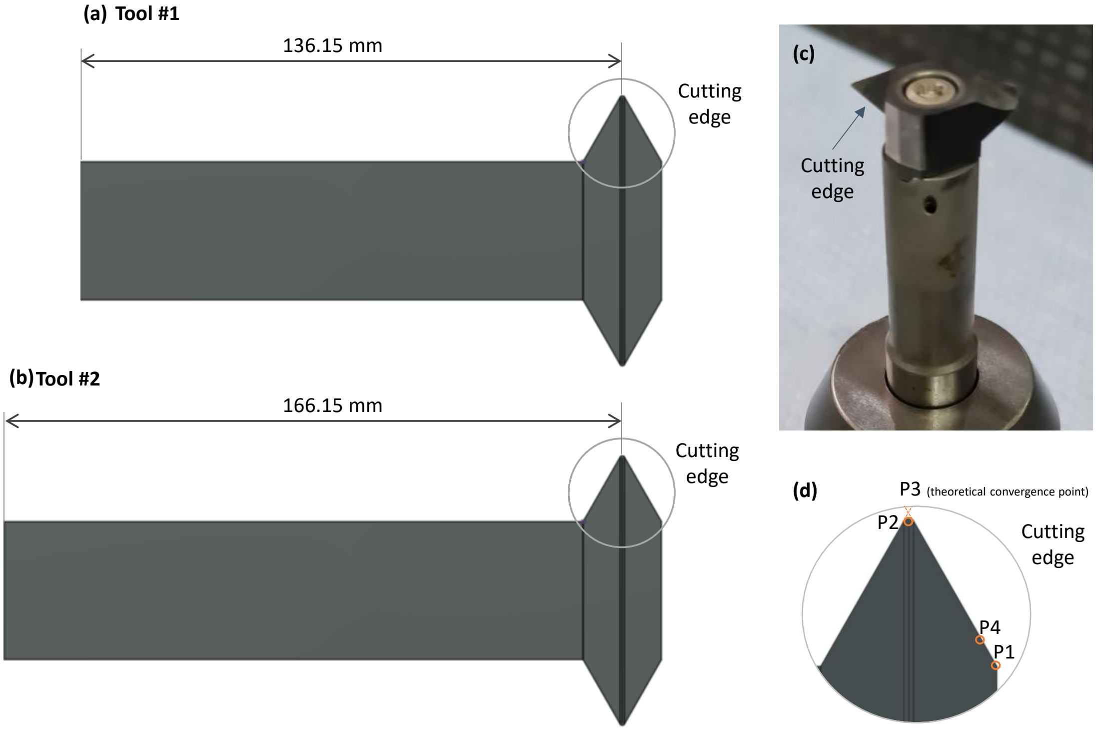

Figure 2. Illustrative representation of the machining tools (a) #1 and (b) #2 used for tool wear evaluation, as well as (c) the real tool and (c) the preset references in the cutting edges, highlighting the tool wear measurement points P1 to P4.

Table 2. Nominal values of the preset references considered for tool wear evaluation.

Tools	P1 (mm)	P2 (mm)	P3 (mm)	P4 (mm)
#1	136.15	132.30	132.30	135.65
#2	166.15	162.30	162.30	165.65

Three measurement stops equally distributed in a previously known tool life of about 45.5 minutes were stated for the measurements, as shown in Tab. 3. For each case, the tool was removed from the machining center for inspection in the presetting and measuring equipment venturion 800/10 Zoller GmbH & Co. (Pleidelsheim, Germany), according to the setup shown in Fig. 3. In this system, the tool was positioned in the center of a rotative platform where an industrial camera coupled with a ring light allows the magnification of tool critical parts for a precise inspection. The obtained geometries are synchronized with the pilot computational software, where the quantitative evaluation of the cutting edge presets (Fig. 2d) could be extracted from the processed image of the tool. After each measurement, the tool was returned to the machining center, and processing proceeded until the cycle finished (tool life).

Table 3. Experimental conditions for tool wear evaluation.

