Optimization of CNC Milling Machining Time through Variation of Machine Parameters and Toolpath Strategy in Various Cross-sectional Shape on Tool Steels and Die Steels Materials

Wirawan Sumbodo, Kriswanto, Murdani, Idhhar Suwanda and Tri Syamsul Allam
Department of Mechanical Engineering, Universitas Negeri Semarang, Semarang, Indonesia

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Abstract: CNC machines are manufacturing machines for mass products that required to operate quickly. Machining Time efficiency will reduce production costs. This paper presents an optimization of CNC milling Machining Time from a variations of machine parameters, toolpath strategy and variations in cross sectional shapes. The method is simulation use simulation software and optimization with constraint machining time. The program is based on parameters (speed, feed rate, and width of cut) for pocket roughing operations. The cross section shape of the workpiece is rectangular with 5 variation size. The width of cut for roughing work is 30%, 50%, and 80%. Endmill uses a diameter of 12 mm and 4 flutes. The optimal machining time value in each cross section workpiece is generated from the zigzag toolpath strategy and 80% width of cut. The optimum Machining Time of W1 is 3 minutes 11 seconds, W2 is 5 minutes 55 seconds, W3 is 12 minutes 25 seconds, W4 is 5 minutes 18 seconds and w5 is 12 minutes 19 seconds. The toolpath strategy that produces the largest Machining Time high speed and true spirals toolpath strategy.

1 INTRODUCTION

Computer Numeric Control machine (CNC) is a manufacturing machine technology widely used in industries. CNC machine is used to produce high-precision mass products quickly. CNC machines with high capability produce products quickly called high speed machine (HSM) CNC machines. The HSM milling machine has a spindle speed of up to 60,000rpm. High speed machining is one of the modern technologies that increases the efficiency, accuracy and quality of workpiece compared to conventional cutting (Awale, 2015). CNC milling machines generally have spindle speeds of 3000 rpm to 6000 rpm. CNC machines with high spindle rates can produce high feed rate and small machine time. Small Machining Time is the efficiency of production time which reduces production costs. Machining time estimation is a critical step towards an optimal and practical production plan (Borkar, 2014). Gavril (2016) study about increase productivity and cost optimization in CNC manufacturing with the results that by increasing the working time by 32.49% may achieve an economy up to 10.33% for the manufacturing cost.

The milling CNC machine with a small spindle rate so that the feed rate produced is small while the Machining Time is large. Parameters that affect the value of Machining Time other than spindle rate and feed rate are stepover and toolpath strategies.

Determination of stepover parameters and toolpath strategies affects machine time. (Romero, 2013), and (Gologlu, 2008). Dimitrov (2012), Saroj (2013), Daneshmand (2013), Prajapati (2013), and Minquiza (2013) study of the reduction in Machining Time CNC milling, the results show that setting toolpath parameters using the help of CAM software can reduce machining time. These parameters include speed, stepover percentage, feed rate, and toolpath strategy. Daneshmand (2011) investigating potential ways to reduce Machining Time with the help of CATIA® and CAM, the results of machining time are reached when using a zigzag toolpath strategy. Study on Machining Time by Akmal (2013) shows that the parallel spiral toolpath strategy has the smallest Machining Time compared to other toolpath strategies by reason of a parallel spiral strategy using

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a down milling process when cutting. Prajapati (2013) study of toolpath optimization for turbine blades in VMC machines with MasterCAM® software resulting in significantly reduced Machining Time and tool paths depending on the workpiece geometry (designed) and cutting conditions.

This paper presents an optimization Machining Time resulting from variations in speed, feed rate, stepover, tollpath strategy from various cross section workpieces of tool steels and die steel materials. The Machining Time of each variation was obtained by simulation using CAM software and CNC simulation software. CAM software makes it possible to achieve and simulate manufacturing processes to check the correctness of a project before it is implemented (Gavril, 2016). This study also aims to get optimal parameters so that CNC machines with low spindle speed specifications (max 3000 rpm) can produce the fastest machine time.

2 METHOD

This research method is simulation and optimization. Simulation of program and Machining Time using CAM software and CNC Simulation software. CAM (Computer Aided Manufacturing) software is used to generate CNC programs by setting the parameters of speed, feed rate, steopover (Width of cut) and toolpath strategy on variations in the cross section of the workpiece. The CAM process uses MasterCAM X4 software on a CNC milling machine. CNC Simulation Software to simulate programs so that Machining Time is obtained. The simulation software used is SSCNC (Swansoft CNC Simulation) with a Fanuc Oi-M system. Parameters of speed, feed rate, and steopover are calculated for machining of the tool steels and die steels materials.

