Simulation and Optimization of Machining Time During Milling AISI P20 Steel

by Wirawan Sumbodo

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Abstract. This paper presents a simulation and optimization of machining time during milling of AISI P20 steel using the Taguchi method. The simulation was conducted using the L9 orthogonal array on a Swansoft CNC Simulation with the Fanuc OiM operating system. Milling simulations provide faster time and lower cost of getting machining time data compared to experiments on actual machines. The cutting tool uses a 12mm flat endmill and 4 number of flutes. Machining simulation parameters on surface finishing are speed, feed rate, and width of cut (WoC), while the depth of cut remains. NC programs, according to zigzag, paralel spiral, and constant overlap spiral toolpath strategies. The parameters of speed and feed rate have been calculated based on WoC values (5%, 10%, and 20%) of the AISI P20 steel material. The lowest machining time from each toolpath strategy is generated from WoC 20%, 3032 RPM speed, and 2286 mm min^{-1} feed rate. Setting these parameters on the three toolpaths simulated gets the lowest machining time. The toolpath strategies that provide the lowest machining time are the constant overlap spiral namely 1.62 min or 1 min 37 seconds. ANOVA analysis on various toolpaths found that the WoC and feed rate were significant factors (P less than 5%) affecting machining time, while the speed factor exceeded P probability (5%). The calculation of the S/N Ratio on various toolpath strategies shows that the width of cut is ranked 1, feed rate as ranked 2, and speed is ranked 3 affected the machining time.

1. Introduction

AISI P20 Steel material is a low alloy tool steel that is commonly used for plastic injection molds and die casting die. Making molds and dies from AISI P20 material using CNC machines with high accuracy. Computer numerically controlled (CNC) machines are used to produce accurate products with high productivity. High productivity can reduce the production costs of manufacturing products; therefore CNC machining time must be short. Optimization of CNC machine parameters (feed rate) shortens manufacturing costs, increasing tool life, and increases accuracy [1]. Optimization of machining time in CNC programming plays an important role in planning and scheduling the manufacturing process [2]. The CNC parameters that influence machining time are spindle rate, feed rate, step over, and tool path strategies [3].

The study of the influence of pocket geometry and tool path strategy in the machining time of pocket milling of UNS A96063 alloy found that the contour-parallel strategy achieved lower machining times [4]. The tool path in research is generated from the CAD CAM software that is CATIA.

The advantages of computer-aided manufacturing technologies allow simulating the working environment [5]. Optimization of machining time in the variation of machine parameters and toolpath strategy in various cross-sectional shapes shows the zigzag toolpath strategy and 80% width of cut produce a short machining time [3].

Tool path strategies for rough machining of turbine blades that produce the lowest machining time are zigzag toolpath [6]. The toolpath strategies for fabrication of thin-walled aluminum alloys have less machining time is parallel Spiral [7]. Another parameter that can be optimized to reduce machining time is the feed rate. Optimizing feed rates to minimize machining time has been studied and simulation results indicated that the machining time could be reduced around 35% [8]. Research on surface quality optimization from various machine parameters (spindle speed, depth of cut, tool diameter) found that the lower the feedrate, the lower the surface roughness [9]. Optimization of surface quality from various machine parameters (feed rate, cutting speed, radial depth of cut) results in higher federate, the higher the surface roughness [10]. Meanwhile, the higher the feed rate, the lower the machining time (fast) [3]. Setting the feed rate to achieve a good surface quality cannot be in line with federate settings to get the value of the fastest machining time.

Many optimizations use the taguchi method, one of the reasons because the taguchi method is a tool to get the best combination of many factors (cutting parameters, cutting condition, work piece and cutting tool material) to produce a high quality product and service [11]. Taguchi methods are statistical methods to improve the quality of manufactured goods and reduce the trial and error-type experiments using a matrix design [12]. Taguchi method is frequently being used for optimization due to saving of cost, time and material [13]. The simulation of the manufacturing process on CNC machine allows the visualization of the toolpath and allows checking the correctness of the NC program before it is implemented [5]. Study of design and optimization of machining parameters for effective AISI P20 removal rate during milling operation found that proper process design and control of the milling parameters reduce the total manufacturing time and increase the metal removal rate, which is a function of productivity [14].

