

The Influence of P2 and PC3 Polygonal Shaft Machining Parameters on the Quality of Machining Results Using a Mazak CNC Type QTE 200-MY SG

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Received: 17.11.2025; Accepted: 27.11.2025; Published: 26.12.2025

Abstract: Shafts are vital components in mechanical systems that function to transmit motion to elements such as rotors and gears. Although keyed and splined joints are commonly used due to their ease of manufacturing, polygonal shafts of the P2 and PC3 types according to DIN standards offer advantages in transmission efficiency and torque resistance. This study focuses on the CAD modeling, CAM simulation, and CNC machining of P2- and PC3-type coupling shafts. The modeling was carried out using SolidWorks based on DIN standard dimensions, while the CAM simulation was conducted using Esprit TNG. The machining process employed a Mazak CNC QTE 200-MY SG machine with parameter variations based on material type (carbon steel and stainless steel). Evaluation was performed through surface roughness measurements using a surface roughness tester and dimensional inspection using a Coordinate Measuring Machine (CMM). The results show that the toolpath runs optimally, and the depth of cut (DoC) has a significant effect on surface quality. A smaller DoC produces a smoother surface but requires longer machining time, whereas a larger DoC speeds up the process but reduces surface quality. Dimensional deviations from the CAD design are suspected to be caused by suboptimal quantity and distribution of reference points during CMM measurement.

Keywords: DIN polygonal shaft; CAD/CAM Modeling; CNC Machining; Surface Roughness; Coordinate Measuring Machine (CMM).

1. Introduction

Shafts are one of the vital elements in mechanical systems that function to transmit power to various components such as gears and rotors. In the manufacturing industry, keyway and spline joints are widely used due to their simplicity in design and ease of fabrication [1]. Nevertheless, shafts with polygonal profiles offer advantages in terms of more uniform torque distribution and higher resistance to rotational loads. However, their application remains limited due to geometric complexity and challenges in the forming process. Advances in Computer Numerical Control (CNC) technology enable the manufacturing of polygonal shafts with higher precision and improved efficiency compared to conventional methods [2]. The quality of machining results is strongly influenced by the selection of machining parameters such as cutting speed, feed rate, and depth of cut, which affect surface roughness and dimensional accuracy [3]. Previous studies have shown that increasing the depth of cut can lead to higher cutting forces and vibrations, resulting in a rougher

surface finish [4]. Research by Rofik (2024) also emphasizes the importance of matching machining parameters, material characteristics, and machine capability to achieve precise dimensional outcomes. Based on these considerations, the present study focuses on machining P2 and PC3 polygonal shaft profiles standardized by DIN, using a Mazak CNC QTE 200-MY SG machine. The objective is to analyze the machining process of P2 and PC3 shaft profiles through CAM simulation and to examine the influence of parameter variations on surface quality and dimensional accuracy, thereby contributing to the advancement of precision manufacturing processes for complex-geometry components in modern industries.

2. Materials and Methods

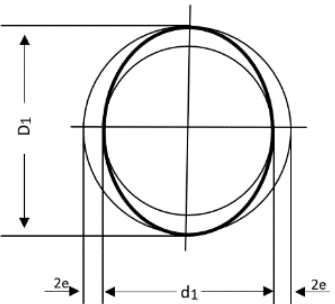
The materials used were carbon steel with a hardness of 30.7 HRD and stainless steel with a hardness of 42.9 HRD for machining the P2 and PC3 profiles.

2.1 Pre-Production-3D Model

The design of the P2 and PC3 shaft profiles was carried out using SolidWorks with reference to the DIN standards, as presented in Table 1 and Table 2. The resulting designs were saved (Save As) in Parasolid format for use in the CAM simulation stage.

Table 1. DIN Standard P2 Shaft Profile Parameters [5]

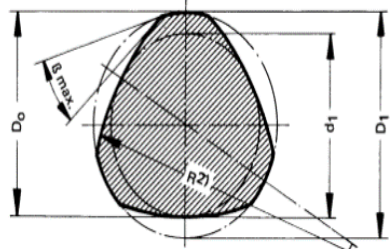
Profile geometry	P2 Standard DIN		
	D1(mm)	d1 (mm)	Profile eccentricity (e)
	18	14,40	0,90
	20	16,00	1,00
	22	17,52	1,12
	25	20,00	1,25
	28	22,40	1,40
	32	25,60	1,60
	36	28,80	1,80
	40	32,00	2,00
	45	36,04	2,24
	50	40,00	2,50
	56	44,80	2,80
	60	48,00	3,00
	70	55,60	3,60
	75	60,00	3,75



The diagram shows a cross-section of a P2 shaft profile. It is an oval shape with a vertical diameter labeled D1 and a horizontal diameter labeled d1. The eccentricity is indicated by two arrows pointing outwards from the horizontal centerline, each labeled 2e.

Table 2. DIN Standard P2 Shaft Profile Parameters [5]

Profile geometry	PC3 Standard DIN				
	D1 (mm)	d1 (mm)	D0 (mm)	Profile eccentricity (e)	Tangent-angle (β max) ^o
	14	11	12,5	2	32
	20	16	18,0	2	28,5
	25	21	23,0	4	28,2
	28	23	25,5	4	29,2
	32	26	29,0	5	29,2
	34	28	31,0	4	27,2
	38	32	35,0	5	25,8
	42	36	39,0	5	25,2
	48	42	45,0	5	22,9



The diagram shows a cross-section of a PC3 shaft profile. It is a rounded, teardrop-like shape. The vertical diameter is labeled D0, and the horizontal diameter is labeled d1. A radius R21 is shown at the bottom. The tangent angle at the top is labeled beta max.

2.2 CAM Simulation

In the production process, CAM functions to convert design data into toolpaths while automatically generating NC code, thereby accelerating and simplifying manufacturing, especially for complex geometries [6]. CAM simulation is used to analyze cutting paths in CNC programming, which includes importing the 3D model, machine setup, feature and toolpath creation, and defining machining parameters based on Table 3 and Table 4, with depth of cut values of 0.2 mm and 0.3 mm. Meanwhile, the feed rate, cutting speed, and spindle speed are automatically configured by Esprit TNG according to the specifications of the Ø8 mm, 3-flute end mill. Subsequently, error checking is performed, followed by NC code generation as machine operating instructions.

