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Accuracy Examination of Hole Machining Methods

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Abstract

The geometric accuracy and surface quality of hole machining processes are fundamentally important for the operational reliability of manufactured components, as supported by the literature review. The aim of this research was to compare the geometric and surface characteristics of circular pockets produced by three different machining methods: turning, boring, and milling. During the investigations, coordinate measuring machine (CMM) and surface roughness measurement methods were applied, and the results were evaluated using the Taguchi method, signal-to-noise (S/N) ratio analysis, and weighted scoring assessment. Based on the results, boring proved to be the most favorable method in terms of geometric accuracy, while milling yielded better surface roughness values. The findings of this research can support the selection of appropriate pre-production machining technologies and contribute to the optimization of manufacturing processes.

Keywords: *geometric tolerance, hole machining, Taguchi experiment design.*

1. Introduction

The attainable geometric accuracy of cylindrical surfaces plays a decisive role in the operational reliability of manufactured components, particularly in applications where bearing fits, interference fits, or sealing functions are required. The aim of modern manufacturing technologies is not only to ensure dimensional accuracy, but also to minimize form deviations (such as cylindricity and roundness errors). For this reason, the comparison of different machining processes and the optimization of their technological parameters are indispensable.

To evaluate the geometric and dimensional accuracy of machined parts, various quantitative indicators can be applied, the definition and interpretation of which are described in detail by ISO standards. The ΔD (diameter deviation) represents the difference between the measured mean diameter and the nominal size, and is interpreted according to ISO 14405-1:2016 concerning dimensional tolerances. In addition to dimensional tolerances, geometric tolerances provide a more detailed description of the deviation of the manufactured feature. The RONt (total roundness deviation) expresses the departure from roundness and is defined according to ISO 12180-1 and ISO 12180-2 (**Fig. 1**/a).). This value represents the difference between the largest and smallest radii of the measured contour within a given cross-section. Similarly, CYLt (total cylindricity deviation) describes the overall departure from cylindricity, as defined in ISO 12181-1 and ISO 12181-2 (**Fig. 1**/b). This characteristic is interpreted as the radial distance between the smallest and largest concentric cylinders that completely enclose the measured surface. All three indicators are generally expressed in micrometers (μm) and are typically determined during form and dimensional inspections performed with coordinate measuring machines (CMM). In the present study *ΔD*, *RONt* and *CYLt* parameters were applied for the geometric characterization of the bore features.

Turning is one of the most widespread methods for producing cylindrical surfaces; however, in certain cases it cannot be applied (e.g., for assembled or non-axisymmetric components). In such situations, alternative machining processes (e.g., milling or boring) come to the fore.

During milling operations, in addition to cutting parameters, other conditions also influence the accuracy of the machined surface, such as cooling and lubrication conditions **[1]**. Based on experimental results, the most promising outcome was obtained with a cutting speed of 65.46 m/min, a table feed rate of 0.3 m/min, and an emulsion flow rate of 1.16 l/h, where the *CYLt* value was 19.20 µm and *CYLv* was 8.52 µm **[1]**.

Measurements have shown that the type and amount of lubricant significantly affect the *CYLt*, *CYLp*, and *CYLv* values. According to research findings, the lowest *CYLt* value (13.31 µm) was achieved with a cutting speed of 188.5 m/min, a feed of 0.05 mm/rev, and an emulsion flow rate of 546 cm^3/min **[2, 3]**.

The analysis of various form errors has also received increasing attention in tangential turning. Due to its specific kinematic characteristics, this method is highly suitable for machining high-precision cylindrical surfaces; however, form deviations – particularly *CYLv* and *RONt* – are strongly dependent on cutting speed and depth of cut **[4]**.

In the comparison of hard machining processes (hard turning of hardened steels and grinding), *RONt*, *CYLt*, *CYLtt* and *Ra* indicate that hard turning can be a competitive alternative to conventional grinding, particularly when machining is performed in a single setup on the same machine **[5]**.

