Optimization of Cutting Parameter CNC Wet Milling Process of Austenitic Stainless Steel on Surface Roughness

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ABSTRACT

Austenitic stainless steel (SS) has widely used in various industries owing to its good mechanical properties and corrosion resistance. However, the machineability of this material remains a challenge to measure for better application. Hence, this research aims to study optimization of machining parameter CNC wet milling process for austenitic stainless steels of AISI 304 and AISI 316. The research method has carried out to determine cutting parameters on CNC milling which subsequently followed by data analysis utilizing Taguchi method (S/N ratio and ANOVA) to demonstrate its machineability specifically on austenitic stainless steels of AISI 304 and AISI 316 surface roughness. The optimum surface roughness of AISI 304 stainless steel is about 0,21 µm within spindle speed of 3184 rpm, feed rate of 1528,4 mm/min in the depth of 0,3 mm. Depth of cut parameter during CNC milling was considered as the most influential parameter to optimize surface roughness in AISI 304 stainless steel. Meanwhile, during the cutting process of AISI 316 stainless steel, the optimum surface roughness was obtained in spindle speed of 3184 rpm, feed rate of 541,4 mm/min in the depth of 0,3 mm with the surface roughness value of 0,24 µm. The results depicted that feed rate held pivotal factor to determine surface roughness in AISI 316 stainless steel milling process. Therefore, this research gives impactful insight to develop good milling process which can increase machineability, quality, and productivity of AISI 304 and AISI 316 stainless steels.

Keywords: *Austenitic Stainless Steel, Cutting Parameter, CNC Wet Milling, Surface Roughness*

ABSTRAK

Austenitik stainless steel secara luas digunakan dalam berbagai industri karena sifat mekanik dan ketahanan korosi yang mumpuni. Namun, sifat mampu mesin tersebut masih perlu untuk ditingkatkan sehingga dapat diaplikasikan lebih baik. Maka dari itu, tujuan penelitian ini yaitu untuk mengetahui optimasi paramater permesinan proses CNC wet milling pada austenitik stainless steel seri AISI 304 dan AISI 316. Metode penelitian yang dilakukan dengan menentukan parameter pemotongan pada mesin CNC milling yang dilanjutkan dengan pengolahan data menggunakan metode Taguchi (S/N Ratio dan ANOVA) sehingga dapat menentukan sifat mampu mesin khususnya terkait kekasaran permukaan pada austenitik stainless steel AISI 304 dan AISI 316. Hasil penelitian ini menunjukkan bahwa kekasaran permukaan optimum stainless steel AISI 304 sebesar 0,21 µm dengan kecepatan spindel 3184 rpm, kecepatan pemakanan 1528,4 mm/menit pada kedalaman pemotongan 0,3 mm. Paramater kedalaman pemotongan selama proses CNC milling merupakan parameter yang paling berpengaruh untuk menghasilkan kekasaran permukaan yang baik untuk stainless steel AISI 304. Sementara itu, pada proses milling stainless steel AISI 316 didapatkan kekasaran permukaan optimum sebesar 0,24 µm pada kecepatan spindel 3184 rpm, kecepatan pemakanan 541,4 mm/menit pada kedalaman pemotongan 0,3 mm. Hasil tersebut juga menunjukkan bahwa kecepatan pemakanan menjadi faktor terpenting yang berpengaruh pada kekasaran permukaan terbaik pada stainless steel AISI 316 selama proses CNC milling. Dengan demikian, hasil penelitian ini dapat memberikan pengetahuan baru bagi pengembangan proses milling yang baik untuk dapat meningkatkan sifat mampu mesin, kualitas, maupun produktivitas dari austenitik stainless steel AISI 304 dan AISI 316.

Kata Kunci: Stainless Steel, Paramater Pemotongan, CNC Wet Milling, Kekasaran Permukaan

I. Introduction

Stainless steel has robustly intriguing due to its favour of high corrosion resistance, low thermal conductivity, and advanced mechanical properties for long-life use(Retno, Wilarso;, & Noor, 2023). Stainless steel is widely applied in various industries such as automotive, manufacture, and aerospace. Although stainless steel is likely more expensive than the other metals, it gives uproar fact that stainless steel has been applied wider in various industries of healthcare, chemical, electronics, military, and nuclear reactor(AlHazaa & Haneklaus, 2020). In general, stainless steel is an alloy steel which assembles by unique chemical composition of chromium (Cr) in 11-18%, besides of ferrous (Fe) and another element.