Table 3. Profiling machining parameters P2

Profiling machining parameters P2				
Material type	Spindle rotation speed (rpm)	Cutting speed (V_c) (mm/min)	Feedrate (f) (mm/min)	Depth of Cut (mm)
Carbon steel	716	18	286,4	0,3
Stainless steel	716	18	286,4	0,3
Carbon steel	716	18	286,4	0,2
Stainless steel	716	18	286,4	0,2

Table 4. Profiling machining parameters PC3

Profiling machining parameters PC3				
Material type	Spindle rotation speed (rpm)	Cutting speed (V_c) (mm/min)	Feedrate (f) (mm/min)	Depth of Cut (mm)
Carbon steel	995	18	398	0,3
Stainless steel	995	18	398	0,3
Carbon steel	995	18	398	0,2
Stainless steel	995	18	398	0,2

2.3 Machining Process

The machining process was carried out using a Mazak CNC machine, type QTE 200-MY SG. Prior to the profiling process, a preliminary machining step was performed to reduce the material diameter according to the outer diameter of the profile. This stage is part of the cutting process, which aims to remove or reduce excess material so that it conforms to the specified shape and dimensions [7]. The turning program was initiated by setting the dimensions according to Table 5. Figure 5 shows the workpiece model generated from the Table 5 input displayed on the Mazatrol SmoothEz interface.

Table 5. Turning dimensional parameters

Turning dimensional parameters	
OD-Max (outer diameter)	30 mm
Length (material length)	55 mm
CPT-X (length of ingestion)	30 mm
FPT-X (inner diameter)	25 mm



Figure 1. Turning programming on Mazatrol SmoothEz

The turning process consists of two stages, namely roughing and finishing. Roughing is the initial stage in which material is removed to approach the final shape, while finishing aims to achieve the desired dimensions, tolerances, and surface roughness⁷. The parameters and tools used refer to Table 6 and are adjusted according to the tool specifications recommended by Sandvik Coromant.

Table 6. Cutting tools and machining parameters

Machining Stage	Tools Type	Cutting speed (vc) (m/min)	Spindle rotation speed (rpm)	Feedrate (f) (mm/rev)	Depth of cut (DoC) (mm)
Roughing	CNMG 12 04 08-PM 4425	125	1000	0,15	0,2
Finishing	DNMG 15 06 04-PF 4425	100	1000	0,10	0,1

After turning is completed, the profiling process is continued by inputting the NC Code from the CAM simulation into Mazatrol SmoothEz as an instruction to control the CNC machine in machining the P2 and PC3 shaft profiles.

2.4 Post-Production Surface Roughness Tester

A surface roughness tester is used to measure the surface roughness of a workpiece, which varies depending on the material structure and the manufacturing process [7]. The level of roughness is influenced by cutting parameters, tool geometry and dimensions, cooling media, material defects, and chip flow irregularities. Surface roughness is an important indicator of machining quality and can be assessed by measuring the distance between the highest peak and the lowest valley [8]. The surface roughness of the P2 and PC3 shaft profiles was measured using the profilometer method, in which a stylus moves along the machined surface, as shown in Figure 2. Measurement guidelines are presented in Figure 3 to ensure consistency and accuracy in the measurement results.



Figure 2. Roughness measurement of shaft profile (a) P2; (b) PC3

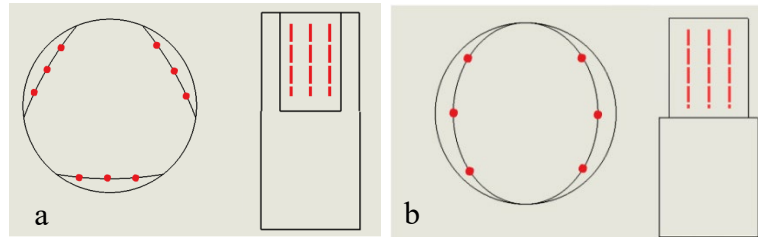


Figure 3. Roughness measurement point of shaft profile (a) P2; (b) PC3

2.5 Coordinate measuring Machine (CMM)

A Coordinate Measuring Machine (CMM) is a precision measurement instrument used to inspect part dimensions with high accuracy, particularly for complex designs and tight tolerances⁹. A CMM operates by moving a probe to detect coordinate points on the surface of an object according to the required measurement specifications [9]. In this study, dimensional measurements of the P2 and PC3 polygonal shaft profiles were performed using a CMM with the contact measurement method. The probe tip makes contact with the material surface to obtain precise dimensional data. To ensure consistency and accuracy in the measurement process, reference points were utilized as shown in Fig 4, where each red and blue point was measured three times on the corresponding profile surface.

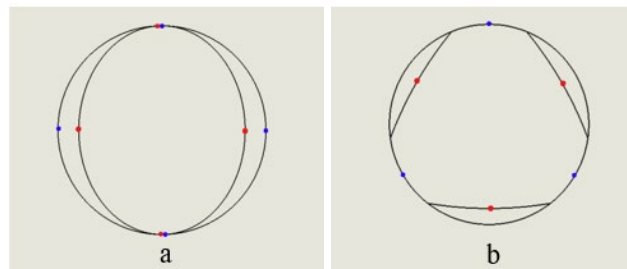


Figure 4. Measurement point of profile dimension (a) P2; (b) PC3

3. Hasil dan Pembahasan

3.1 Pre-Production 3D Model of P2 and PC3 Shaft Profiles

The study began with the development of 3D models of the P2 and PC3 shaft profiles using SolidWorks, following the dimensional parameters specified in the DIN standard. For the P2 profile, the parameters used included $D1 = 25$ mm (outer diameter), $d1 = 20$ mm (inner diameter), $e = 1.25$ mm (eccentricity), and a tolerance of -0.020 mm. Meanwhile, the PC3 profile employed the parameters $D1 = 25$ mm (outer diameter), $d1 = 21$ mm (inner diameter), $D0 = 23$ mm (inner diameter), $e = 1.25$ mm (eccentricity), $R2 = 93$ mm, and a tolerance of -0.020 mm. The resulting models are shown in Figure 5.