The limit of parameters calculating in this study is cutting roughing with a width of cut (WoC) 30%, 50% and 80% of the tool diameter. The tool used is a 12 mm diameter flat endmill 4 flutes with material of TiAN coated carbide (Titanium Aluminum Nitride).

Table 1: Data of speed and feed rate for tool steels and die steels (Guhring, 2015).

WoC (%)	Speed (SFM)	Feed rate (IPT)
30	300	0.024
50	200	0.022
80	200	0.022

The cross-sectional design of the workpiece consists of 5 variations which are generally used in mold and die products. The shape of the rectangular cross section is varied with the comparison of the sides as in Table 2. The design of the workpiece and the dimensions are shown Figure 1.

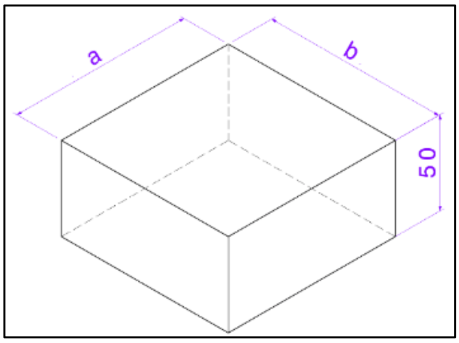

Figure 1: Shape and geometry of the cross section of the workpiece.

Table 2: Variations in the sizes of cross section shapes.

Workpiece Code	Sides Comparison (a:b)	Size (mm)
W1	1:1	100:100
W2	1:2	100:200
W3	1:4	100:400
W4	2:1	200:100
W5	4:1	400:100

Spindle speed in SFM is converted in RPM units using equation 1. Selection of SFM using WoC is 30%, 50%, and 80% which is the WoC criterion for roughing cutting. Feed rate is calculated using IPT data Table 1 then converted to IPM units (Inch per Minutes) according to equation 2. Feed rate in IPT is converted to units of mm / minute using equation 3. Dept of Cut (DoC) uses standard DoC for roughing with values 0,5 d1.

$$\mathrm{RPM} = \frac{\mathrm{SFM}}{\mathrm{d1}} \times 3.82 \quad (1)$$

$$\mathrm{IPM} = \mathrm{z} \times \mathrm{IPT} \times \mathrm{RPM} \quad (2)$$

$$\mathrm{mm/min} = \mathrm{IPM} \times 25{,}4 \quad (3)$$

Where SFM the Surface Feet minutes, RPM the Rotation Per Minutes, IPM is Inch per Minute, IPT is Inch per teeth, and z is number of flute/teeth. IPT value on WoC is 30% multiplied by factor 1.1 while in WOC 50% and 80% multiplied by 1.

Table 3 is the result of speed calculation (RPM), feed rate (mm / min), and width of cut (mm) on stepover 30%, 50%, and 80% . Data speed and feed rate on the WoC 50% and 80% have the same value, even though the WoC dimension is different. The same speed value is obtained from the same SFM which is 200, while the feed rate (IPT) value is obtained the same because multiplied by a factor of 1.

Table 3: Results of calculation speed, feed rate, and width of cut.

Width of Cut		Speed	Feed rate	Speed	Feed rate
%	mm	(SFM)	(IPT)	(RPM)	mm/min)
30	3.6	300	0.024	2426	596
50	6.0	200	0.022	1617	361
80	9.6	200	0.022	1617	361

The number of variations in toolpath strategy in CAM software is 8 namely zigzag, constant overlap spiral, parallel spiral, parallel spiral clean corners, morph spirals, high speed, one way and true spirals. The toolpath strategy variation is coded TS1 to TS8. The toolpath strategy parameter is found in pocketing work. The design toolpath strategy is shown Figure 2.

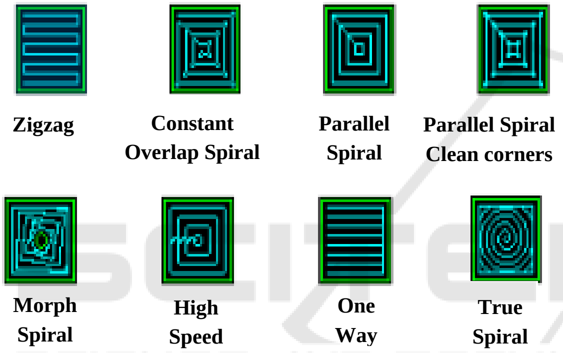

Figure 2: Toolpath strategy.