Honing, as a finishing operation, also contributes to the production of bores with excellent form accuracy. In the work of Nagypál and Sztankovics **[6]**, it was demonstrated that the structure of the abrasive tool and the feed rate influence *CYLt*, *CYLtt* and *RONt* – the use of smaller grain sizes and denser structures resulted in improved cylindricity.

Special attention should also be given to processes based on mechanical surface modification (non-cutting). Ferencsik and Varga investigated the effects of diamond tool burnishing on microhardness and cylindricity in several studies **[7, 8]**, and demonstrated that, with appropriate burnishing parameters, form accuracy can be significantly improved.

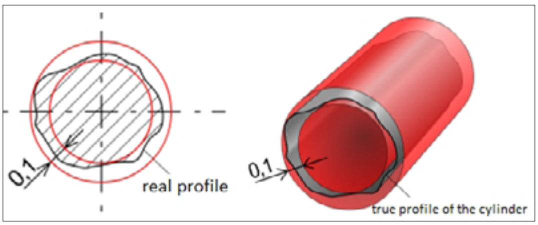

Fig. 1. *Determination of geometric deviations in circularity (a) and cylindricity (b).*

The combined findings of these studies indicate that various cutting and forming processes affect the development of geometric form accuracy, and that the careful selection of technological parameters is always required to achieve the desired outcome.

The aim of the present study is to investigate to what extent the geometric accuracy of bored cavities – particularly in terms of cylindricity, roundness, and surface roughness parameters – approaches that of workpieces produced by turning. The results may help to determine whether, in future experiments, boring alone is sufficient for the pre-machining stage.

2. Materials and methods

During the machining experiments, circular pockets were produced using three different machining technologies. In all three cases, cemented carbide tools supplied by Walter Hungária Ltd. were employed. For the circular pockets produced by turning, an A20S-SDQCL11 boring bar equipped with a DCMT11T304-MP4-WPP20G insert was applied (**Table 1**/No. 1). For the workpieces machined by boring, a B4030G.T28.33-41.Z tool and a TCMT06T104-FP4 insert were used (**Table 1**/No. 2), while for the circular pockets produced by milling, an H4021017-20 end mill was employed (**Table 1**/No.3).

The machining experiments were carried out on a MAZAK SQT 10 MS CNC turning center and a Mazak Nexus 410A-II CNC milling machine. Tool condition assessment and verification of their geometric dimensions (actual tool diameter determination for boring and milling tools) were performed using an Elbo Controlli Hathor laser tool presetter.

The machining tests were conducted on C45 (1.0503) quenched and tempered carbon steel with the following chemical composition: C: 0.43-0.5%; Si: <0.4%; Mn: 0.5-0.8%; Ni: <0.4%; P: <0.045%; Cr: <0.4%; Mo: <0.1%. Due to its excellent mechanical properties, this material is widely applied as a base material for mechanical and structural components. The workpieces used in the experiments, with a geometry of Ø80 x 70 mm, exhibited a hardness of HV30 185 ± 7.3 (σ: 3.65).

The preforms of the workpieces used in the experiments were produced on the MAZAK SQT 10 MS CNC turning center in two setups. During the tests, a circular pocket of Ø34 mm was finished to a depth of 32 mm (Fig. 2). The depth of cut (a) (in the case of milling, width of cut (ae)) was 0.5 mm. To ensure comparability of the experimental results, the material removal rate (V' [mm³/min]) was kept identical for all three machining processes. The machining experiments were performed under flood cooling conditions using a 6% solution of MOL Emolin 420.

The machining experiments were designed according to the Taguchi experimental design method (L9). During the investigation, for each machining process the cutting speed (v_c) and the feed per tooth (f_z) were varied at three levels. The applied technological parameter values are presented in Table 2.

2.1. Coordinate measurement investigations

Following the machining experiments, the geometric errors of the circular pockets (*RONt*, *CYLt*) and their dimensional deviations from the theoretical geometry (*ΔD*) were determined using a Mitutoyo CRYSTA-Apex V544 CMM. The investigated geometric deviations were evaluated at eleven depth levels (h: 2; 4.5; 7; 9.5; 12; 14.5; 17; 19.5; 22; 24.5; 27 mm), with 24 measurement points per level (total: 264 points).