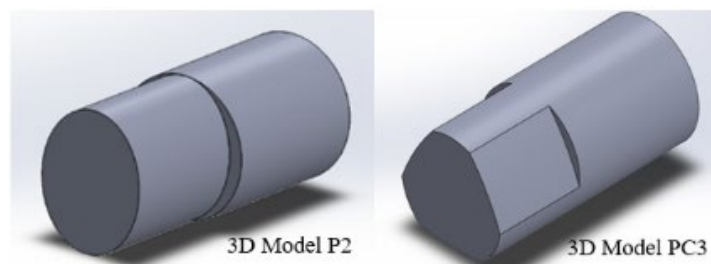


Figure 5. P2 and PC3 Shaft Design Results

3.2 CAM Processing of P2 and PC3 Shaft Profiles

The polygonal shafts P2 and PC3 were formed through a horizontal profiling contouring milling process with an end mill according to the CAD design, simulated using Esprit CAM to visualize and verify the cutting path according to the designed profile, as shown in Figure 6.

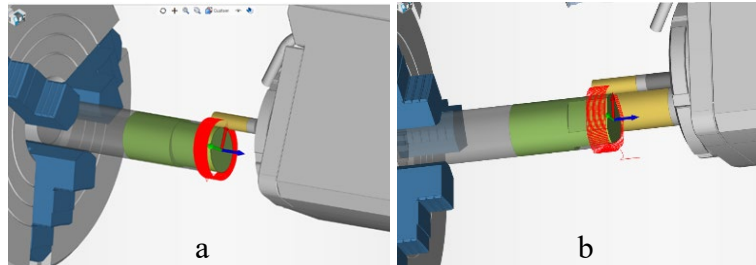


Figure 6. Simulation of Profiling Contouring Milling Horizontal (a) P2; (b) PC3

The simulation in Figure 6 shows the simulation running according to an accurate toolpath based on the CAD design, including tool selection and machining parameters. After the simulation is complete and the results are satisfactory, the next stage is to generate an NC Code file. Where NC Code is the instructions required by the CNC machine to perform the machining process according to the specified design and parameters. Tables 7 are examples of NC Code output results from the machining process of shaft profiles P2 and PC3.

Table 7. Example of NC Code results for P2 and PC3 Shaft Profiles

Contouring (Profil Contouring)	Contouring (Profil Contouring)	Contouring (Profil Contouring)	Contouring (Profil Contouring)
<p>NC CODE P2 doc 0,2</p> <pre> ***** TOOL LIST ***** (T09 ENDMILL D12 Z) ***** G18 G21 G40 G80 G97 G99 G123.1 G53.5 G0 G53 X0. Y0. G0 G53 Z0. N1 (SOLIDMILL - CONTOURING) G53.5 G0 G90 G53 X0. Y0. G0 G90 G53 Z0. T0909 (ENDMILL D12 Z) G122.1 M200 G97 S716 M200 M248 M212 C182.4299 Z10.5 M8 X19.0030 Y0. G1 G98 Z.5 F286.4 X19.0055 C182.0015 F909.67 X19.0070 C183.1729 F909.53 X19.011 C183.5443 F909.29 X19.015 C183.9155 F909. </pre>	<p>NC CODE P2 doc 0,3</p> <pre> ***** TOOL LIST ***** (T09 ENDMILL D12 Z) ***** G18 G21 G40 G80 G97 G99 G123.1 G53.5 G0 G53 X0. Y0. G0 G53 Z0. N1 (SOLIDMILL - CONTOURING) G53.5 G0 G90 G53 X0. Y0. G0 G90 G53 Z0. T0909 (ENDMILL D12 Z) G122.1 M200 G97 S716 M200 M248 M212 C182.4299 Z10.5 M8 X19.0030 Y0. G1 G98 Z.5 F286.4 X19.0055 C182.0015 F909.67 X19.0070 C183.1729 F909.53 X19.011 C183.5443 F909.29 X19.015 C183.9155 F909. </pre>	<p>NC CODE PC 3 doc 0,2</p> <pre> ***** TOOL LIST ***** (T09 ENDMILL D12 Z) ***** G18 G21 G40 G80 G97 G99 G123.1 G53.5 G0 G53 X0. Y0. G0 G53 Z0. N1 (SOLIDMILL - CONTOURING) G53.5 G0 G90 G53 X0. Y0. G0 G90 G53 Z0. T0909 (ENDMILL D12 Z) G122.1 M200 G97 S716 M200 M248 M212 C270. Z10.5 M8 X19.5 Y0. G1 G98 Z.5 F286.4 X19.5004 C270.3698 F888.91 X19.5016 C270.7397 F888.86 X19.5037 C271.1094 F888.74 X19.5065 C271.4791 F888.57 </pre>	<p>NC CODE PC3 doc 0,3</p> <pre> ***** TOOL LIST ***** (T09 ENDMILL D12 Z) ***** G18 G21 G40 G80 G97 G99 G123.1 G53.5 G0 G53 X0. Y0. G0 G53 Z0. N1 (SOLIDMILL - CONTOURING) G53.5 G0 G90 G53 X0. Y0. G0 G90 G53 Z0. T0909 (ENDMILL D12 Z) G122.1 M200 G97 S716 M200 M248 M212 C270. Z10.5 M8 X19.5 Y0. G1 G98 Z.5 F286.4 X19.5004 C270.3698 F888.91 X19.5016 C270.7397 F888.86 X19.5037 C271.1094 F888.74 X19.5065 C271.4791 F888.57 </pre>

3.3 Machining Process

The machining process is carried out through two main stages, namely turning and profiling. The turning stage begins to form the basic dimensions of the material by reducing the outer diameter, while reducing the feed load during the profiling stage to minimize excessive vibration. The turning process consists of two stages, roughing and finishing. Roughing aims to reduce the diameter of the material to approach the final dimensions, while finishing is done to obtain a smoother and more precise end result. The results are shown in Figure 7 (roughing) and Figure 8 (finishing), while Figure 9 shows the final result of the turning process.



