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THE ANALYSIS OF MACHINED HOLE DIAMETER’S DEVIATIONS

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Abstract: Determining the accuracy of a machine tool is an essential aspect of quality assurance in the machining industry. To determine this accuracy, precise measurements are conducted on the analysed characteristics of the machined parts, comparing the obtained values with the nominal values specified in the technical documentation. Through statistical analysis of this data, potential issues can be identified and corrected, thus contributing to increased efficiency and quality of the production process. In this study, the accuracy of the HAAS V1 vertical milling center in drilling holes of various diameters while maintaining dimensional accuracy was determined. The measurement of hole diameters was performed using the Sinowon 3D video measurement system. A total of 9 holes were drilled for each diameter, resulting in a total of 27 holes. The obtained data were statistically analysed to determine the variations in hole diameters and to test the accuracy of the machine tool. The machine accuracy indices, Cm and Cmk, are used to assess the ability of the vertical milling center to ensure the required accuracy when drilling the 2024 T351 alloy. In the analyzed case, the characteristic under consideration is the deviation of the diameter of each machined hole from the nominal diameter of the drill. This approach allows the determination of the limits of the diameter characteristic, corresponding to the maximum and minimum deviations permitted by the standard for the accuracy class achieved by the drilling process. The results show that there is a relatively high probability that non-conforming products can be detected through the application of statistical control methods.

Key words: machine accuracy, statistical control, machining, drilling.

1. INTRODUCTION

In the machining industry, ensuring the quality and accuracy of manufactured parts is an important aspect of the production process. One of the most important control parameters is the ability of machine tools to maintain dimensional variations within tolerance limits. Statistical analysis of the machining process allows for the identification and correction of variations, thus contributing to improving production accuracy and reliability.

To better understand the influence of process factors on dimensional variations, the concept of statistical process control is analyzed. Figure 1 represents a schematic model of how an industrial process can be analyzed and statistically controlled in order to maintain quality and production efficiency.

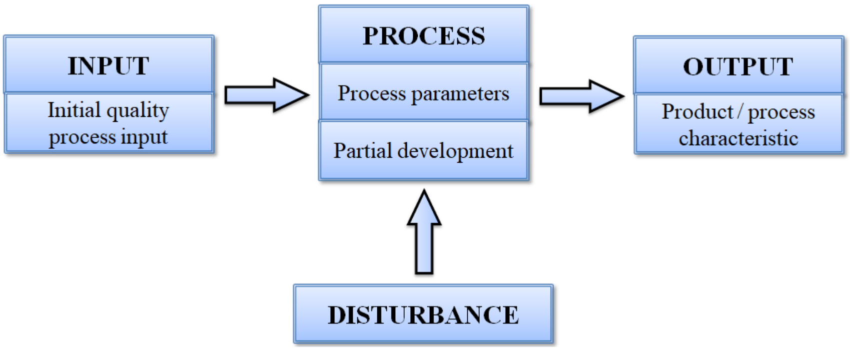


Fig. 1. Statistically controlled process model, [1, 2]

According to Figure 1, the *Input* zone represents the parameter values at the beginning of the process. It is important to remember that any variation in these parameters can influence the final result. The *Process* zone illustrates how the process parameters influence the production process.

At this stage, the process factors can be adjusted to maintain the stability and accuracy of the operation. The *Output* zone represents the final characteristics of the product or process, the direct result of the input and the process parameters. A properly controlled process must provide an output according to the desired specifications. At the same time, the *Disturbance* zone is represented by external factors or internal variations that can influence the process, causing deviations from the nominal values. These can include various variations, tool wear, temperature fluctuations etc.

Statistical process control (SPC [3]) is an effective tool for evaluating process accuracy. The application of SPC methods allows the identification of both normal and abnormal variations that can affect the quality of the final product. Continuous monitoring and adjustment of processes based on statistical analyses contribute to the reduction of losses.

Process accuracy is a fundamental concept in quality assurance and in the optimization of manufacturing processes. It reflects the ability of a production process to obtain parts in accordance with the imposed specifications, minimizing variations and maintaining the stability of the dimensions obtained in relation to the prescribed tolerances. In the context of mechanical processing, determining the accuracy of machine tools is fundamental for increasing efficiency and reducing losses caused by manufacturing errors [1-3].

In the literature, numerous studies have approached process accuracy analysis and methods for improving precision in component manufacturing. The researchers have focused on applying advanced quality control methods to reduce variations and optimize the performance of the machining process.