Austenitic type of stainless steel is specifically used in machining and manufacture industries owing to its high machineability, easy-formability and simple processing. Austenitic stainless steel is specifically categorized with the composition of chromium 16-18,5 %. Due to its chromium composition, this type of stainless steel has high corrosion resistance and used in numerous industries. Nonetheless, the machining process of austenitic stainless steels remains a challenge to develop for obtaining good surface roughness and better machineability(Acayaba & Escalona, 2015).

Several works have been devoted to observing machineability properties of austenitic stainless steels. Singh et.al reported the evaluation of carbide-coated cutter in face milling process of AISI 304 stainless steel in dry and wet conditions(P. Singh, Dureja, Singh, & Bhatti, 2019). The surface roughness of AISI 304 has alleviated during milling process in dry condition. Meanwhile, Equbal et.al. studied the milling process of AISI 316 stainless steel in different feed rates and depth of cut parameters(Equbal et al., 2022). The surface tension has reportedly decreased in low feed rates and depth of cut which affected to obtain better surface roughness AISI 316 stainless steel. In addition, Gutzeit et.al. reported a cryogenic milling of AISI 347 austenitic stainless steel which demonstrated the improvement results of surface roughness(Gutzeit, Basten, Kirsch, & Aurich, 2021). This increment of surface roughness due to induction phase transformation in deformation process during cryogenic milling.

However, there were limited studies to observe cutting parameter effect on surface roughness using the comparison of austenitic stainless steels.

Therefore, in this work, the CNC wet milling process has been developed using various cutting parameters aim to analyze the change of surface roughness and machineability of AISI 304 and AISI 316 austenitic stainless steels. The samples of AISI 304 and AISI 316 austenitic stainless steels were undergo by the CNC wet milling using coolant along with several cutting parameters of speed, feed rate, and depth of cut.

II. Materials and Method

The methodology to undergo this research involves experimental process via several trial test of CNC wet milling process using two pieces austenitic stainless steels of AISI 304 and AISI 316. The stages of research consist of material selection, spectrometry test, milling process, surface roughness test, and data analysis.

1. Materials Selection

Work piece materials used in this research are commercial austenitic stainless steels of AISI 304 and AISI 316 obtained from PT. Bhinneka Bajanas which have dimensions of 180x100x12 millimeter.

2. Spectrometry Test

The spectrometry test conceives of chemical composition process in austenitic stainless steel to ensure the samples are suitable with the standard of AISI (American Iron and Steel Institute) 304 and 316. Spectrometer test was evaluated by using ARL 3460 Optical Emission Spectrometer in Balai Besar Logam dan Mesin, Kementerian Perindustrian - Republik Indonesia.

3. Milling Process

The milling process was carried out by using Computer Numerical Control (CNC) machine of CNC Chevallier 2443 VMC (Vertical Machine Centers) in wet ambient condition along with Ascella coolant. This machine has a power capacity of 11 kW and voltage capacity of 15 kV.

Figure 1. CNC Milling Machine

The milling cutter used in milling process has specification of HGT EB1010 and Senyo Tungsten Carbide Z1MPCR with each diameter of 10 millimeter.

Figure 2. Milling cutter of HGT (top) and Senyo (bottom)

4. Cutting Parameter

The cutting parameter in this research was evaluated using various parameter of spindle speed, feed rate, and depth of cut parameter. Each parameter uses three level variable values which are demonstrated in Table 1.

Table 1. Cutting Level and Paramater

Parameter	Level 1	Level 2	Level 3
Spindle Speed (rpm)	2707	3184	3821
Feed Rate (mm/minute)	541,4	1018,58	1528,4
Depth of Cut (mm)	0,3	0,4	0,5

5. Surface Roughness Test

Surface roughness test was assessed to observe the value of surface roughness (Ra) from the samples of austenitic stainless steels (AISI 304 and AISI 316) which has been processed by machining in CNC Wet Milling machine. Mitutoyo Surface Roughness Tester SJ-310 was used for this examination in Metrology Laboratory, Politeknik Negeri Bandung.

Figure 3. Surface Roughness Tester

6. Data Analysis

Data analysis was the final stage of research which can be used to study the effect of optimization cutting parameter of CNC wet milling austenitic stainless steels on surface roughness. Data analysis was processed by utilizing Taguchi method and ANOVA which continues by calculation process aided MiniTab software.