Figure 7. The results of the roughing process of carbon steel and stainless steel materials

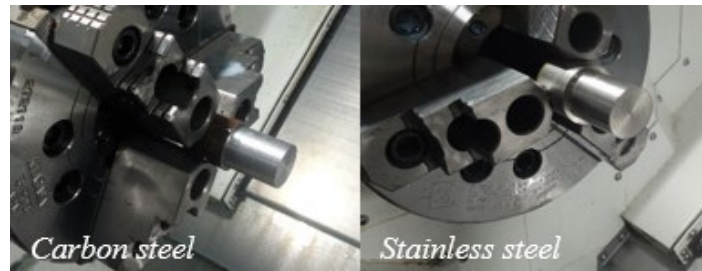


Figure 8. The results of the finishing process for carbon steel and stainless steel materials



Figure 9. The results of the turning machining for carbon steel and stainless steel materials

After Turning Machining is done, the next step is horizontal milling contouring profiling using NC Code obtained after determining the machining parameters, tools, toolpaths and simulations in Esprit Tng software. The final results of P2 and PC3 profiling are shown in Figure 10 and visually match the previous CAD design (Figure 5).



Figure 10. Final results of profiling P2 and PC3; (a) top view of P2 profiling results; (b) side view of P2 profiling results; (c) top view of PC3 profiling results; and (d) side view of PC3 profiling results

3.4 Post-Production-Surface roughness measurement

The surface roughness test data of the P2 and PC3 shaft profiles were obtained from measurements using a surface roughness tester on carbon steel and stainless steel materials. The measurements were carried out after the profiling machining process with depth of cut parameters of 0.2 mm and 0.3 mm. The average roughness values measured include Ra, Rq, and Rz. The results of the P2 shaft profile measurements are shown in Table 9.

Table 8. Surface roughness tester measurement results for P2 Shaft Profile

Pengujian	Nilai	Pengukuran Kekasaran Permukaan Profil P2						Rata-rata
		1	2	3	4	5	6	
P2 CR 0,2	Ra	0,376	0,296	0,307	0,346	0,383	0,216	0,309
	Rq	0,457	0,369	0,38	0,427	0,476	0,266	0,395
	Rz	1,941	1,696	1,699	1,817	2,257	1,295	1,784
P2 SS 0,2	Ra	0,232	0,419	0,211	0,177	0,202	0,374	0,269
	Rq	0,285	0,509	0,252	0,232	0,25	0,461	0,331
	Rz	1,282	2,211	1,196	1,273	1,311	2,134	1,567
P2 CR 0,3	Ra	0,29	0,371	0,317	0,338	0,524	0,458	0,383
	Rq	0,366	0,443	0,4	0,395	0,608	0,547	0,459
	Rz	1,78	1,977	1,658	1,554	2,128	2,212	1,884
P2 SS 0,3	Ra	0,425	0,256	0,267	0,256	0,434	0,266	0,317
	Rq	0,505	0,309	0,329	0,322	0,499	0,338	0,383
	Rz	2,179	1,397	1,56	1,49	1,956	1,68	1,710

Figure 11 shows the results of surface roughness measurements on one side of the measurement with different materials and depth of cut (DoC).



Figure 11. The results of measuring the surface roughness of the PC3 profile on one side of each test, (a) carbon steel with DoC 0.2 (b) stainless steel with DoC 0.2 (c) carbon steel with DoC 0.3 (d) stainless steel with DoC 0.3

The results of surface roughness measurements of profile P2 show variations in values that affect machining time.

Table 9. Machining time of shaft profile P2

Testing	Materials	Depth of Cut (mm)	Time (min)
1	Carbon steel	0,2	38,23
2	Stainless Steel	0,2	38,15
3	Carbon steel	0,3	26,00
4	Stainless Steel	0,3	26,13

Surface roughness analysis yields average values of Ra, Rq, and Rz. These variations significantly influence surface roughness during the machining process. Figure 12 is a graph of the surface roughness of the P2 shaft profile.

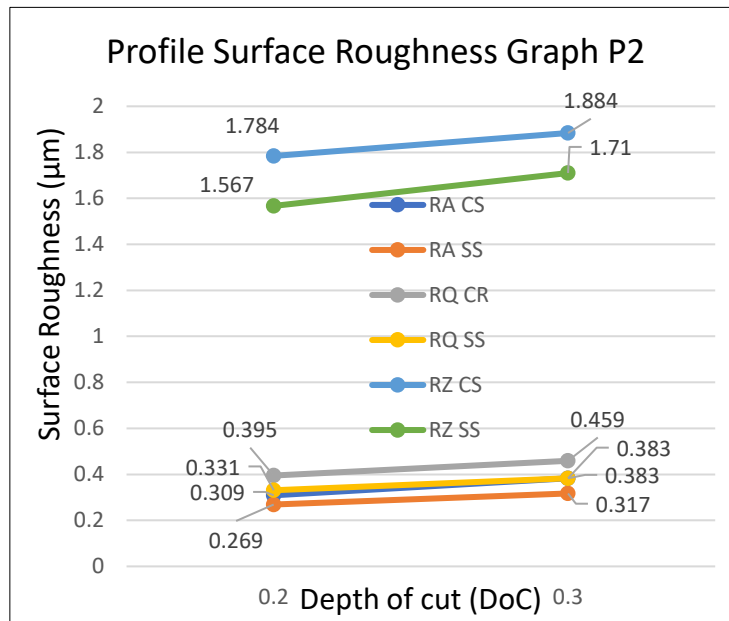


Figure 12. Surface roughness graph of shaft profile P2

The test results in Figure 12 show that the depth of cut significantly affects the surface roughness values of both tested materials. In carbon steel (CS), the use of a DoC of 0.2 mm produces surface roughness values with Ra values of 0.309 µm, Rq 0.395 µm, and Rz 1.784 µm. Increasing the DoC to 0.3 mm results in an increase in roughness to Ra 0.383 µm, Rq 0.459 µm, and Rz 1.884 µm. A similar situation occurred in stainless steel (SS), where a DoC of 0.2 mm produced a Ra of 0.269 µm, an Rq of 0.331 µm, and an Rz of 1.567 µm, while a DoC of 0.3 mm increased to Ra of 0.317 µm, an Rq of 0.383 µm, and an Rz of 1.710 µm. Therefore, a DoC of 0.2 mm produced a smoother surface than a DoC of 0.3 mm, indicating that increasing the depth of cut tends to increase surface roughness in both materials.