Runs	Machining time (min)	Quantity of machined components
#1	10.5	15
#2	28	40
#3	45.5	65

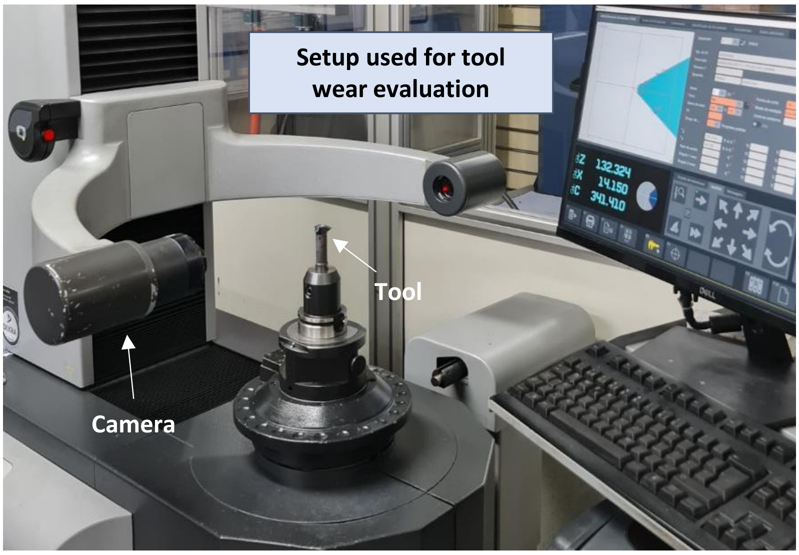

Figure 3. Equipment used for tool wear inspection.

Following the experimental studies, the dimensional differences found for each preset reference were considered the tool wear when the measurement variation did not influence the expected behavior for this physical phenomenon. Thus, the experimental data could be modeled using linear regression to provide a better in-situ tool wear compensation strategy.

3. RESULTS AND DISCUSSION

As a result of the technical visit, an Ishikawa diagram, which allows clustering error sources within a standard classification, could be structured to support the investigations (Realyvásquez-Vargas et al., 2018). So, Figure 4 shows the potential influence factors for dimensional variation in the grippers-clamp lever sets, subdivided by their nature in the processing context. It was covered in the analysis just the internal activities of the manufacturer, which could be improved. Regarding the processing parameters, cutting variables and tool wear can affect the working accuracy of the machine tool, giving rise to geometrical errors (Fauzer, 1997). Similarly, the material conditions, like hardness, can provide dimensional variations because of changed material responses during machining (Bai et al., 2021). Also, if the stock to leave varies depending on the part, it changes the dimensional accuracy within a working batch. In terms of operations and machines, each activity is susceptible to dimensional variations because of different procedures, occasional mistakes during the setup for different parts, or even noises (Weck and Brecher, 2006). The measurement process is another critical source of dimensional variation if there are calibration issues and non-standard statements of the uncertainty relations among the multiple measurement techniques (Zanini et al., 2021). Finally, environmental conditions, such as temperature, may also induce dimensional deviations because of their potential effects on the material and measurement systems (Albertazzi and Sousa, 2008).

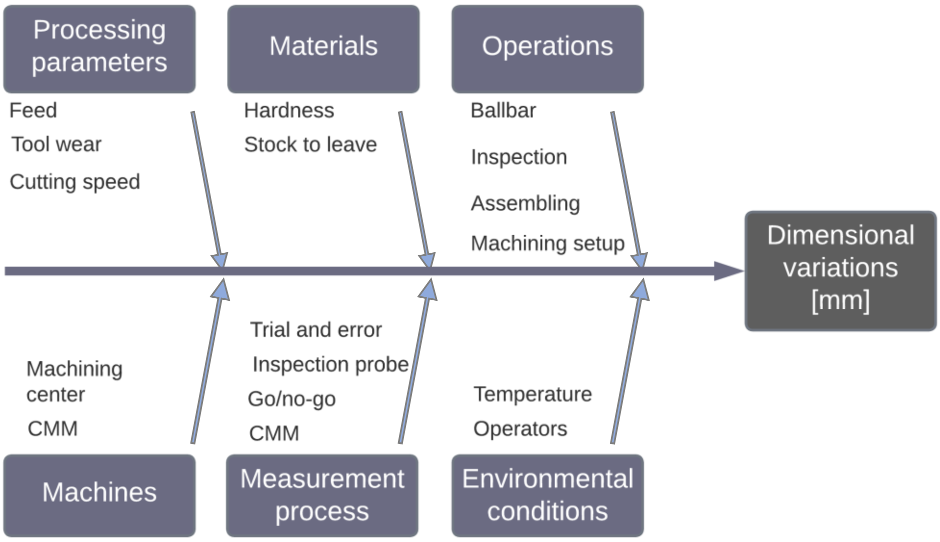

Figure 4. Ishikawa diagram with the leading potential causes of dimensional variations in the studied machining-based process.