III. Results and Discussion

1. Spectrometry Test Result

Spectrometer test was carried out to assess the similarity of chemical composition of austenitic stainless-steel samples which were used in this research with the standard of AISI (American Iron and Steel Institute) 304 and 316(Maurotto, Tsivoulas, Gu, & Burke, 2017). This examination was very crucial because the work piece samples are commercial austenitic stainless steels which have not tested its actual chemical composition. The chemical composition from spectrometer result of austenitic stainless steels which used in this research is portrayed in Table 2.

Table 2. Chemical Composition of AISI 304 and AISI 316 Austenitic Stainless Steels

No	Element	AISI 304 (%)	AISI 316 (%)
1	Ferro (Fe)	69,8	68
2	Carbon (C)	0,0401	0,0287
3	Silicon (Si)	0,354	0,675
4	Manganese (Mn)	1,73	1,43
5	Phosporus (P)	0,0415	0,0285

6	Sulfur (S)	0,0205	0,0030
7	Chromium (Cr)	18,1	16,5
8	Molybdenum (Mo)	0,273	1,91
9	Nickel (Ni)	8,01	9,81
10	Copper (Cu)	1,16	1,23
11	Cobalt (Co)	0,354	0,276
12	Titanium (Ti)	0,0050	0,0050
13	Tin (Sn)	0,0094	0,0020
14	Aluminium (Al)	0,0030	0,0034
15	Lead (Pb)	0,0150	0,0150
16	Vanadium (V)	0,0737	0,0837
17	Niobium (Nb)	0,0093	0,0050
18	Wolfram (W)	0,0500	0,0500

From the data shown in Table 2, the stainless steels contain both chromium (Cr) 18,1 % and 16,5 % along with high nickel content of 8,01 % and 9,81 % as the main non-iron elements. Accordingly, it is clearly demonstrated that the work piece samples have similar with standard AISI 304 and AISI 316 stainless steels(Martinez-Ubeda, Warren, Griffiths, & Flewitt, 2016; Zhang et al., 2020).

2. Surface Roughness Test Result

The Taguchi method was used to determine the variable value of each parameter during the milling process. This was chosen by choosing a suitable orthogonal array. Ortogonal array selection was envisaged not to less from total amount degree of freedom(Setiawan, Lubis, & Rosehan;, 2022). Table 3 depicts the total amount of degree of freedom from parameters which used in milling process of AISI 304 and AISI 316 stainless steel.

Table 3. Total Amount Degree of Freedom Parameter

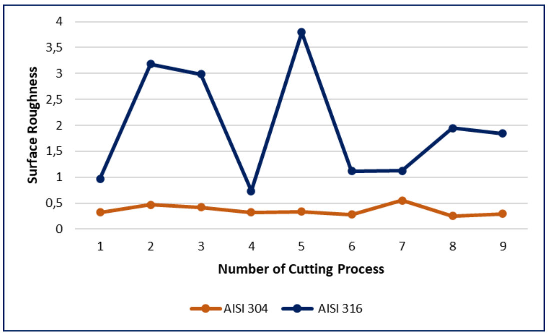
Parameter	Level Amount	DoF (Degree of Freedom)
Spindle Speed	3	2
Feed Rate	3	2
Depth of cut	3	2
	Total	6

Based on the table, it can be assumed that orthogonal array was used in L9. By using MiniTab software, the parameter variation was obtained for orthogonal array L9(Afringga, Prayitnoadi, & Erafeli, 2017). The resulted variations become the basis to undergo cutting process in CNC milling. Afterward, surface roughness measurement was evaluated for each cutting parameters of CNC milling AISI 304 and AISI 316 stainless steels. Surface roughness evaluation was pivotal to measure the resulted CNC milling machining process which has finished(T. Singh, Dureja, Dogra, & Bhatti, 2018). The number of variations and obtained roughness values were shown in Table 4.

Table 4. Cutting Parameter Variation and Surface Roughness

No	Spindle Speed (Rpm)	Feed Rate (mm/min)	Depth of cut (mm)	Ra (µm) AISI 304	Ra (µm) AISI 316
1	2707	541,4	0,3	0,324	0,975
2	2707	1018,58	0,4	0,471	3,182
3	2707	1528,4	0,5	0,424	2,985
4	3184	541,4	0,4	0,321	0,735
5	3184	1018,58	0,5	0,339	3,796
6	3184	1528,4	0,3	0,282	1,119
7	3821	541,4	0,5	0,552	1,122
8	3821	1018,58	0,3	0,254	1,947
9	3821	1528,4	0,4	0,298	1,843

The effect of cutting parameter on surface roughness of austenitic stainless steels AISI 304 and AISI 316 is demonstrated in Graph 1.