Next, we present the results of surface roughness testing of the PC3 and PC3 shaft profiles in carbon steel and stainless steel. Measurements were conducted after the profiling process with depth of cut parameters of 0.2 mm and 0.3 mm. The average roughness values measured included Ra, Rq, and Rz. The results of the P2 shaft profile measurements are shown in Table 11.

Table 10. Surface roughness of PC3 shaft profile

Pengujian	Nilai	Pengukuran Kekasaran Permukaan Profil PC3									Rata-rata
		1	2	3	4	5	6	7	8	9	
PC3 CS 0,2	Ra	0,151	0,417	0,224	0,149	0,299	0,188	0,187	0,282	0,22	0,235
	Rq	0,186	0,498	0,286	0,184	0,365	0,231	0,225	0,361	0,274	0,29
	Rz	0,956	2,168	1,413	0,915	1,813	1,258	0,999	1,784	1,293	1,399
PC3 SS 0,2	Ra	0,134	0,265	0,251	0,111	0,221	0,191	0,137	0,344	0,317	0,219
	Rq	0,168	0,324	0,304	0,144	0,271	0,237	0,168	0,4	0,378	0,266
	Rz	0,855	1,486	1,355	0,845	1,319	1,22	0,946	1,71	1,895	1,292
PC3 CS 0,3	Ra	0,138	0,32	0,245	0,118	0,339	0,42	0,124	0,382	0,35	0,270
	Rq	0,172	0,395	0,31	0,145	0,419	0,483	0,155	0,463	0,433	0,330
	Rz	0,884	1,857	1,623	0,683	1,824	1,97	0,9	2,039	2,03	1,534
PC3 SS 0,3	Ra	0,167	0,291	0,193	0,175	0,274	0,232	0,162	0,312	0,212	0,224
	Rq	0,215	0,35	0,232	0,216	0,352	0,281	0,208	0,384	0,272	0,278
	Rz	1,089	1,662	1,153	1,231	1,681	1,296	1,146	1,697	1,403	1,373

Figure 13 shows the results of surface roughness measurements on one side of the measurement with different materials and depth of cut (DoC).

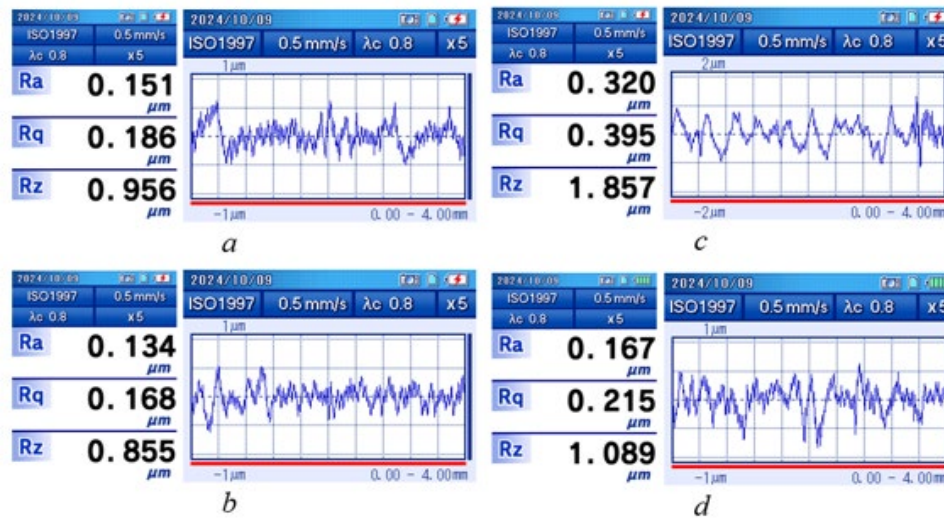


Figure 13. The results of measuring the surface roughness of the PC3 profile on one side of each test, (a) carbon steel with DoC 0.2 (b) stainless steel with DoC 0.2 (c) carbon steel with DoC 0.3 (d) stainless steel with DoC 0.3

The results of the surface roughness measurements of the PC3 profile show variations in values that affect the machining time. Table 12 shows the machining time of the PC3 shaft profile.

Table 11. PC3 shaft profile machining time.

Testing	Materials	Depth of Cut (mm)	Time (min)
1	Carbon steel	0,2	38,01
2	Stainless Steel	0,2	37,57
3	Carbon steel	0,3	25,57
4	Stainless Steel	0,3	26,00

Surface roughness analysis yields average values of Ra, Rq, and Rz. These variations significantly influence surface roughness during the machining process. Figure 14 is a graph of the surface roughness of the PC3 shaft profile.