Abdolahi A. and colleagues [4] conducted a study on the application of machine learning algorithms to optimize the accuracy analysis in the domain of additive manufacturing processes. The paper proposed a predictive model capable of anticipating dimensional deviations of parts produced by 3D printing, thus providing an innovative solution to support quality control. The results highlighted that machine learning-based methods can significantly aid in increasing process precision and in the early detection of deviations from established tolerances.

Benkova M. et al. [5] analyzed the use of accuracy indices C_p and C_{pk} for the evaluation of the manufacturing process, emphasizing their importance in the statistical process control. The study demonstrated that by applying *SPC*, uncontrolled variations in a machining process can be identified and quickly corrected, which leads to a high level of conformity of finished products. The paper also highlighted the benefits of using accuracy indices in preventing defects and improving process performance.

Tianlong L. et al. [6] proposed a process accuracy analysis, using Tail-type modeling to improve the accuracy of determining dimensional variation in multivariate manufacturing processes. This method allowed a more accurate estimation of the distribution of variations in the case of complex processes, having direct applications in the mechanical processing industry, where tolerances must be strictly respected.

Khan A. et al. [7] conducted a study on a manufacturing process in an industrial environment. By statistical analysis of the collected data, the authors demonstrated how process accuracy determination methods can identify critical points that affect the dimensional accuracy of the produced parts. The study provided solutions for improving process control and reducing its variability.

Juran J. and De Feo J. [8] provided an overview of quality assurance methods, including fundamental techniques for determining process accuracy. Thus, it is explained how statistical process control and accuracy analysis contribute to continuous performance improvement in industry. The authors emphasize the importance of implementing a quality management system based on accurate measurements and rigorous statistical analysis.

Arcidiacono G. and Nuzzi S. [9] conducted a study on the fundamental concepts of process accuracy and introduced a new concept called *Process Sigma Split*. This methodology allows a clearer differentiation between process variations and systematic deviations, thus facilitating decision-making for performance improvement. The study is particularly relevant for precision manufacturing processes, where minimizing variations is essential.

Shinde J. H. and Katikar R. S. [10] investigated the importance of process accuracy and performance indices in the machine tool industry. The paper highlighted their impact on quality control and productivity, demonstrating that a well-controlled process not only ensures compliance with technical specifications but also contributes to optimizing production costs.

Baroiu N. et al. [2] conducted an analysis of the repeatability of drill positioning in a CNC vertical machining center, to determine the influence of drill positioning on the accuracy of processed holes. The study showed that deviations can have a significant impact on the quality of the final product, highlighting the importance of rigorous calibration of machining equipment.

Qader H. et al. [11] proposed the use of wavelet analysis as a method for optimizing process specifications by improving process accuracy. By applying this technique, the authors demonstrated that complex patterns of variation within the manufacturing process can be identified, allowing precise adjustments to reduce dimensional deviations.

Czarski A. and Matusiewicz P. [12] analyzed the quality influence of the measurement systems on the evaluation of accuracy indices. The authors emphasized that an inadequate measurement system can lead to erroneous conclusions regarding process accuracy, thus affecting improvement decisions.

Therefore, the importance of process accuracy analysis is not limited to ensuring product conformity, but also contributes to optimizing costs and reducing production times. By applying a rigorous methodology for evaluating equipment performance, the machining industry can benefit from better control over process variability and improve the quality of delivered products.

As previously mentioned, determining accuracy involves applying statistical methods to analyze the results obtained from the machining process. Accuracy indices, such as C_p and C_{pk}, are used to evaluate the extent to which the process is within the imposed tolerance limits. These parameters are used for monitoring and continuous improvement of manufacturing processes, thus ensuring product compliance with quality requirements.

The process accuracy index, C_p, is determined by the position and width of the distribution in relation to the two tolerance limits: *USL* (*Upper Specification Limit*) and *LSL* (*Lower Specification Limit*), which can be either symmetrical or asymmetrical with respect to the nominal value [13], equation (1):

$$C_p = \frac{USL - LSL}{6\sigma}. \tag{1}$$

where 6σ represents the dispersion degree.

To analyze the position of the distribution in relation to the tolerance limits, process accuracy index – centered capability, C_{pk}, is used, which indicates the position of the mean value relative to the center of the tolerance interval [13], equation (2):

$$C_{pk} = min\left(C_{pk\ lx}, C_{pk\ rx}\right), \tag{2}$$

where $C_{pk\ lx}$ represents **U**pper **S**pecification **L**imit (*USL*) and $C_{pk\ rx}$ **L**ower **S**pecification **L**imit (*LSL*).