Machining Time simulation results in each cross section of the workpiece are optimized by constraint the value of the Machining Time below 15 minutes. The most optimum Machining Time is the smallest / lowest Machining Time data from various shapes of cross section workpieces.

3 RESULTS AND DISCUSSIONS

NC program was created base on machine parameters data in speed, feed rate, and width of cut appropriate table 3 for tool steels and die steels. A variety of toolpath strategies (TS1.d. TS8) in sequence are zigzags, constant overlap spirals, parallel spirals, parallel spiral clean corners, morph spirals, high speed, one way and true spirals.

3.1 Optimization Machining Time of W1 Workpiece

The cross section of the W1 workpiece is a square with a sizes of 100 mm x 100 mm as shown Figure 3. Figure 3 is a cutting of the zigzag toolpath on the workpiece. The results of the simulation Machining Time of the W1 workpiece are shown in Table 4.

SCNC software simulation shown in Figure 4. Machining Time simulation using this SSCNC software generates same value as the actual machine. This study does not use the Machining Time value of MasterCAM but uses Machining Time from SSCNC. Setting the SSCNC software according to the actual machine is set spindle speed and feed rate at 100% work. Prajapati (2013) found that, there is a deviation of MasterCAM software simulation time with experimental machining time may be due to time required for tool change in the CNC machine. This study did not replace the cutting tools to make workpieces, while in the study Prajapati replaced cutting tools.

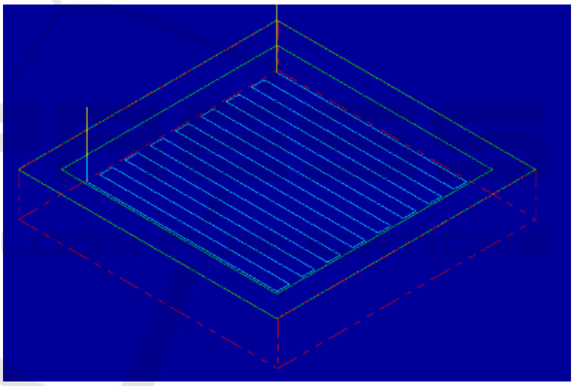

Figure 3: Zigzag toolpath on W1 workpiece.

Figure 4: Simulation in CAM software.

Machining time simulation results in the cross section of the W1 workpiece show that the fastest Machining Time of various WoC and toolpath strategy variations is 80% WoC on TS1 (Zigzag) which is 3 minutes 11 seconds. The longest Machining Time (slow) is 50% WoC with TS6 (high speed) which is 18 minutes 45 seconds.

Table 4: Machining Time of W1 workpiece.

Variation	Machining Time (minute, seconds)		
	WoC 30%	WoC 50%	WoC 80%
W1TS1	4,33	4,23	3,11
W1TS2	4,17	4,32	3,25
W1TS3	4,16	4,31	3,12
W1TS4	4,39	4,53	3,28
W1TS5	5,57	6,20	4.28
W1TS6	13,01	18,45	15,17
W1TS7	5,44	5,40	4,02
W1TS8	6,02	6,17	04,15

The constraint of machining time optimization is 4 min, 8sec. The value of 4 min, 8 sec is obtained from CNC milling machining time calculations in accordance with equation 4.

$$Tm = \frac{L + A + O}{Fr} \quad (4)$$

$$A = O = \frac{D}{2} \quad (5)$$

$$L = \frac{a}{D} x \, b \quad (6)$$

Where Tm is machining time (Min.), *L* is length of cut, *A* the approach distance O is cutter run out distance, *Fr* is feed rate (Dist./Min.), *D* is tool diameter, *a* is width of workpiece, and *b* is length of workpiece.

Size of workpieces is 100 mm in X and 100 mm in Y, width of cut 50%, feed rate 361 mm/min, D endmill 12 mm. A or O is equal to 0 because the tool is in the pocket area. L is 88 x ((100-12)/6+1)+ 88 = 1584 mm.

Table 5: Machining time calculation of W1.

Size		L (mm)	A=O (mm)	Fr (mm/min)	Tm (min, sec)
a (mm)	b (mm)				
100	100	1496	0	361	4,9

The plot of machine time with the machine parameters and toolpath variations is shown in Figure 5, and the machine time constraint, Tm ≤ 4min, 23sec.