Graph 1. Surface Roughness Comparison of Austenitic Stainless Steels

From the graph abovementioned, it is clearly seen that austenitic stainless steel AISI 304 posses good surface roughness and better machineability compared than austenitic stainless steel AISI 316.

3. Effect of Cutting Parameter Individually

In this study, the effect of individual cutting parameter was shown in the F and P tests which are represented in Table 5 for AISI

304 stainless steel and Table 6 for AISI 316 stainless steel.

Table 5. Data F and P of AISI 304

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed (Rpm)	2	0,012798	19,08%	0,012798	0,006399	0,65	0,605
Feed Rate (mm/min)	2	0,004531	6,75%	0,004531	0,002265	0,23	0,812
Depth of cut (mm)	2	0,030172	44,98%	0,030172	0,015086	1,54	0,394
Error	2	0,019580	29,19%	0,019580	0,009790		
Total	8	0,067080	100,00%				

Table 6. Data F and P of AISI 316

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed (Rpm)	2	0,8604	8,77%	0,8604	0,4302	3,26	0,235
Feed Rate (mm/min)	2	6,1885	63,09%	6,1885	3,0942	23,45	0,041
Depth of cut (mm)	2	2,4958	25,45%	2,4958	1,2479	9,46	0,096
Error	2	0,2639	2,69%	0,2639	0,1319		
Total	8	9,8086	100,00%				

4. Calculation of S/N Ratio

The calculation of S/N ratio was examined to find out the influence factor on surface roughness. The characteristic of S/N ratio calculation based on term “smaller is the better”(Nguyen, Nguyen, & Tran, 2019). The resulted calculation was shown in Table 7.

Table 7. S/N Ratio Calculation

No	Spindle Speed (Rpm)	Feed Rate (mm/min)	Depth of cut (mm)	S/N Ratio 304	S/N Ratio 316
1	2707	541,4	0,3	9,7891	0,21990769
2	2707	1018,58	0,4	6,539582	-10,054004
3	2707	1528,4	0,5	7,452683	-9,4988867
4	3184	541,4	0,4	9,869899	2,67425322
5	3184	1018,58	0,5	9,396006	-11,586524
6	3184	1528,4	0,3	10,99502	-0,9766017
7	3821	541,4	0,5	5,161218	-0,9998571
8	3821	1018,58	0,3	11,90333	-5,787319
9	3821	1528,4	0,4	10,51567	-5,3105067
					-4,5910598

After obtaining the surface roughness data, the S/N ratio data was classified into A1, A2, B1, B2, C1, C2, and so on. Furthermore, the average values of each factor and level were calculated. A1 indicates that the result of Ra which involved A1 or Spindle Speed level 1 namely at 2707 rpm, B1 indicates the result of Ra which involved B1 or feed rate level 1 namely at a speed of 541.4 mm/min, and C1 indicates the result of Ra which involved C1 or depth of cut level 1 is 0.3 mm. The example of equation for data processing tables obtained from the grouping process and the average value of these parameters was demonstrated below:

S/N average value for A1 (Spindle Speed Level 1)

= (9.7891+6.539582+7.452683)/3
= 7.927122

The comprehensive calculation was shown in Table 8.

Table 8. S/N Ratio Response

Parameters	S/N 304	S/N 316
A1	7,927122	-6,44433
A2	10,08697	-3,29629
A3	9,193406	-4,03256
B1	8,273406	0,631435
B2	9,279638	-9,14262
B3	9,654458	-5,262
C1	10,89581	-2,18134
C2	8,975052	-4,23009
C3	7,336636	-7,36176

From Table 8, it can be obtained that the optimum parameters for AISI 304 stainless steel consisted of combination of A2 B3 C1, namely the combination of spindle speed with a speed of 3184 rpm, feed rate of 1528.4 mm/min, and depth of cut with a depth of 0.3 mm. Conversely, the optimum parameter of AISI 316 stainless steel is the combination of A2 B1 C1, namely a combination of spindle speed with a speed of 3184 rpm, a feed rate of 541.4 mm/min, and a depth of cut with a depth of 0.3 mm.

5. Effect of Cutting Parameter on Surface Roughness

After the S/N ratio value was obtained, ANOVA technique performed for all cutting parameters to calculate contribution of parameter on surface roughness of austenitic stainless steel of AISI 304 and AISI 316(Airao, Chaudhary, Bajpai, & Khanna, 2018). The resulted data were demonstrated in Table 9 for AISI 304 and Table 10 for AISI 316 stainless steel.