Optimization of the machining time of a CNC milling machine from various machine parameters is mostly done in roughing cutting. Optimization of the finishing cutting of milling machines is mostly done to get the optimal surface quality (smaller roughness surface). It is necessary to optimize the machining time in the finishing process to reduce machining production costs. This paper deals with simulation and optimization machining time of milling CNC from variations in speed, feed rate, width of cut, and toolpath strategy of AISI P20 material. This optimization contributes to obtaining machine parameters on 3 tool path strategies to produce the fastest machining time value in the process of finishing tool and die steel materials. The NC program generated by MasterCAM software and the machining time of each variation was obtained by simulation using CNC simulation software.

2. Method

The research method is a simulation with help CADCAM software and CNC simulator software as well as machining time optimization using the Taguchi method. NC code for CNC milling machine is obtained from CADCAM Software with work piece geometry 100 mm long, 100 mm wide, and 20mm thick. The CAD-CAM program is generated from MasterCAM on a type of CNC Milling machine. The CADCAM program's use is more efficient in designing, producing NC programs, and simulating processes. CAD-CAM programs that design and simulate products can reduce production time and contribute to lower production costs [15-16].

Milling parameters of speed, feed rate, and width of cut (WoC) refer to AISI P20 material. The selected machining process is finishing cutting with a depth of cut of 0.2 mm and a width of cut (WoC) of 5%, 10%, and 20% of the tool diameter. The cutting tool used is a 12 mm diameter flat endmill material of TiAN coated carbide with 4 flutes. Simulation of the milling process to obtain machining time values using SSCNC (Swansoft CNC Simulation) with a Fanuc Oi-M.

Table 1: Speed, feed rate, and multiplied factor of AISI P20 [17].

WoC (%)	Speed (SFM)	Feed rate (IPT)	Multiply factor
5	550	0.022	2.3
10	450	0.022	1.8
20	375	0.022	1.5

Table 1 is the speed data and feed rate data of AISI P20 material for the finishing process from Guhring [17]. The spindle speed value in SFM according to WoC finsihing is 5%, 10%, and 20% of the flat endmill diameter. SFM is converted to RPM units according to equation (1). The feed rate value (mm min^{-1}) is calculated using equation (2). based on IPT in table 1.

$$RPM = \frac{SFM}{d1} \; x \; 3.82 \qquad\qquad (1)$$

$$Fr = z \; x \; IPT \; x \; RPM \; x \; 25.4 \; x \; MF \qquad\qquad (2)$$

Where SFM the Surface Feet minutes, RPM the Spindle speed in Rotation Per Minutes, Fr the feed rate in mm per min, d1 is tool diameter, mm / min the millimeter per minutes, IPT is Inch per teeth, z is the number of flute / teeth, and Mf is multiplied by factor. The variation of machine parameters is designed using an orthogonal matrix. Table 2 is the independent variable, the number of levels and the value of the independent variables. Table 3 shows the L9 orthogonal array of machine parameters used on a variety of toolpath strategies (TS). An orthogonal array suitable in the case of three-factors (or parameters) and three-levels is used to plan experiments. The toolpath strategies studied are zigzag, parallel spiral, and constant overlap spiral. The three toolpath shapes are shown in Figure 1. The three toolpaths are the fastest toolpaths in rough cutting square workpiece shapes [3]. The machining time of SSCNC simulation results according to the parameters of Table 3 for 3 toolpath strategies were analyzed using ANOVA and the calculation of the S/N ratio. Identification of the influence of the factor level on machining time is carried out by processing the data by calculating the S/N ratio. The suitable S / N ratio characteristic used in this study is Smaller is Better. The S/N ratio characteristics of smaller is better is given by equation (3).