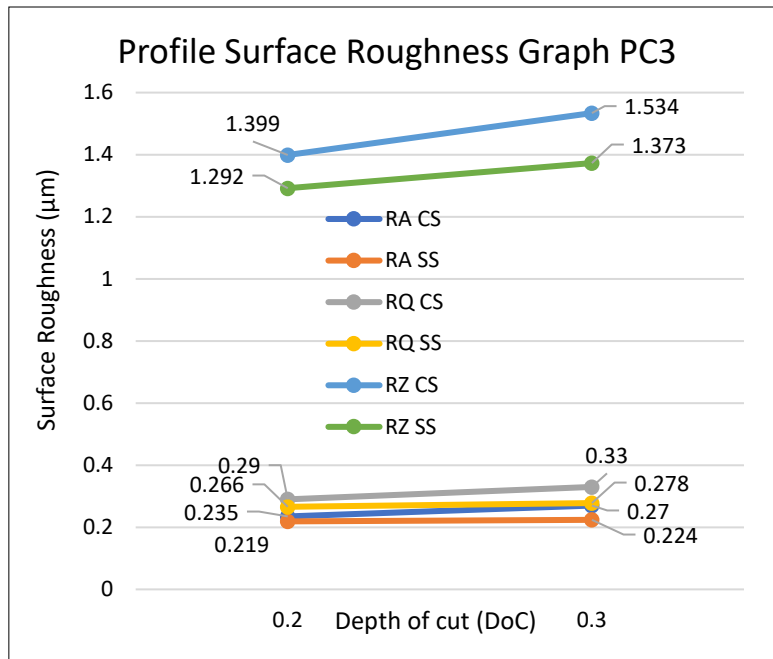


Figure 14. PC3 shaft profile surface roughness graph

The test results shown in Figure 14 indicate that the depth of cut (DoC) has a significant effect on surface roughness for both materials. In carbon steel, a DoC of 0.2 mm produces lower surface roughness compared to a DoC of 0.3 mm, and the same pattern is observed in stainless steel. This indicates that the smaller the depth of cut, the smoother the resulting surface. These findings are consistent with previous studies, which state that increasing the DoC increases cutting forces and vibrations, thereby leading to higher surface roughness. A larger DoC generates higher cutting forces, which induce vibrations in the machine, tool, and workpiece, resulting in a rougher surface. Therefore, DoC is directly proportional to surface roughness. From the machining time perspective, using a 0.2 mm DoC results in better surface quality but requires a longer processing time, approximately 38 minutes for both materials. In contrast, a 0.3 mm DoC shortens machining time to about 26 minutes but at the expense of surface quality. This trend is consistent for both the P2 and PC3 shaft profiles.

Differences in the results between the two materials are also influenced by their mechanical properties. Stainless steel, which has higher hardness (42.9 HRD) compared to carbon steel (30.7 HRD), tends to produce a smoother surface at the same DoC. Materials with higher hardness are more resistant to plastic deformation in the cutting zone, resulting in lower surface roughness [10]. Therefore, the selection of DoC must consider the material type and the required surface quality. For applications that demand high surface quality, a smaller DoC is recommended to minimize cutting forces, vibrations, and plastic deformation on the machined surface [11][12].

3.5 Coordinate Measurement Machine (CMM)

Contact inspection is a dimensional measurement method using a probe that directly touches the surface of the workpiece to obtain dimensional data from the machining process. This measurement produces accurate information about the shaft profile dimensions, which are then compared to nominal values or predetermined specifications to ensure conformity to the machining

results. The measurement data is presented in tabular form for subsequent analysis, while also determining whether the measured dimensions meet specifications (pass) or experience deviations that could lead to failure (fail). Hasil pengukuran dimensi profil poros P2

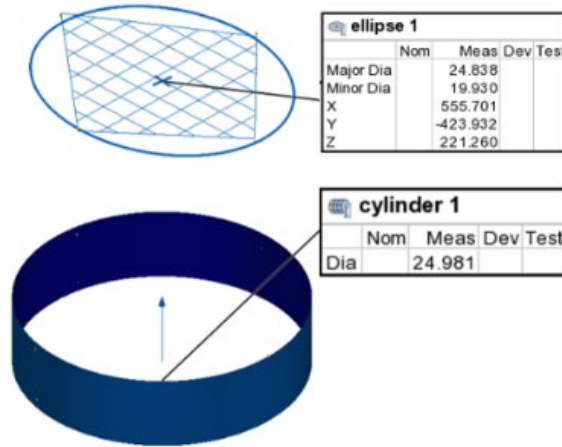


Figure 15. Testing Result CMM P2 CS 0,3

Table 12. The results of measuring the dimensions of P2 with DoC 0.3 using carbon steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	24.981	- 0.020	- 0,019	pass	
Ellipse 1 Major Dia	25.00	24.838	- 0,020	- 0,162	fail	0,142
Ellipse 1 Minor Dia	20.00	19.930	- 0,020	- 0,07	fail	0,07

The results of the P2 shaft profile dimension measurements in Table 13 using CMM show that in cylinder 1 the value is 24.981 mm from the nominal 25.00 mm with a deviation of -0.019 mm, still within the tolerance limit so it is declared pass. However, in ellipse 1 major dia obtained 24.838 mm showing a deviation of -0.162 mm which exceeds the tolerance limit, with a violation difference of 0.142 mm so it is declared fail. Likewise in ellipse 1 minor dia with a measurement result of 19.930 mm from the nominal 20.00 mm, with a deviation of -0.070 mm which exceeds the tolerance with a violation difference of 0.07 mm, so it is declared fail.

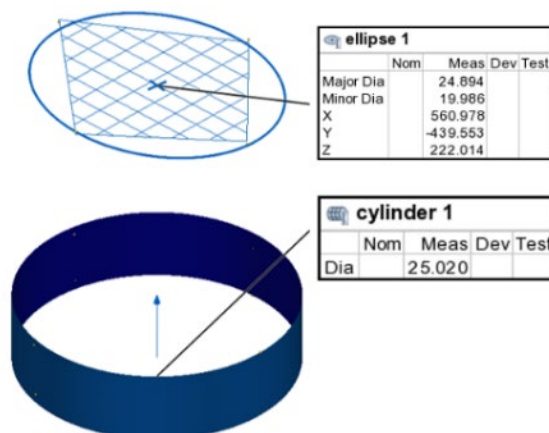


Figure 16. Testing Result CMM P2 SS 0,3

Table 13. Results of measuring the dimensions of P2 with DoC 0.3 using stainless steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	25.020	- 0,020	+ 0.02	fail	
Ellipse 1 Major Dia	25.00	24.894	- 0,020	- 0.106	fail	0,086
Ellipse 1 Minor Dia	20.00	19.986	- 0,020	-0.014	pass	

The results of the P2 shaft profile dimension measurements in Table 14 using CMM show that in cylinder 1 the value is 25.020 mm from the nominal 25.00 mm with a deviation of + 0.02 mm which is right on the tolerance limit so it is declared a fail. In ellipse 1 major, the value is 24.894 mm showing a deviation of -0.106 mm which exceeds the tolerance limit, with a violation difference of 0.086 mm so it is declared a fail. Meanwhile, in ellipse 1 minor, the value is 19.986 mm from the nominal 20.00 mm, with a deviation of -0.014 mm which is within the tolerance limit, so it is declared a pass.