Figure 5 shows the activities in the workflow defined for the case study development. According to the potential causes identified (Fig. 2), experimental tests were planned and conducted during a working shift to be closer to actual processing conditions. Based on the interpretation of the collected data, further detailed in sections 2.1 and 2.2, the main root causes that needed improvement were defined. Thus, it was possible to state action plans for solving two issues: in-situ measurement uncertainties and tool wear control during machining (Sections 2.1 and 2.2). The results of these plans' implementation are detailed in Sections 3.1 and 3.2.

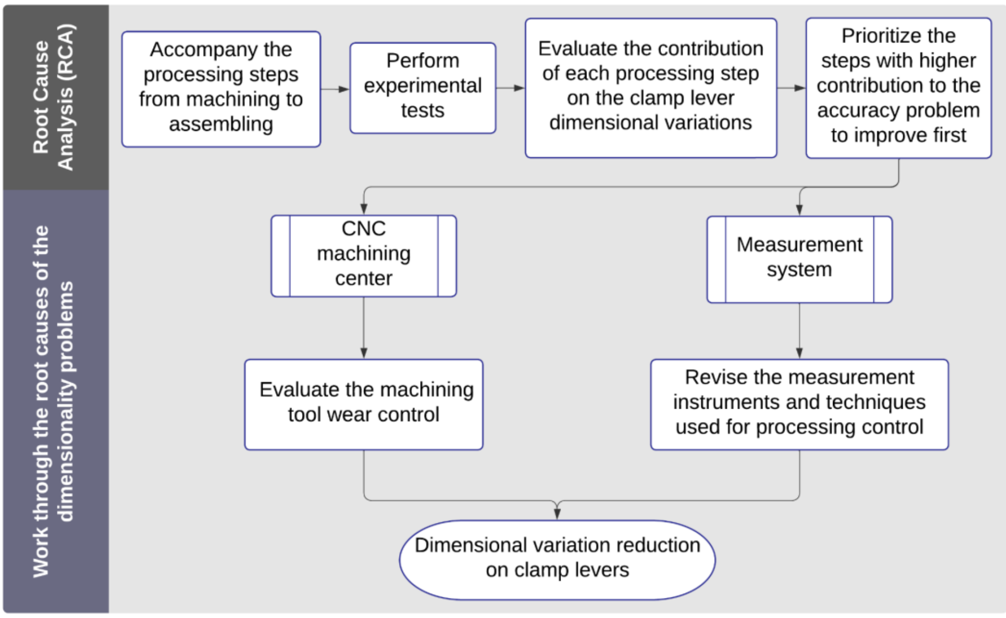

Figure 5. Workflow used for root cause mapping and operations improvements.

3.1 In-situ dimensional measurements

Table 4 shows the statistical metrics obtained for the measurements performed with the ISM and CMM. When comparing both average measurements, systematic errors of 0.019 and -0.009 mm were found for dimensions C1 and C2, respectively. These deviations can be adjusted in the ISM to improve the machining results. A lower precision of the ISM may be responsible for the higher standard deviation in CMM. Additionally, the uncertainties of the ISM (U_{ISM}) determined with an adaptation of the substitution method are shown in Tab.4. Calculated U_{ISM} showed that the ISM uncertainty was very close to the C2 dimension tolerance (Tab. 1) but remained within the acceptable interval. However, the ISM uncertainties exceed the C1 tolerance shown in Tab. 1. Also, it highlighted a high ISM expanded uncertainty compared to the one obtained with the substitution method application for X-ray computed tomography inspection of additively manufactured lattices (Zanini et al., 2021). Thus, actions should be taken to improve the measurement system.

Table 4. Comparison of the ISM and CMM (reference) measurements for dimensions C1 and C2.

Critical dimensions	C1		C2	
Metrics	ISM (mm)	CMM (mm)	ISM (mm)	CMM (mm)
Average measurements	140.009	139.990	10.029	10.038
Systematic errors	0.019	-	-0.009	-
Range	0.028	0.037	0.026	0.006
Standard deviation	0.007	0.012	0.001	0.006
U_{ISM}	0.045	-	0.022	-

Figure 6 shows the scatter plots of the experimental ISM measurement data and their estimated systematic errors. Additionally, correlation metrics between ISM measurements and estimated systematic errors were determined to investigate how these errors could be adequately controlled, as shown in Tab. 5. C1 and C2 dimensions showed different behaviors between the ISM measurements and estimated errors, evidencing the necessity to elaborate two different routes for variations management.