The surface roughness parameters (*Ra, Rz*) were measured using a Mahr MarSurf GD 120 profilometer. During the investigation, each machined surface was measured in three angular positions (0°, 120°, 240°) and at three depths (0, 9, 18 mm), resulting in a total of nine measurements, applying an evaluation length of $l_t = 4.8 + 2 \cdot 0.8$ mm according to MSZ EN ISO:21920:2022.

The measurement results were evaluated using the dedicated software of the measuring devices and further analyzed with MINITAB 22 software.

For the determination of the results, the Least Squares Cylinder Fit method was applied, which minimizes the sum of squared distances between the measured points and the theoretical diameter, perpendicular to the axis of the fitted circle or cylinder center. The obtained results were also represented graphically.

3. Presentation of the measured values

The results of the deviation from the theoretical diameter (*ΔD*) are presented in Fig. 3, where the distribution of 264 measurement results is shown. Based on the data, it can be established that the different machining processes can be clearly distinguished. For turning and boring technologies, it was observed that the machining process had only a minor influence on the deviation from the theoretical geometry, while in the case of milling this effect was significant. Turning produced the smallest *ΔD* deviation (on average −0.02 mm), whereas boring resulted in circular pockets with an average oversize of +0.09 mm. Based on the

Table 1. *Tools used in the experiments*

No.	Tool	Insert
1	A20S-SDQCL11	DCMT11T304-MP4-WPP20G
2	B4030G. T28. 33-41.Z	TCMT06T104-FP4
3	H4021017-20	

Table 2. *Technological parameters used in the experiments*

Turning			Boring			Milling		
No.	v_c (m/min)	f_z (mm)	No.	v_c (m/min)	f_z (mm)	No.	v_c (m/min)	f_z (mm)
1	180	0.05	4	180	0.1	7	180	0.15
2	200	0.1	5	200	0.15	8	200	0.05
3	220	0.15	6	220	0.05	9	220	0.1

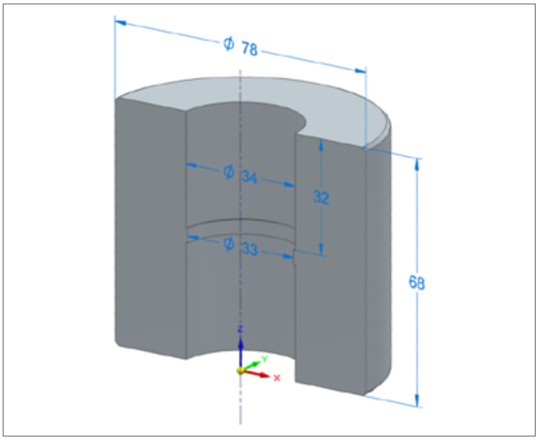

Fig. 2. *Workpiece used in the experiment.*

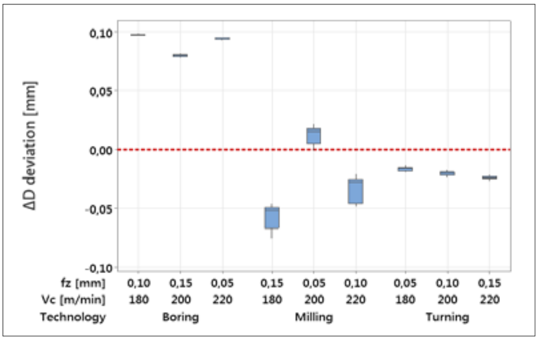

Fig. 3. *Deviation from theoretical size.*

force measurement results and the experiments conducted in Necurom 651 artificial wood, it was concluded that the geometric deviation of the diameter was caused by tool deflection.

Using the measured points, the roundness deviation (*RONt*) corresponding to each depth level was determined (**Fig. 4**). Based on the data, it can be established that turning and boring result in nearly identical roundness deviations, while in milling not only is the scatter of the data considerably larger, but the investigated geometric deviation is also 2.8 times higher compared to the average value obtained for turning. The results once again confirm that, in the case of milling, the technological parameters exert a significant influence on the magnitude of roundness deviation.