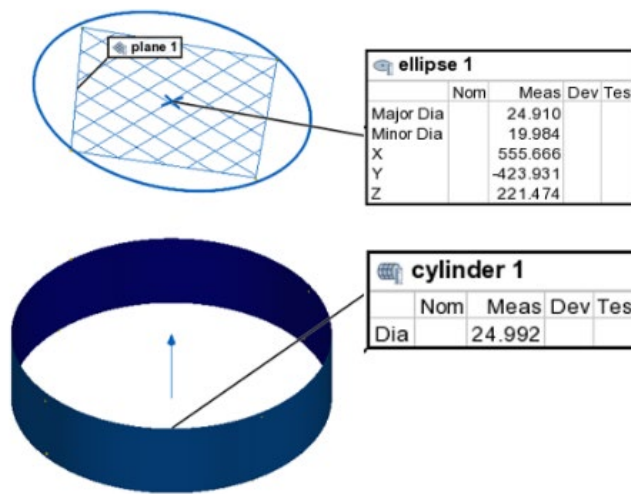


Figure 17. Testing Results CMM P2 CS 0,2

Table 14. The results of measuring the dimensions of P2 with DoC 0.2 using stainless steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	24.992	- 0,020	-0,008	pass	
Ellipse 1 Major Dia	25.00	24.910	- 0,020	-0,09	fail	-0,07
Ellipse 1 Minor Dia	20.00	19.984	- 0,020	-0,016	pass	

The results of the P2 shaft profile dimension measurements in Table 15 using CMM show that in cylinder 1 the value is 24.992 mm from the nominal 25.00 mm with a deviation of -0.020 mm, still within the tolerance limit so it is declared pass. However, in ellipse 1 major, it is obtained 24.910 mm showing a deviation of -0.09 mm which exceeds the tolerance limit, with a violation difference of - 0.07 mm so it is declared fail. Meanwhile, in ellipse 1 minor, the measurement result is 19.984 mm

from the nominal 20.00 mm, with a deviation of -0.016 mm which is within the tolerance limit, so it is declared pass.

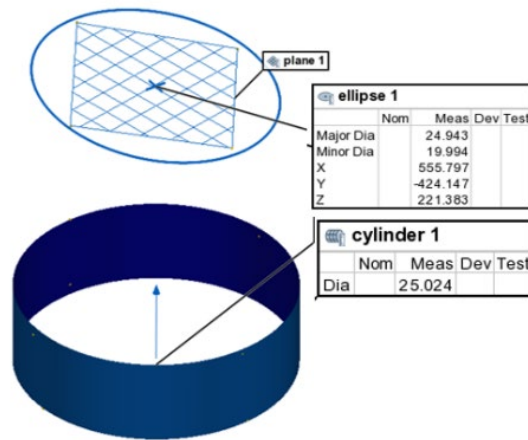


Figure 18. Testing Results CMM P2 SS 0,2

Table 15. The results of measuring the dimensions of P2 with DoC 0.2 using stainless steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	25.024	- 0,020	+ 0.024	fail	0,004
Ellipse 1 Major Dia	25.00	24.943	- 0,020	- 0.057	fail	0,037
Ellipse 1 Minor Dia	20.00	19.994	- 0,020	- 0.006	pass	

The results of the P2 shaft profile dimension measurements in Table 16 using CMM show that in cylinder 1 the value is 25.024 mm from the nominal 25.00 mm with a deviation of + 0.024 mm which exceeds the tolerance limit, with a violation difference of 0.004 so it is declared a fail. In ellipse 1 major, the value is 24.943 mm showing a deviation of - 0.057 mm which also exceeds the tolerance limit, with a violation difference of 0.037 mm so it is declared a fail. Meanwhile, in ellipse 1 minor, the measurement result is 19.994 mm from the nominal 20.00 mm, with a deviation of - 0.006 mm which is within the tolerance limit, so it is declared a pass.

3.6. Results of measuring the dimensions of the PC3 shaft profile

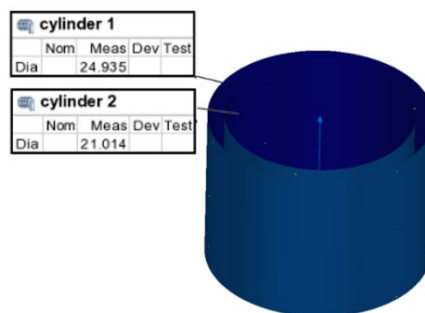


Figure 19. Testing Result CMM PC3 CS 0,3

Table 16. Results of PC3 dimension measurements with DoC 0.3 using carbon steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	24.935	- 0.020	- 0,065	fail	0,045
Cylinder 2	21.00	21.014	- 0,020	+ 0,014	fail	0,034

The results of the PC3 shaft profile dimension measurements in Table 17 using CMM show that in cylinder 1 the value obtained is 24.935 mm from the nominal 25.00 mm with a deviation of -0.065 mm which exceeds the tolerance limit, with a violation difference of 0.045 so it is declared a fail. In cylinder 2 the result obtained is 21.014 mm from the nominal 21.00 mm, with a deviation of +0.014 mm which exceeds the tolerance, with a violation difference of 0.034 mm so it is declared a fail.