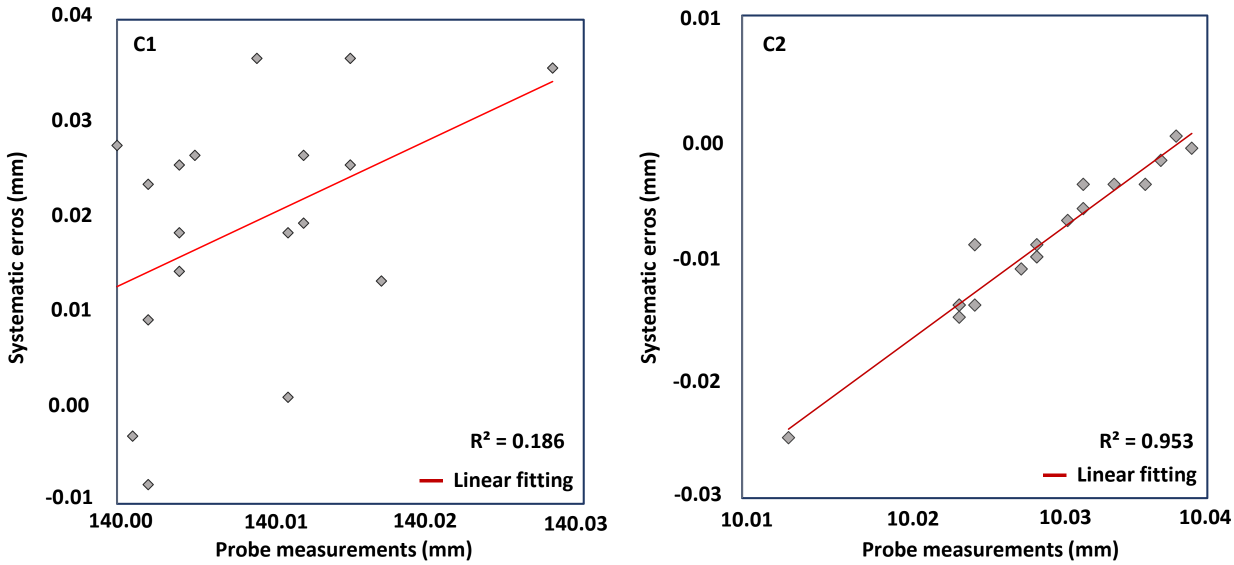

Figure 6. Scatter plots of ISM measurements and systematic errors for C1 and C2.

Regarding the C1 dimension, based on the Pearson coefficient (r), the coefficient of determination (R^2), and the scatter plot, the lack of relationship between the ISM measurements and respective estimated systematic errors could be stated. In this case, the suggested approach was to use the estimated error value (Tab. 4) for compensating the in-situ measurements associated with the C1 dimension during machining. This correction could be implemented directly in the NC machining program.

Table 5. Correlation metrics between ISM measurements and estimated systematic errors.

Correlation metrics	C1	C2
Pearson coefficient, *r*	0.431	0.976
p-value	0.074	$4.802 \cdot 10^{-12}$
Coefficient of determination, R^2	0.186	0.953
Adjusted R^2	0.135	0.950

On the other hand, the C2 dimension expressed a high correlation between the ISM measurements and their systematic errors. This conclusion could be supported by the statistics of r = 0.976 and R^2 = 0.953, shown in Tab. 4. In this way, it would be possible to implement a linear fitting upon the experimental data for compensating systematic errors generated during the in-situ measurement of the C2 dimension. Equation 4 defines the obtained relation for the adjustment, considering that M_c refers to the measurement compensation and P_m to the ISM measurement. As a result, the established relation could also be implemented in the NC code to improve the dimensional accuracy of the manufactured grippers.

$$M_c = 0.9424 - 9.4606 * P_m \quad (4)$$

3.2 On-machine tool wear compensation

Tool wear values were estimated based on the variations from the nominal presets measured for each machining stop. It is essential to highlight that preset references in which the measures did not follow a feasible physical behavior within the studied interval, for example, decreasing from run #1 to #2 and then increasing from run #2 to #3, were disregarded for the mean determination and tool wear modeling. Thus, plots of the tool wear measurements are shown in Fig. 7.