In the C_{pk} notation, the letter *k* indicates that this index refers to the actual capability of the process and allows it to be distinguished from the potential capability index, denoted as C_p. Unlike C_p, which assumes a perfectly centered process, C_{pk} penalizes any shift of the process mean.

According to the C_{pk} index, the confidence level of the process accuracy can be evaluated, as shown in Table 1. These values provide a measure of how well the process is centered and stable in relation to the tolerance limits.

Table 1. Confidence level of process accuracy, [13]

C_{pk} value	Significance
$C_{pk} < 1$	The process frequently produces non-conforming results.
$C_{pk} = 1$	Any change in the process can lead to non-conforming results that will not be detected.
$C_{pk} = 1.33$	It is difficult to anticipate the occurrence of non-conforming results through control charts.
$C_{pk} = 1.5$	Control charts are not very effective because the probability of detecting non-conforming results is still low.
$C_{pk} = 1.6$	There is a high probability that control charts will identify non-conforming products.
$C_{pk} = 2$	The chances that non-conforming products will be detected are very high, providing a high level of confidence in their detection.

Factors that can influence dimensional deviations include tool wear, machine tool stability, operating conditions, and the materials used. Therefore, to ensure optimal accuracy, regular equipment maintenance and continuous monitoring of the machining process are essential.

Determining the dimensional deviations of machined surfaces is a valuable tool for assessing the accuracy of a machine tool. Through statistical analysis of this data, potential issues can be identified and corrected, thus contributing to increased efficiency and quality of the production process.

In this context, the paper aims to determine the capacity of the HAAS V1 vertical milling center to produce holes with precise diameters, respecting the imposed technical specifications. The diameter measurement process was carried out with the help of the Sinowon 3D video measurement system, available in the computing and measurement laboratory of the Manufacturing Engineering Department at the Faculty of Engineering, „Dunarea de Jos” University of Galați, and the obtained results were statistically analyzed to evaluate the deviations from the nominal values.

To verify the machine tool's accuracy, drills with diameters of Ø6, Ø8, and Ø10 mm were used. A total of 9 holes were drilled for each diameter, resulting in a total of 27 holes. The obtained data was statistically analysed to determine the variations in hole diameters and to test the accuracy of the machine tool.

2. MATERIALS AND METHODS

The processed material was duralumin 2024 T351 type, whose chemical composition is presented in Table 2.

Table 2. Chemical composition of the 2024 T351 alloy [15]

***Si* ≤** [%]	***Fe* ≤** [%]	***Cu*** [%]	***Mn*** [%]	***Mg*** [%]	***Cr*** [%]	***Zn* ≤** [%]	***Ti*** [%]	**Others elem. ≤**	***Al***
0.50	0.50	3.8÷4.9	0.3÷0.9	1.2÷1.8	0.1	0.25	0.15	0.05	Remainder

The machining was performed on the HAAS V1 vertical milling center, using drills with diameters of Ø6, Ø8, and Ø10 mm. We used two-flute twist drills with nominal diameters of Ø6, Ø8, and Ø10 mm, in new condition, unaffected by wear. The drills used had cylindrical shanks, were made of high-speed steel (HSS), and were coated with a titanium nitride (TiN) layer.

The machining process was performed using a cutting fluid. The fluid available on the Haas VF-1 machine tool was employed; it is a water-soluble coolant based on synthetic oil, specifically formulated for CNC machine tools and metalworking operations.

The holes had a depth of 20 mm each. This means that each drill machined a total length of 180 mm, which, considering the machined material as well, allows us to state that tool wear had a negligible influence on machining accuracy.

Figure 2 shows the hole arrangement and the machining sequence.