The results of the cylindricity (*CYLt*) analysis of the circular pockets are presented in **Fig. 5**, where the outcomes of 36 measurements (9·4) are shown. Based on the results, it can be concluded that the smallest cylindricity deviation was obtained for the circular pockets produced by turning. In the case of boring, the cylindricity value deviated on average by 10% compared to the turned pockets, while for the workpieces produced by milling the average deviation was 2.9 times higher. The data also clearly indicate that, in milling, the technological parameters exert a stronger influence on the cylindricity values.

3.1. Surface roughness investigations

The results of the average surface roughness (*Ra*) are summarized in **Fig. 6**. The lowest Ra values were obtained with milling. In comparison, turning resulted in an average *Ra* that was 2.6 times higher, while boring produced an average *Ra* that was 2.8 times higher. For milling, the technological parameters had no significant effect on the average surface roughness, whereas in turning and boring the Ra values were strongly influenced by the cutting parameters. Furthermore, it was established that surface homogeneity is considerably more advantageous when using single-edge tools compared to multi-edge tools.

In the surface roughness investigations, the other parameter examined was the mean peak-to-valley height (*Rz*), the results of which are presented in **Fig. 7**. The lowest *Rz* values were obtained for the circular pockets produced by milling, while boring resulted in values that were on average 1.8 times higher, and turning produced Rz values that were on average 2.1 times higher. Based on the scatter of the results, it can be stated that the homogeneity of the workpieces produced

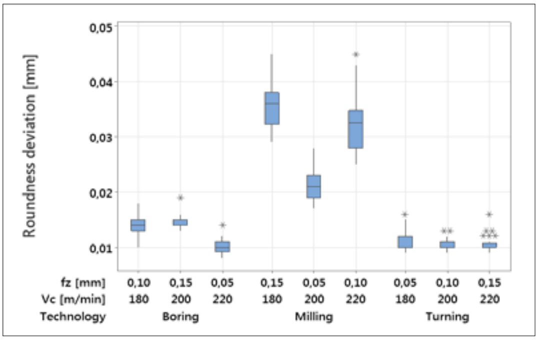

Fig. 4. *Development of roundness deviation during the examination.*

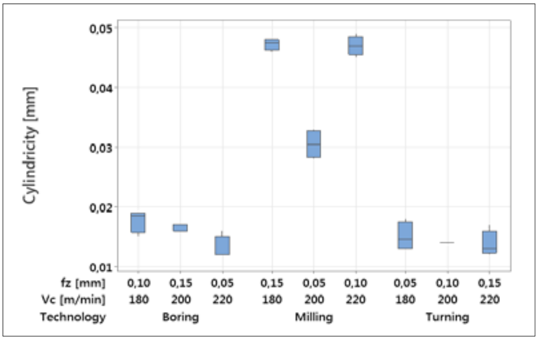

Fig. 5. *Development of cylindricity during the examination.*

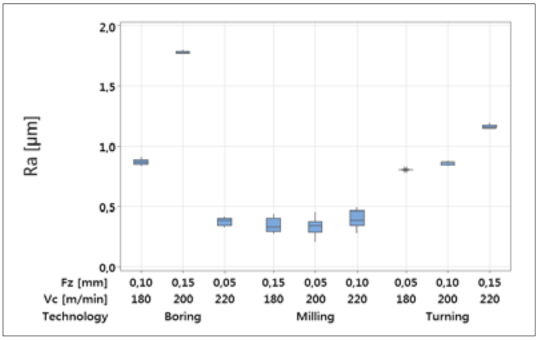

Fig. 6. *Average surface roughness development during the test.*

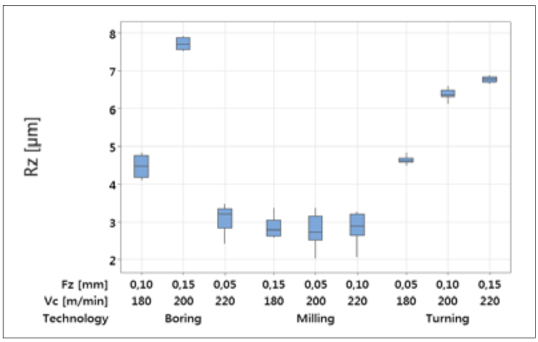

Fig. 7. *Development of mean peak-to-valley height during the examination.*

by turning is much more favorable than with the other processes. In the case of boring, the lack of sufficient cooling intensity likely caused the scatter of the Rz results, since the continuous chip could not be effectively removed from the pocket.