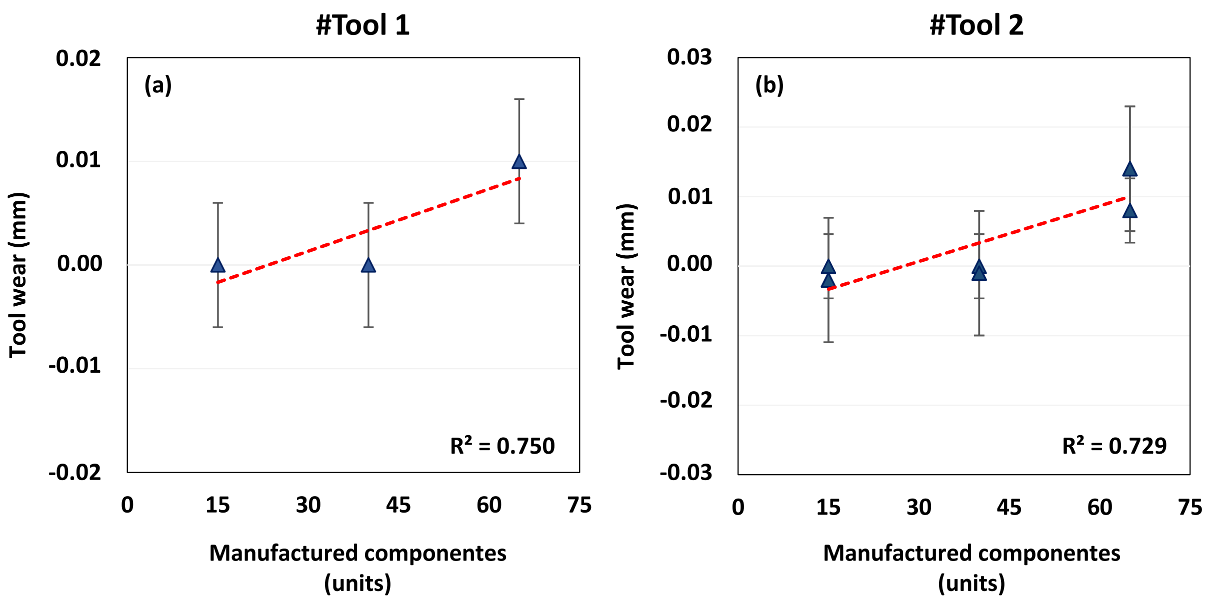

Figure 7. Tool wear evaluation results for (a) Tool 1 and (b) Tool 2.

Significant tool wear could be identified in the third run, considering values higher than the order of magnitude of tolerances of the critical dimensions (Tab. 1). This implies that a compensation strategy would be required for dealing with dimensional accuracy. So, the tool wear modeling can be used as the primary dimensional variation control as an on-machine quality tool. Equations 5 and 6 provide the linear fitting models that could be used for tool wear compensation when using tools 1 and 2, respectively.

$$t_w = 0.0002*p_{comp} - 0.0047 \quad (5)$$

$$t_w = 0.0003*p_{comp} - 0.0073 \quad (6)$$

As a next step through the 4.0 Industry, more data could be collected under complementary manufacturing conditions to improve quality control by modeling with machine learning techniques. The proposed data-driven strategies benefit the definition of in-situ monitoring and correction of dimensional accuracy according to actual observations analyzed with statistical tools. So, it would support a transition to a manufacturing structure more suitable for 4.0 Industry pillars, mainly regarding real-time integration and connectivity feasibility (Klingenberg, Borges and Antunes Jr., 2019).

4. CONCLUSIONS

Data-driven strategies were proposed to improve the dimensional accuracy of clamp levers and grippers manufactured by milling. Based on experimental studies, it was possible to obtain the systematic errors related to critical dimensions of the grippers using the CMM and ISM comparison and the influence of tool wear behavior through the machining cycle. As a result, two different routes of corrections to be applied directly in the NC program could be proposed to improve the final dimensional accuracy. Regarding the quantitatively determined deviations between ISM and CMM, the C1 dimension could be adjusted based on the observed systematic errors of 0.019 mm. In contrast, the C2 dimension would be better managed by the linear relation dependent on the ISM measurement. Concerning the tool wear, this variation source increased with the manufacturing cycle, reaching values even higher than 0.01 mm after 65 machined components, which is also the value of the C1 tolerance. Thus, linear fitting models were also defined for tool wear compensation to enhance dimensional accuracy. The proposed approaches take advantage of the data-based decision to improve the in-situ measurement control, bringing highlights for future 4.0 Industry implementation.

5. ACKNOWLEDGEMENTS

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