Result from optimization of machine time show machine parameters and toolpath strategies that produce machine time data less than Tm namely W1TS1 on WoC80%; W1TS2 on WoC80%; W1TS3 on WoC80%; W1TS4 on WoC80%, and W1TS7 on WoC80%. Machine parameters and toolpath strategies that produce an optimum machine time (small/fastest) is W1TS1 (zigzag toolpath strategy) on WoC 80% with time 3 min, 23 sec.

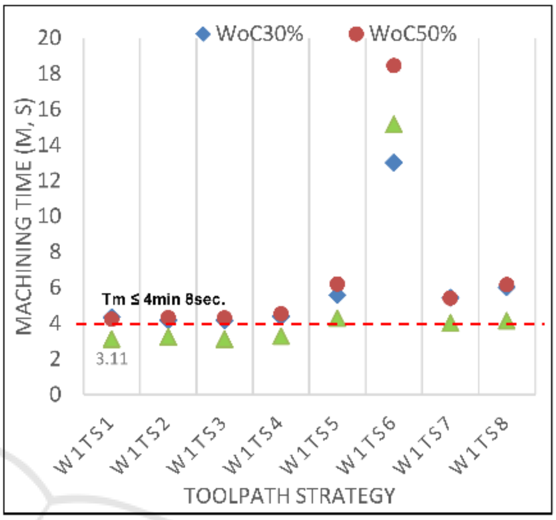

Figure 5: Plot Machine Time vs toolpath strategy on W1.

3.2 Optimization Machining Time of W2 Workpiece

The cross section of the W2 workpiece is a rectangular with a size of 100 mm x 200 mm as shown Figure 6. The results of the simulation Machining Time of the W2 workpiece are shown in Table 6.

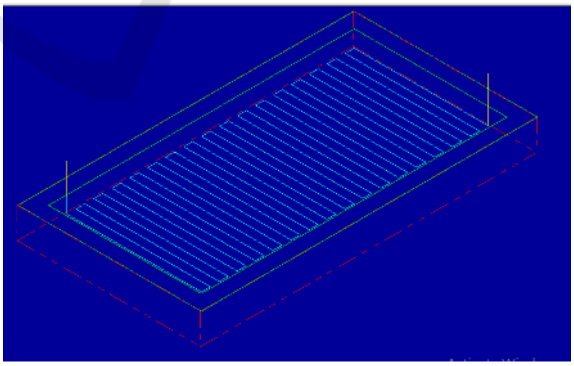

Figure 6: Zigzag toolpath on W2 workpiece.

Table 6 shows that the fastest Machining time of WoC variation and toolpath strategy for cross section W2 is 80% WoC on TS1 (Zigzag) which has a time of 5 minutes 55 seconds. The longest Machining time is WoC 50% on TS6 (high speed) which is 38 minutes 21 seconds.

The constraint of machining time optimization on W2 workpiece is 8 min, 9 sec. The constraint value is obtained from CNC milling machining time calculations with size of W2 workpieces is 100 mm and 200 mm, width of cut 50%, feed rate 361 mm/min, D endmill 12 mm. L is 88 x ((200-12)/6+1)+ 188 = 3092 mm.

Table 6: Machining time of W2 workpiece.

Variation	Machining Time (minute, seconds)		
	WoC 30%	WoC 50%	WoC 80%
W2TS1	8,32	10,31	5,55
W2TS2	8,40	10,52	6,44
W2TS3	8,37	10,56	6,32
W2TS4	9, 2	11,20	6,49
W2TS5	14,30	16,30	10,7
W2TS6	19,58	38,21	23,28
W2TS7	13,44	16,16	9,48
W2TS8	15,47	17,13	10,51

Table 7: Machining time calculation of W1.

Size a (mm)	Size b (mm)	L (mm)	A=O (mm)	Fr (mm/min)	Tm (min, sec)
100	100	3092	0	361	8,9

The plot of machine time with the machine parameters and toolpath variations is shown in Figure 5, and the machine time constraint, Tm ≤ 8min, 9sec.