4. Analysis of the measured values and findings

For the evaluation of the experimental results, the Taguchi method was applied, which enables the simultaneous investigation of the effects of multiple factors with a relatively small number of experiments. During the analysis of the data, evaluation was performed exclusively on the basis of the Signal-to-Noise Ratio (S/N). The calculation of the S/N ratio makes it possible to consider not only the average results, but also the scatter and stability of the measurement data. This provides a more reliable picture of the consistency and predictability of a given technological setup performs. The method is widely used in Design of Experiments (DOE), manufacturing technology, and quality assurance, especially in situations where the aim is to improve process robustness [9, 10].

In assessing the effects of the factors, the magnitude of the delta value (Δ) was taken into account, which represents the difference between the S/N ratios obtained at the best and worst levels of a given factor (Eq. 1). The magnitude of the delta value is proportional to the effect of the factor on the outcome, and thus the order of importance of the factors can be established based on these values [9].

$$\Delta = S/N_{max} - S/N_{min} \qquad (1)$$

For the “Nominal is Best” case read:

$$S/N = -10 \cdot log_{10}(s^2) \qquad (2)$$

where:

s: the standard deviation of the *y* values.

For the “Smaller is Better” case, the equation is:

$$S/N = -10 \cdot log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (3)$$

where:

y_i: *i*-th measured value,

n: number of measurements.

4.1. Coordinate measurement investigations

Fig. 8 shows the main effects plot of the signal-to-noise ratios calculated from the deviation of the theoretical diameter. According to the “Nominal is Best” type signal-to-noise ratio (Eq. 2), a higher value indicates better process stability. The greatest effect on diameter accuracy was exerted by the machining method (*Δ* = 21.87), while feed (*Δ* = 1.75) and cutting speed (*Δ* = 1.05) had smaller influences. Although boring produced larger deviations (Fig. 3), this method nevertheless ensured the most stable and repeatable results, which can be corrected to achieve higher accuracy. Milling exhibited a 35% lower signal-to-noise ratio, and thus its accuracy proved to be suboptimal. The best result was obtained at a cutting speed of 180 m/min and a feed of 0.05 mm.

For the evaluation of roundness deviations, the “Smaller is Better” type signal-to-noise ratio was applied, since the aim was to minimize form errors (Eq. 3). Based on Fig. 9, the greatest effect was exerted by the machining method (*Δ* = 8.67), while feed (*Δ* = 2.36) and cutting speed (*Δ* = 1.47) had smaller influences on the result. Turning ensured the best stability, while boring showed a 4% less favorable signal-to-noise ratio, and milling exhibited a 22% less favorable value. The best results were obtained at a cutting speed of 200 m/min and a feed of 0.05 mm.

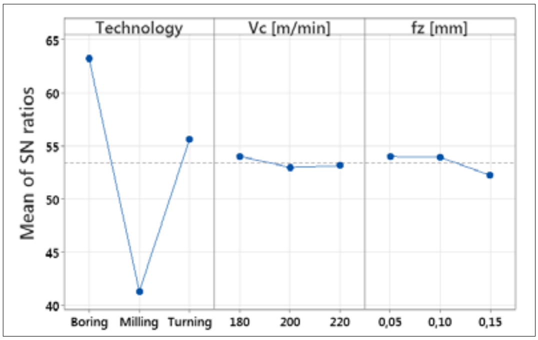

Fig. 8. *Main effects plot of the signal-to-noise ratio for the deviation from the theoretical diameter.*