$$rasio \; S/N_1 = -10 \; x \; \log\left(\frac{1}{n}\sum y^2\right) \qquad\qquad (3)$$

Mathematical machining time calculations of CNC Milling were done according to the equation (4). Where Tm is machining time (Min.), L is length of cut, Fr is feed rate (Dist./Min.), D is tool diameter, a is width of workpiece, and b is length of workpiece.

$$Tm = \frac{L}{Fr} \qquad\qquad (4)$$

$$L = \frac{a}{D} \; x \; b \qquad\qquad (5)$$

Table 2. Factors and levels setting

Factor	1	2	3
width t of cut, mm	0.6	1.2	2.4
speed, RPM	3032	3638	4447
feed rate, mm min^{-1}	1017	1464	2286

Figure 1. Toolpath strategy: (a) zig zag; (b) parallel spiral; (c) constant overlap spiral
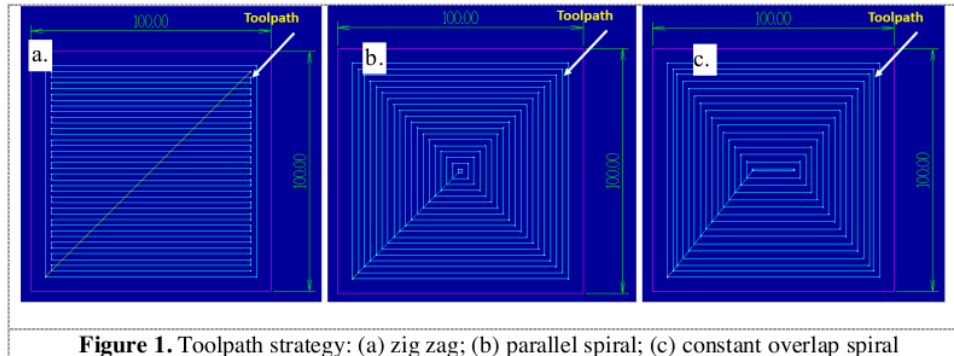
Table 3. The orthogonal array of variation of L9 machine parameters (3^3)

No	Factor		
	Width of Cut	Speed	Feed rate
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3. Results and Discussion

3.1. Machining time of the zigzag, parallel spiral, and constant overlap spiral toolpath strategies

The machining time of zigzag, parallel spiral, and constant overlap spiral toolpath strategies according to the L9 orthogonal array is presented in Table 4. The lowest machining time of the three toolpath strategies is generated from setting machine parameter no.7, namely 20% WoC, 3032 RPM speed, and 2286 mm/min feed rate. The highest *Tm* value from the three toolpaths is generated at the parameter no. 1, namely at 5% WoC, 3032 RPM speed, and 2286mm/min feed rate. The lowest machining time on the three toolpaths is in accordance with equation (4) where the *L* value is short because *D* uses the largest WoC (20%), and the largest *Fr* value (2286 mm/min). The highest machining time was due to the long *L* value where *D* used the smallest WoC (5%), and the smallest *Fr* value (1017 mm min^{-1}). A longest value *L* divided by the smallest value of *Fr* will get a high value of machining time.

Table 4. Machining time on zig zag, parallel spiral, and constant overlap spiral toolpath

No	Factor			Machining time (min)		
	Width of Cut, (mm)	Speed "*S*", (RPM)	Feed rate "*Fr*",, (mm min^{-1})	Zigzag	Parallel Spiral	Constant Overlap Spiral
1	1	1	1	12.08	12.07	9.42
2	1	2	2	8.48	8.45	6.42
3	1	3	3	5.52	5.48	4.29
4	2	1	2	4.73	4.78	4.22
5	2	2	3	3.17	2.98	1.88
6	2	3	1	6.62	6.60	5.95
7	3	1	3	1.90	1.88	1.62
8	3	2	1	3.60	3.60	3.40
9	3	3	2	2.57	2.57	2.34

3.2. ANOVA for S/N ratio of the zigzag toolpath strategies

ANOVA analyzed the effect of each factor (machine parameters) on machining time. Table 5 displays the analysis of the variance of each factor at each level tested in the finishing cutting using the zigzag tool path strategies.