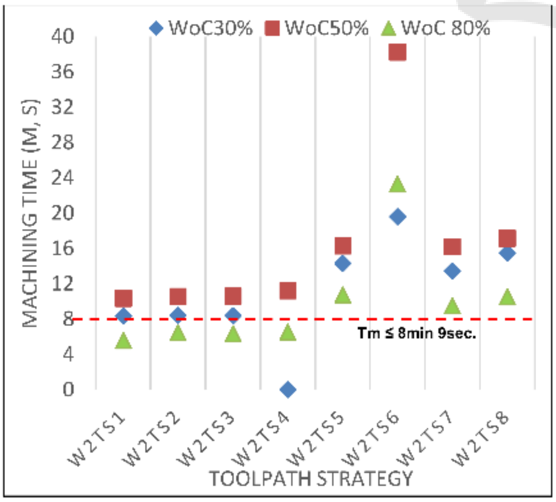

Figure 7: Plot Machine Time vs toolpath strategy on W2.

Result from optimization of machine time show machine parameters and toolpath strategies that produce machine time data less than Tm (≤ 8min 9sec) namely W2TS1 on WoC80%; W2TS2 on WoC80%; W2TS3 on WoC80%; W2TS4 on WoC80%. Machine parameters and toolpath strategies that produce an optimum machine time (small/fastest) is W2TS1 (zigzag toolpath strategy) on WoC 80% with time of 5 min, 55 sec.

3.3 Optimization Machining Time of W3 Workpiece

The cross section of the W3 workpiece is a rectangular with a sizes of 100 mm x 400 mm as shown Figure 7. The results of the simulation Machining time of W3 workpiece are shown Table 7.

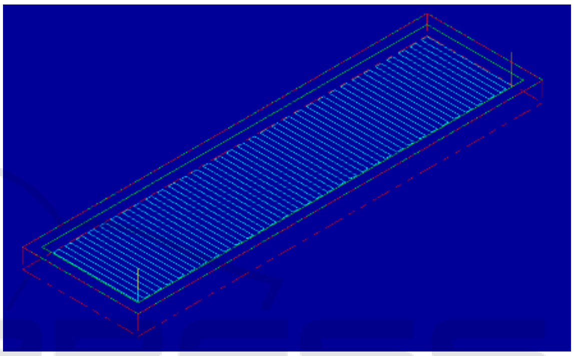

Figure 7: Zigzag toolpath on W3 workpiece.

Table 7: Machining time of W3 workpiece.

Variation	Machining Time (minute, seconds)		
	WoC 30%	WoC 50%	WoC 80%
W3TS1	16,50	17,14	12,25
W3TS2	17,24	17,50	12,48
W3TS3	17,19	17,26	12,33
W3TS4	17,42	18,00	12,49
W3TS5	45,51	46,32	28,50
W3TS6	30,45	41,14	36,12
W3TS7	23,28	22,53	14,23
W3TS8	49,02	49,52	30,27

Results of machine times in Table 7 shows that the fastest Machining time of 80% WoC and TS1 (Zigzag) which has a time of 12 minutes 25 seconds. The longest Machining time is WoC 50% on TS8 (true spirals) which is 49 minutes 52 seconds

The constraint of machining time optimization on W3 workpiece is 17 min, 10 sec. The constraint value is obtained from CNC milling machining time calculations with size of W2 workpieces is 100 mm and 200 mm, width of cut 50%, feed rate 361 mm/min, D endmill 12 mm. L is 88 x ((400-12)/6+1)+ 388 = 6196 mm.

Table 8: Machining time calculation of W3.

Size		L (mm)	A=O (mm)	Fr (mm/min)	Tm (min, sec)
a (mm)	b (mm)				
100	100	6196	0	361	17,10

The plot of machine time with the machine parameters and toolpath variations is shown in Figure 8, and the machine time constraint, Tm ≤ 17min, 10sec.

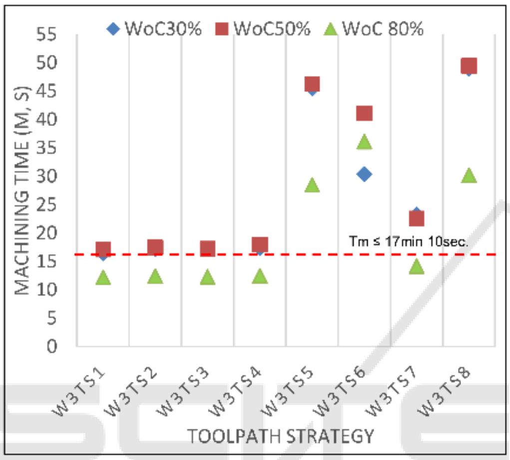

Figure 8: Plot Machine Time vs toolpath strategy on W3.