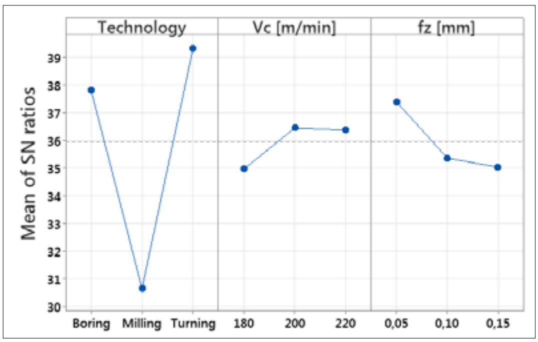

Fig. 9. *Main effects plot of the signal-to-noise ratio for roundness.*

The evaluation of cylindricity deviations was also conducted using the “Smaller is Better” type signal-to-noise ratio, since the objective was to reduce geometric errors (Eq. 3). According to Fig. 10 the greatest effect was exerted by the machining method (Δ = 9.09), while feed (Δ = 1.91) and cutting speed (Δ = 1.68) had a smaller influence on the results. Turning ensured the most stable cylindricity values, boring showed a 2% lower but still promising signal-to-noise ratio, while milling resulted in a 25% lower ratio, indicating higher scatter and instability. The best results were obtained at a cutting speed of 200 m/min and a feed of 0.05 mm.

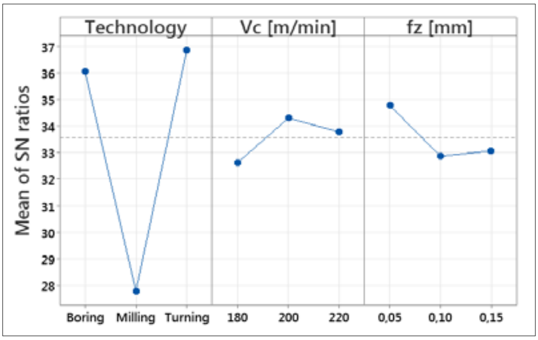

Fig. 10. *Main effects plot of the signal-to-noise ratio for cylindricity.*

4.2. Surface roughness investigations

For the evaluation of surface roughness (Ra), the “Smaller is Better” type signal-to-noise ratio was applied, in order to achieve smoother surfaces (Eq. 3). According to Fig. 11 the machining method had the most significant effect (Δ = 8.21), with milling providing the best surface quality. In the case of turning, the *Ra* value was 93% higher, representing the most unfavorable result. Feed also had a strong influence on roughness (Δ = 5.66), with the 0.05 mm value producing the smoothest surfaces. Cutting speed had a smaller effect (Δ = 3.17), with the best results obtained at 220 m/min, while 200 m/min yielded the lowest stability.

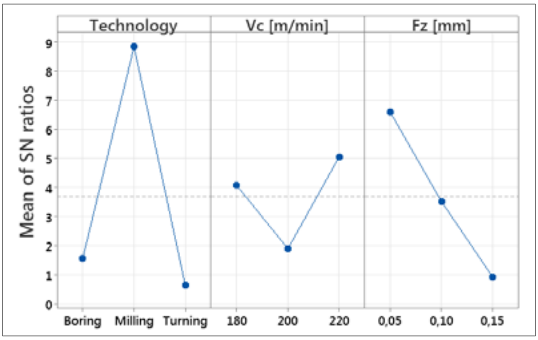

Fig. 11. *Main effects plot of the signal-to-noise ratio for arithmetic mean height (Ra).*

For the *Rz* roughness parameter, similar results were obtained as for *Ra*, therefore the evaluation was also carried out using the “Smaller is Better” type signal-to-noise ratio (Eq. 3). According to Fig. 12 s, the machining method had a decisive effect on the stability of *Rz* (Δ = 6.27), with milling providing the most favorable results. In the case of turning, the *Rz* value was 69% higher, indicating poorer surface quality. Feed also had a significant influence (Δ = 3.80), with the lower feed (0.05 mm) producing the smoothest surface. Based on the effect of cutting speed (Δ = 2.45), the best results were observed at 220 m/min, while at 200 m/min the greatest deterioration was recorded.