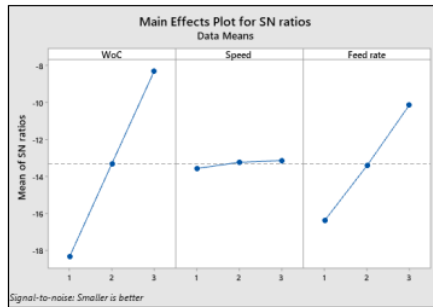**Table 5.** Anova for SN ratios of the zigzag toolpath strategies

Variation	DF	Adj SS	Adj MS	F-Value	P-Value
WoC	2	151.606	75.8028	733.95	0.001
Speed	2	0.307	0.1534	1.49	0.402
Feed rate	2	58.715	29.3577	284.25	0.004
Error	2	0.207	0.1033		
Total	8				

The analysis showed that WoC and feed rate had a significant effect on machining time, because the P value was less than P (0.05). WoC factor has the most significant influence on machining time compared to feed rate and speed.

Table 6. The S/N ratio with smaller is better of the zigzag toolpaths strategies

Level	Width of Cut	Speed	Feed Rate
1	-18.350	-13.574	-16.394
2	-13.309	-13.236	-13.421
3	-8.296	-13.145	-10.140
Delta	10.053	0.429	6.254
Rank	1	3	2

Table 6 shows the S/N ratio of machining time for each factor. The results show that WoC is ranked 1 or is the most significant factor influencing machining time. The data from the calculation of the S/N ratio is plotted in Figure 2. Figure 2 shows each factor influencing each level. The WoC factor at level 3 has a big influence on the value of *Tm*. The WoC at level 3 (WoC 20%) cuts more areas than level 1 and 2, causing a short length of cut (L). The speed factor of each level has little effect on the value of *Tm*. The feed rate factor at level 3 has the highest effect compared to levels 1 and 2, because the largest feed rate makes the low value of *Tm* according to equation (4).

Figure 2. Plot of S/N ratio of the zigzag toolpath strategies
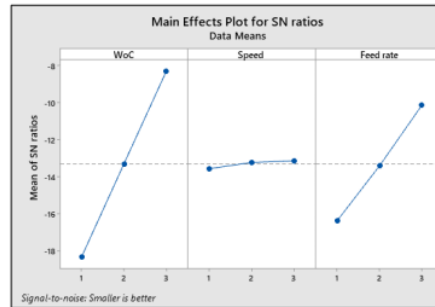
Figure 3. Plot of S/N ratio of the parallel spiral toolpath strategies

3.3. ANOVA for S/N ratio of the parallel spiral toolpath strategies

The analysis results of each factor's variance for each level tested in the finishing cutting using the parallel spiral toolpath strategies.showed table 7. The WoC and Fr factors have a significant effect on machining time, where the P value is less than P (0.05). ANOVA analysis of the parallel spiral toolpath strategies shows similar results to the zigzag toolpath where the WoC factor has the most significant effect on machining time compared to feed rate and speed.

Table 7. Anova for SN ratios of the parallel spiral toolpath strategies

Variation	DF	Adj SS	Adj MS	F-Value	P-Value
WoC	2	151.417	75.7084	639.57	0.002
Speed	2	0.485	0.2424	2.05	0.328
Feed rate	2	62.730	31.3650	264.96	0.004
Error	2	0.237	0.1184		
Total	8				

Table 8. The S/N ratio with smaller is better of the parallel spiral toolpaths strategies

Level	Width of Cut	Speed	Feed Rate
1	-18.317	-13.575	-16.383
2	-13.160	-13.052	-13.440
3	-8.271	-13.120	-9.924
Delta	10.046	0.523	6.458
Rank	1	3	2

Table 8 shows the value of the S/N ratio of the machining time for each factor. The WoC factor is ranked 1 while the feed rate is rank 2 and speed is ranked 3. The results of the calculation of the S/N ratio are plotted in Figure 4. The WoC factor at level 3 has a large effect on the value of Tm (see Figure 3). Width of cut level 3 (WoC 20%) cuts more area, length of cut (L) is short so the value of Tm is low. The analysis results on the WoC factor and feed rate show similar results to the zig zag toolpath, where both factors at level 3 gives the highest effect compared to levels 1 and 2.