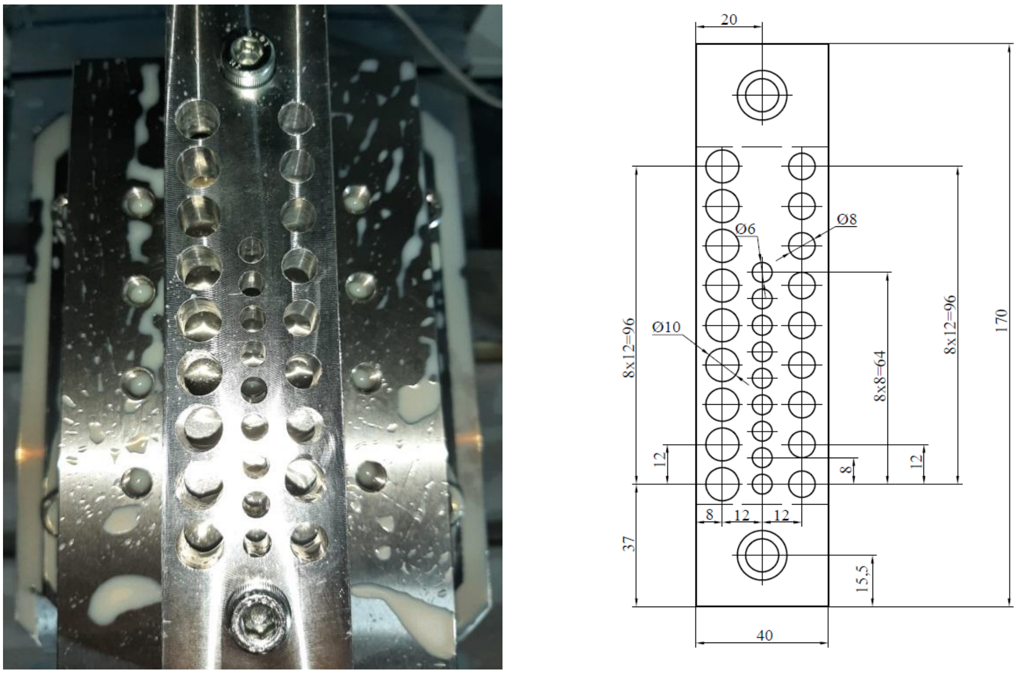


Fig. 2. Hole arrangement and machining sequence on the blank

The measurement of the hole diameters and the determination of the actual positions of their centers was performed on a Sinowon 2.5D measuring machine, which is a non-contact measuring system with a measurement accuracy of 1 µm. Each of the measured values was compared with the nominal values , and the errors were calculated.

3. RESULTS AND DISCUSSIONS

The measured values for the analyzed characteristics are presented in Table 3, where D_0 represents the nominal diameter of the holes, D represents the diameter obtained from the measurements, and ε represents the error obtained.

Since the processed holes have different diameters, in calculating the accuracy of the drilling process, the deviation from the nominal diameter was analyzed. In order to achieve statistical control of the process, frequency histograms must be constructed. For this purpose, the analyzed quality characteristics are arranged in ascending order and the amplitude of their variation is determined.

For the data presented in Table 3, the minimum error value is ε_{min}=-0.450 mm, and the maximum value ε_{max}=0.102 mm. Therefore, the error amplitude will be R=0.552 mm. The number of intervals, k, into which the string of values is divided will be, equation (3):

$$k = 1 + 3.322 \cdot lg\left(27\right) = 5.75. \tag{3}$$

Table 3. Nominal and measured values of drilled hole diameters

Crt. no.	D_0 [mm]	D [mm]	ε [mm]
1	10.000	9.922	-0.078
2	10.000	10.030	0.030
3	10.000	10.098	0.098
4	10.000	9.844	-0.156
5	10.000	10.078	0.078
6	10.000	9.816	-0.184
7	10.000	9.762	-0.238
8	10.000	10.102	0.102
9	10.000	10.042	0.042
10	8.000	7.964	-0.036
11	8.000	7.550	-0.450
12	8.000	7.766	-0.234
13	8.000	8.002	0.002
14	8.000	8.042	0.042
15	8.000	8.018	0.018
16	8.000	7.938	-0.062
17	8.000	8.088	0.088
18	8.000	7.918	-0.082
19	6.000	5.844	-0.156
20	6.000	5.884	-0.116
21	6.000	5.878	-0.122
22	6.000	5.852	-0.148
23	6.000	5.888	-0.112
24	6.000	5.860	-0.140
25	6.000	5.982	-0.018
26	6.000	5.864	-0.136
27	6.000	5.866	-0.134

5 intervals will be considered. The amplitude of the intervals is determined by the equation (4):

$$a = \frac{R}{k} = 0.067\,\text{mm} \tag{4}$$

The frequencies corresponding to each interval are presented in Table 4.