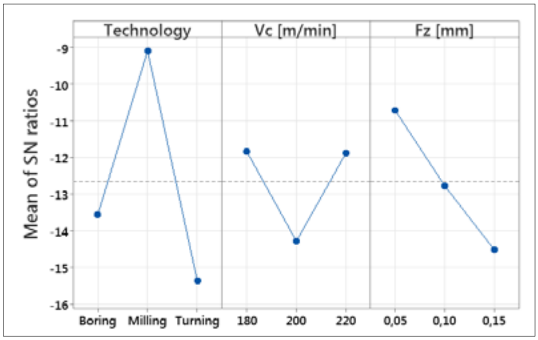

Fig. 12. *Main effects plot of the signal-to-noise ratio for peak-to-valley height (Rz).*

4.3. Evaluation of the data

Based on the results of the signal-to-noise ratios, it can be established that the machining method exerted the most significant effect on all of the investigated response parameters. According to Table 3 sthe deviation from the theoretical diameter was most strongly influenced by the applied machining process, while the effect of cutting speed and feed was considerably smaller.

Table 3. *Summary values of the signal-to-noise ratio for ΔD*

Level	Technology	V_c m/min	f_z mm
1	55.61	54.02	53.97
2	63.19	52.97	53.92
3	41.32	53.14	52.23
Delta	24.87	1.05	1.75
Rank	1	3	2

Table 4. *Summary values of the signal-to-noise ratio for RONt*

Level	Technology	V_c m/min	f_z mm
1	39.32	34.97	37.40
2	37.82	36.45	35.37
3	30.65	36.37	35.03
Delta	8.67	1.49	2.36
Rank	1	3	2

Table 5. *Summary values of the signal-to-noise ratio for CYLt*

Level	Technology	V_c m/min	f_z mm
1	36.87	32.63	34.78
2	36.06	34.31	32.87
3	27.79	33.78	33.07
Delta	9.09	1.68	1.91
Rank	1	3	2

Table 6. *Summary values of the signal-to-noise ratio for Ra*

Level	Technology	V_c m/min	f_z mm
1	0.6367	4.0839	6.5947
2	1.5678	1.8993	3.5221
3	8.8488	5.0701	0.9365
Delta	8.2121	3.1708	5.6582
Rank	1	3	2

Table 7. *Summary values of the signal-to-noise ratio for Rz*

Level	Technology	V_c m-min	f_z mm
1	-15.355	-11.830	-10.711
2	-13.544	-14.277	-12.764
3	-9.084	-11.876	-14.508
Delta	6.270	2.447	3.797
Rank	1	3	2

A similar trend can be observed in **Table 4** and **5** where the stability of roundness and cylindricity deviations was also most strongly affected by the machining method.

In terms of surface roughness characteristics (**Table 6** and **7**) milling provided the most beneficial signal-to-noise ratio. In contrast, with respect to roundness and cylindricity deviations, turning yielded the best results.

Summarizing the geometric and surface roughness outcomes, it can be concluded that boring ensured the most balanced and stable machining performance, with favorable accuracy and surface quality.

The influence of cutting speed (v_c) was of moderate magnitude, with the best values generally obtained in the range of 200–220 m/min. For feed (f_z), a clear trend was observed: the low feed value of 0.05 mm consistently produced an outstanding signal-to-noise ratio across all response parameters.

5. Conclusions

The aim of this research was to compare circular pockets produced by three different machining methods (turning, boring, and milling) based on geometric deviations (*ΔD, RONt, CYLt*) and surface roughness parameters (*Ra, Rz*). Coordinate measurement and surface roughness measurement procedures were applied, and the results were evaluated using the Taguchi method by calculating signal-to-noise ratios.

Based on simple average values, turning provided the most favorable results regarding geometric characteristics, closely followed by boring. In contrast, milling exhibited larger deviations and scatter in all geometric parameters.

According to the surface roughness data, the milling process resulted in the lowest average Ra and Rz values; however, turning and boring ensured more stable and homogeneous surface quality.

Overall, the best combined results were obtained with the boring process. Among the cutting parameters, the combination of the highest cutting speed (220 m/min) and the lowest feed rate (0.05 mm) yielded the best accuracy and surface quality.

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