3.4. ANOVA for S/N ratio of the constant overlap spiral toolpath strategies

The analysis of variants on the constant overlap spiral toolpath strategies showed on table 9. Parameter of WoC and Fr has have a significant effect on machining time, where the P value is less than P (0.05). Speed parameter been affected to machining time, but not significant because the P value is more than P (0.05). Parameter of speed has been affected to machining time, but not

significant because the P value is more than P (0.05). The most influential factor is feed rate compared to WoC and speed.

Table 9. Anova for SN ratios of the constant overlap spiral toolpath strategies

Variation	DF	Adj SS	Adj MS	F-Value	P-Value
WoC	2	110.622	55.311	54.74	0.018
Speed	2	4.145	2.073	2.05	0.328
Feed rate	2	89.359	44.680	44.22	0.022
Error	2	2.021	1.010		
Total	8				

Table 10 shows the value of the S/N ratio of the machining time for each factor. The most influential factor of the machining time is WoC. The WoC factor is ranked 1 Feed rate is rank 2 and speed is ranked 3. The results of the calculation of the S/N ratio are plotted in Figure 4. The WoC factor at level 3 has a large effect on the value of Mt (see Figure. 4). The analysis results on the WoC factor and feed rate show similar results to the zig zag and parallel spiral toolpath, where the WoC at level 3 gives the highest effect compared to levels 1 and 2.

Table 10. The S/N ratio with smaller is better of the constant overlap spiral toolpath strategies

Level	Width of Cut	Speed	Feed Rate
1	-16.219	-12.151	-15.199
2	-11.264	-10.758	-12.383
3	-7.667	-12.240	-7.568
Delta	8.552	1.482	7.632
Rank	1	3	2
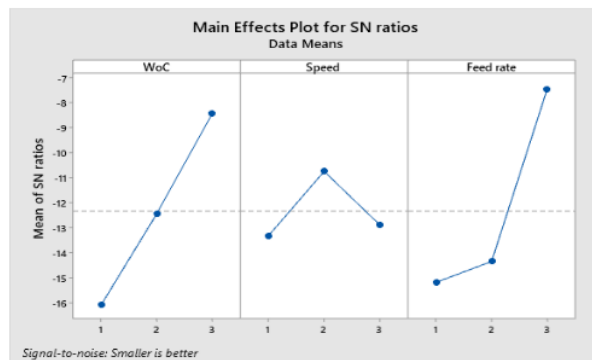
Figure 4. Plot of S/N ratio of the constant overlap spiral toolpath strategies

Previous studies on roughing cutting with a variety of tool path strategies, width of cut, speed, and feed rate concluded that the zigzag is the toolpath that produces the lowest time [3]. Other studies have also found that the zigzag toolpath strategies are the toolpaths that generate the fastest time [6-7]. In this research, it was found that constant overlap spiral is the toolpath that can produce the fastest machining time.

4. Conclusions

The lowest value of the machining time simulation results from each toolpath strategy is generated from the WoC parameter of 20%, the highest speed and feed rate. The toolpath strategies for finishing procces of AISI P20 material that produce the lowest machining values is constant overlap

spirals. ANOVA analysis on various tool paths found that the width of cut and feed rate factors were significant factors affecting machining time where the P value was less than the P probability value (5%), while the speed factor exceeded P probability (5%). The calculation of the S/N Ratio on various tool path strategies show that the width of cut is ranked 1, feed rate as ranked 2, and speed is ranked 3 which affects the value of machining time. Based on the optimization, it can determine the parameters that produce the fastest machining time (the lowest value). The lowest machining time from the simulation results can reduce production time and reduce production costs.

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