Table 4. Frequency distribution of errors in each selected interval

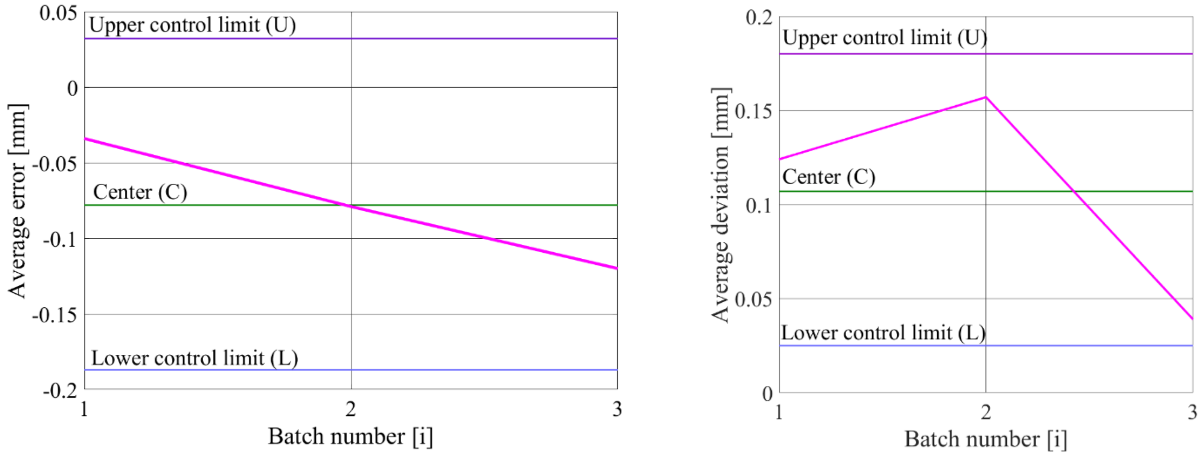
From	To	No. val.
-0.4500	-0.3396	1
-0.3396	-0.2292	2
-0.2292	-0.1188	8
-0.1188	-0.0084	7
-0.0084	0.1020	9

Since measurements were made for three different drill diameters, the errors were grouped into 3 batches, corresponding to each diameter. The measured values, averages and standard deviations of the three groups are presented in Table 5.

Table 5. Errors, averages and amplitudes within the three groups

Measured error [mm]		
D 10	***D 8***	***D 6***
-0.078	-0.036	-0.156
0.030	-0.450	-0.116
0.098	-0.234	-0.122
-0.156	0.002	-0.148
0.078	0.042	-0.112
-0.184	0.018	-0.140
-0.238	-0.062	-0.018
0.102	0.088	-0.136
0.042	-0.082	-0.134
Average error [mm]		
-0.034	-0.079	-0.120
s		
0.124	0.157	0.039

The positioning of the average error, $\bar{\varepsilon}_i$ and average deviation $\bar{s}_i$ parameters, i = 1÷3, relative to the control limits is shown in Figure 3.



a. b.

Fig. 3. Positioning of the average error (a) and the average deviation from the control limits (b), for each batch (i)

The average of the standard deviations will be s_{med} = 0.107 mm. The control limits are calculated with the equations (5):

$$U=\bar{X}+\frac{Z_{1-\alpha/2}}{d_3(m)\cdot\sqrt{m}}\cdot\bar{s};\ C=\bar{X};\ L=\bar{X}-\frac{Z_{1-\alpha/2}}{d_3(m)\cdot\sqrt{m}}\cdot\bar{s}, \tag{5}$$

where $\bar{X}$ represents the average of the values of the analyzed characteristic, $\bar{s}$ - average deviations, and m - observations of quality characteristics, where U represents the upper control limit, and L represents the lower control limit. These limits are calculated based on the process mean and statistical variation (see equation (5)). If a point exceeds U or L, the process is considered unstable (a special cause is present), even if the part still falls within the specification tolerances.

In equation (5), $Z_{1-\frac{\alpha}{2}}=3$, and the $d_3(m)$ constant is calculated using the relation (6), [17]:

$$d_3(m)=\begin{cases}\dfrac{2(k-1)\left(2^{k-2}(k-2)!\right)^2}{(2k-3)!}\cdot\sqrt{\dfrac{2}{\pi(2k-1)}}; & \text{for } m=2k,\\[2ex] \dfrac{(2k-1)!}{2\left(2^{k-1}(k-1)!\right)^2}\cdot\sqrt{\dfrac{\pi}{k}}, & \text{for } m=2k+1.\end{cases} \tag{6}$$

For $k = 4$, $d_3(m) = 0.969$ is obtained. With these values, the limits $L = -0.188$ mm., $C = -0.078$ mm and $U = 0.032$ mm.