Table 9. ANOVA S/N Ratio AISI 304

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed (Rpm)	2	7,240	20,22%	7,240	3,620	0,82	0,549
Feed Rate (mm/min)	2	2,340	6,54%	2,340	1,170	0,27	0,790
Depth of cut (mm)	2	17,412	48,64%	17,412	8,706	1,98	0,336
Error	2	8,808	24,60%	8,808	4,404		
Total	8	35,800	100,00%				

Table 9 demonstrates the big contribution of cutting parameter due to the Signal to Noise (S/N) ratio in AISI 304 stainless steel was the depth of cut with a percentage and error of 48.64% and 24.60%, respectively.

Table 10. ANOVA S/N Ratio AISI 316

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed (Rpm)	2	16,269	7,87%	16,269	8,134	3,81	0,208
Feed Rate (mm/min)	2	145,324	70,30%	145,324	72,662	34,01	0,029
Depth of cut (mm)	2	40,841	19,76%	40,841	20,421	9,56	0,095
Error	2	4,273	2,07%	4,273	2,136		
Total	8	206,707	100,00%				

Meanwhile, Table 10 shows the enormous contribution of cutting parameter based on the Signal to Noise (S/N) ratio in AISI 316 stainless steel was the feed rate with a percentage and error of 70.30% and 2.07%, respectively.

6. Prediction of Optimum Surface Roughness

By using MiniTab, it is capable to estimate the cutting parameter variation which resulted optimum surface roughness. Parameter values and optimum surface roughness in the milling process for AISI 304 stainless steel were shown in Table 11 and Table 12.

Table 11. Optimum Condition Parameter of AISI 304 Stainless Steel

Variable	Value
Spindle Speed (Rpm)	3184
Feed Rate (mm/min)	1528,4
Depth of cut (mm)	0,3

Table 12. Optimum Surface Roughness of AISI 304 Stainless Steel

Fit	95% CI
0,216444	(-0,159004; 0,591893)

Simultaneously, parameter values and optimum surface roughness in the milling process for AISI 316 stainless steel were demonstrated in Table 13 and Table 14.

Table 13. Optimum Condition Parameter of AISI 316 Stainless Steel

Variable	Value
Spindle Speed (Rpm)	3184
Feed Rate (mm/min)	541,4
Depth of cut (mm)	0,3

Table 14. Optimum Surface Roughness of AISI 316 Stainless Steel

Fit	95% CI
0,240111	(-1,13819; 1,61841)

From Table 11 and Table 12, it can be obtained that the optimum cutting parameter for AISI 304 stainless steel was garnered at the spindle speed of 3184 rpm, cutting speed of 1528.4 mm/min and depth of cut in 0.3 mm with predicted optimum surface roughness of 0.21 µm along minimum and maximum interval values of - 0.15 and 0.59 µm. Depth of cut was a significant influence factor on transformation of surface roughness values in CNC milling process of AISI 304 stainless steel. This was caused by vibration of machine during CNC milling process(Policena, Devitte, Fronza, Garcia, & Souza, 2018).

From Table 13 and Table 14, it can be acquired that the optimum cutting parameter for AISI 304 stainless steel was considered at spindle speed of 3184 rpm, cutting speed of 541.4 mm/min and depth of cut in 0.3 mm with predicted optimum surface roughness of 0.24 µm along minimum and maximum interval values of -1.1 and 1.6 µm. Depth of cut is a very significant determining factor in changes in surface roughness values in the CNC wet milling process of AISI 316 stainless steel. Apparently, depth of cut remained as the pivotal factor of surface roughness alteration in CNC milling process of AISI 316 stainless steel.

IV. Conclusion

CNC wet milling process has successfully finished to study the optimum condition of cutting parameter on surface roughness of AISI 304 and AISI 306 austenitic stainless steels. The optimum surface roughness (Ra) of AISI 304 stainless steel is about 0,21 µm within spindle speed of 3184 rpm, feed rate of 1528,4 mm/min in the depth of 0,3 mm. The surface roughness factor of AISI 304 stainless steel was dominantly affected by the depth of cut parameter. During the cutting process of AISI 316 steel, the optimum surface roughness was obtained in spindle speed of 3184 rpm, feed rate of 541,4 mm/min in the depth of 0,3 mm with the surface roughness value of 0,24 µm. Therefore, the surface roughness factor of AISI 316 stainless steel was dominantly influenced by feed rate parameter.

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