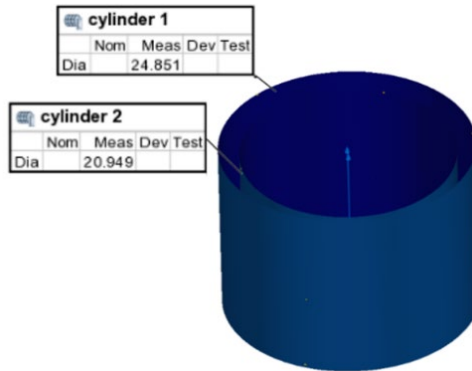


Figure 20. Testing Result CMM PC3 SS 0,3

Table 17. Results of PC3 dimension measurements with DoC 0.3 using stainless steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	24.851	- 0.020	- 0,149	fail	0,129
Cylinder 2	21.00	20.949	- 0,020	- 0,051	fail	0,031

The results of the PC3 shaft profile dimension measurements in Table 18 using CMM show that in cylinder 1 the value obtained is 24.851 mm from the nominal 25.00 mm with a deviation of -0.149 mm which exceeds the tolerance limit, with a violation difference of 0.129 so it is declared a fail. In cylinder 2 the result obtained is 20.949 mm from the nominal 21.00 mm, with a deviation of -0.051 mm which exceeds the tolerance, with a violation difference of 0.031 mm so it is declared a fail.

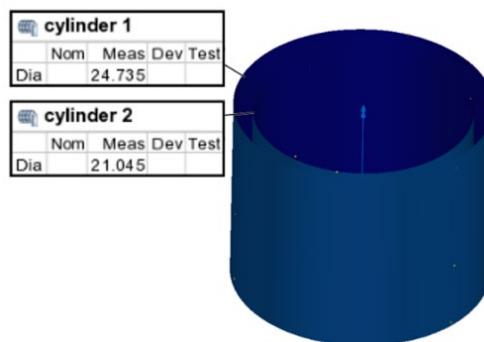


Figure 21. Testing Results CMM PC3 CS 0,2

Table 18. Results of PC3 dimension measurements with DoC 0.2 using carbon steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	24.735	- 0.020	+ 0,955	fail	0,245
Cylinder 2	21.00	21.045	- 0,020	+ 0,955	fail	0,935

The results of the PC3 shaft profile dimension measurements in Table 19 using CMM show that in cylinder 1 the value obtained is 24.735 mm from the nominal 25.00 mm with a deviation of + 0.955 mm which exceeds the tolerance limit, with a violation difference of 0.245 so it is declared a fail. In cylinder 2 the result obtained is 21.045 mm from the nominal 21.00 mm, with a deviation of + 0.955 mm which exceeds the tolerance, with a violation difference of 0.935 mm so it is declared a fail.

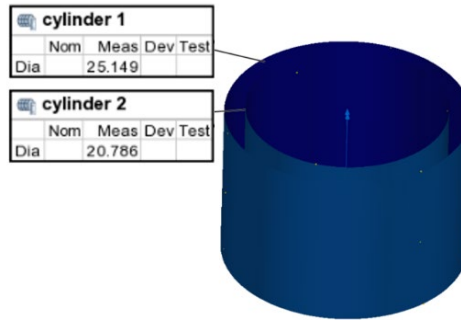


Figure 22. Testing Results CMM PC3 SS 0,2

Table 19. Results of PC3 dimension measurements with DoC 0.2 using stainless steel material

Name	Nominal	Measure	Tolerance	Deviation	Test	Out Tolerance
Cylinder 1	25.00	25.149	- 0.020	+ 0,149	fail	0,129
Cylinder 2	21.00	20.786	- 0,020	- 0,214	fail	0,194

The dimensional measurement results of the PC3 shaft profile in Table 20 show that cylinder 1 has a measured value of 25.149 mm compared to the nominal 25.00 mm, with a deviation of +0.149 mm, which exceeds the tolerance and is therefore classified as failed. Cylinder 2 also does not meet the tolerance, with a measurement of 20.786 mm from the nominal 21.00 mm and a deviation of +0.214 mm. Overall, the dimensional measurements of the P2 and PC3 shaft profiles made of carbon steel and stainless steel for various depths of cut indicate discrepancies when compared to the CAD design. These inconsistencies are presumed to result from an insufficient number of measurement points and their uneven distribution along the profile, leading to an inaccurate representation of the geometric shape. Kuruc (2011) emphasizes that an inadequate number and pattern of points can cause geometric features to go undetected by CMM interpolation [13]. Similarly, Sangnuan & Laosiritaworn (2016) state that too few measurement points can reduce measurement stability and accuracy, especially for small or complex profiles. Therefore, a well-designed measurement strategy is essential, including a sufficient number of points, even distribution, and proper probe approach direction to ensure valid measurement results [14].

5. Conclusions

The CAD modeling of the P2 and PC3 shaft profiles using SolidWorks produced models that comply with DIN standards. The CAM simulation conducted with Esprit TNG successfully generated toolpaths according to the milling contouring strategy and automatically produced precise NC codes for CNC machine operation. The test results show that the selection of machining parameters, particularly the depth of cut (DoC), has a significant influence on surface roughness quality and production time. A smaller DoC of 0.2 mm produces a smoother surface but requires a longer machining time, whereas a larger DoC of 0.3 mm speeds up the process but increases surface roughness. Stainless steel, having higher hardness, produces smoother surfaces than carbon steel at the same DoC.

Dimensional evaluation using a CMM revealed deviations in the machined results. This was caused by uneven distribution of measurement points, which failed to represent the entire profile accurately. For future research, it is recommended to verify the zero point (origin) and tool offset more precisely, increase and evenly distribute the dimensional measurement points, and add more machining parameter variations such as feed rate and cutting speed. Additionally, exploring other polygonal profile types such as P0, P1, P3, and P4 could provide broader insights into the influence of profile shape on machining quality..

Acknowledgments

The author would like to thank the National Research and Innovation Agency (BRIN) Subang for the support and facilities provided for this research through the Independent Learning Independent Campus (MBKM) program.

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