The process is declared to have a deviation from the average at *i* time if the $\bar{X}_i$ mean of sample *i*, for the analyzed characteristic *X*, is outside the control limits *U* and *L*.

When the process is controllable, the average deviations s_i can be estimated with $\bar{s}$.

Thus, the control limits are calculated using the relation, derived from equation (5):

$$U = \bar{s} + \frac{Z_{1-\alpha/2}\sqrt{1-d_3^2(m)}}{d_3(m)}\bar{s};\ C = \bar{s};\ L = \bar{s} - \frac{Z_{1-\alpha/2}\sqrt{1-d_3^2(m)}}{d_3(m)}\bar{s}. \tag{7}$$

The values $L = 0.025$, $C = 0.107$, and $U = 0.188$ are obtained.

4. PROCESS AND MACHINE TOOL ACCURACY ANALYSIS

Considering the analyzed case, the deviation of the diameter of each processed hole from the nominal diameter of the drill will be considered as the analyzed characteristic. This allows determining the limits of the *diameter* characteristic as the upper and lower deviations allowed by the standard for the accuracy class that can be achieved by the drilling process.

The literature shows that when drilling with double-edged twist drills, the deviations from the hole diameters can be of the order of tenths of a millimeter. In addition, it is known that, in drills, the hole diameter is generally larger than the nominal diameter of the drill. Considering that the processed material is relatively difficult to cut and has a tendency to form a deposit edge, which leads to large dimensional deviations, and based on previous experience in processing the 2024 T351 alloy, the tolerance limits for the processed holes are considered as U=1.500 mm and L=0.950 mm.

With these values, a process accuracy index is obtained, equatin (8):

$$C_p = \frac{U-L}{6\cdot\sigma} = 1.61 \tag{8}$$

According to Table 1, this indicates a high probability of identifying non-conforming products. The position of the spreading field in relation to the tolerance limits is indicated by the C_{pk} index, determined using the relation (9) :

$$C_{pk} = min\left(C_{ps}, C_{pi}\right), \tag{9}$$

where:

$$C_{ps} = \frac{LSL-\bar{X}}{3\sigma};\ C_{pi} = \frac{USL-\bar{X}}{3\sigma} \tag{10}$$

These relationships lead to the values: $C_{ps} = 3.218$ and $C_{pi} = 4.931$, resulting in $C_{pk} = 3.218$.

Another accuracy index, which describes the accuracy of the machine tool, is the machine accuracy index, denoted C_m. The machine accuracy index is calculated with the relation (11):

$$C_m = \frac{USL-LSL}{6\sigma} \tag{11}$$

To study the position of the spreading field in relation to the tolerance limits, the C_{mk} index is used, which describes the value of the spreading field corrected with the position of the average value, equation (12):

$$C_{mk} = min\left(C_{ms}, C_{mi}\right) \tag{12}$$

where,

$$C_{ms} = \frac{LSL-\bar{X}}{3\sigma};\ C_{mi} = \frac{USL-\bar{X}}{3\sigma} \tag{13}$$

The obtained values are: $C_{ms} = 6.436$; $C_{mi} = 9.862$; $C_{mk} = 9.862$.

5. CONCLUSIONS

The results indicate that there is a significant probability that non-conforming products can be detected through the application of statistical process control. The previously calculated values ($C_m \approx 1.6$) support this conclusion, see also table 1, highlighting the effectiveness of statistical methods in identifying deviations from established specifications and preventing the production of non-compliant parts.

In this study, the accuracy of the drilling process performed on the HAAS V1 vertical machining center was analyzed using statistical methods to evaluate the dimensions obtained from the machining operations. The application of these methods allowed not only the monitoring of process variability but also the quantification of the equipment's performance in maintaining the specified tolerances.

To assess the accuracy of the process to meet tolerance limits, the statistical indices C_p and C_{pk} were used, reflecting the extent to which the process conforms to the technical specifications. In parallel, the indices C_m and C_{mk} were employed to evaluate the capability of the vertical machining center to achieve the desired accuracy when drilling the 2024 T351 alloy, taking into account its material characteristics and functional requirements.

These parameters serve as essential tools for continuous monitoring and improvement of manufacturing processes. Their use ensures a stable production process compliant with quality standards, reduces the risk of non-conforming products, and optimizes the efficiency of the technological process. In this way, statistical process control becomes a key element in quality management, enabling reproducible and reliable results in material machining.

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