Result from optimization of machine time show machine parameters and toolpath strategies that produce machine time data less than Tm (≤ 17min 10sec) namely W3TS1 on WoC 30% and 80%; W3TS2 on WoC80%; W3TS3 on WoC80%; W3TS4 on WoC80%; and W3TS7 on WoC80%. Machine parameters and toolpath strategies that produce an optimum machine time is W3TS1 (zigzag toolpath strategy) on WoC 80% with time of 12 min, 25 sec.

3.4 Optimization Machining Time of W4 Workpiece

The cross section of the W4 workpiece is a rectangular with a sizes of 200 mm x 100 mm as shown Figure 9. The results of the simulation machining time of W4 workpiece shown on Table 9.

Machining time simulation results in the cross section of the W4 workpiece show that the fastest Machining time of various WoC and toolpath strategy variations is 80% WoC on TS1 (Zigzag) which is 5 minutes 18 seconds. The longest Machining time is 50% WoC with TS6 (high speed) which is 27 minutes 38 seconds.

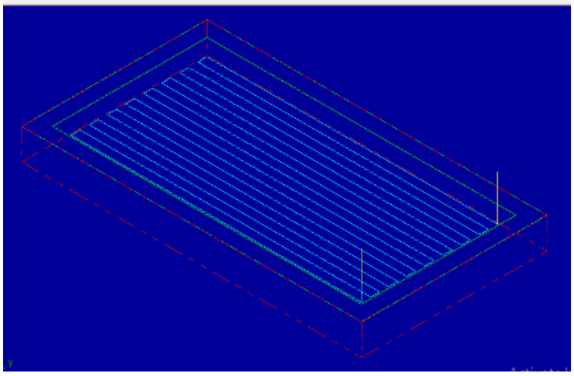

Figure 9: Zigzag toolpath on W4 workpiece.

Table 9: Machining time of W4 workpiece.

Variation	Machining Time (minute, seconds)		
	WoC 30%	WoC 50%	WoC 80%
W4TS1	08,34	08,48	05,18
W4TS2	08,19	08,58	05,44
W4TS3	08,38	08,54	05,33
W4TS4	09,02	09,18	05,47
W4TS5	14,30	15,00	08,34
W4TS6	18,44	27,38	18,11
W4TS7	10,31	10,20	06,12
W4TS8	15,17	16,06	08,51

The constraint of machining time optimization on W4 workpiece is 8 min, 34 sec. The constraint value is obtained from CNC milling machining time calculations with size of W2 workpieces is 200 mm and 100 mm, width of cut 50%, feed rate 361 mm/min, D endmill 12 mm. L is 188 x ((100-12)/6+1)+ 88 = 3096 mm.

Table 10: Machining time calculation of W4.

Size		L (mm)	A=O (mm)	Fr (mm/min)	Tm (min, sec)
a (mm)	b (mm)				
100	100	3096	0	361	8,34

The plot of machine time with the machine parameters and toolpath variations is shown in Figure 8, and the machine time constraint, Tm ≤ 8min, 34sec. Result from optimization of machine time show machine parameters and toolpath strategies that produce machine time data less than Tm (≤ 8min 34sec) namely W4TS1 on WoC 30% and 80%; W4TS2 on WoC 30% and 80%; W4TS3 on

WoC80%; W4TS4 on WoC80%; W4TS5 on WoC80%; and W4TS7 on WoC80%. Machine parameters and toolpath strategies that produce an optimum machine time (small/fastest) is W3TS1 (zigzag toolpath strategy) on WoC 80% with time of 5 min, 18 sec.

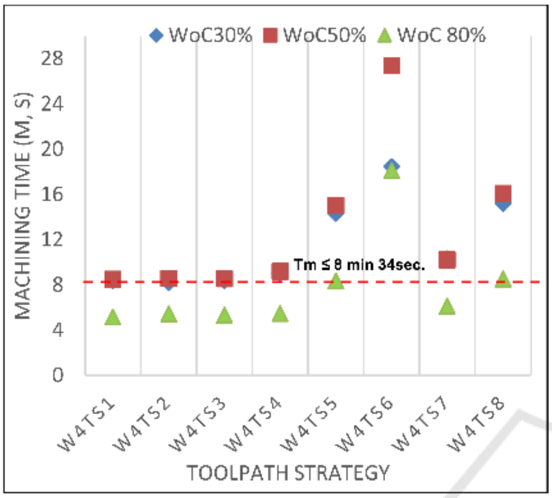

Figure 10: Plot Machine Time vs toolpath strategy on W4.

3.5 Optimization Machining Time of W5 Workpiece

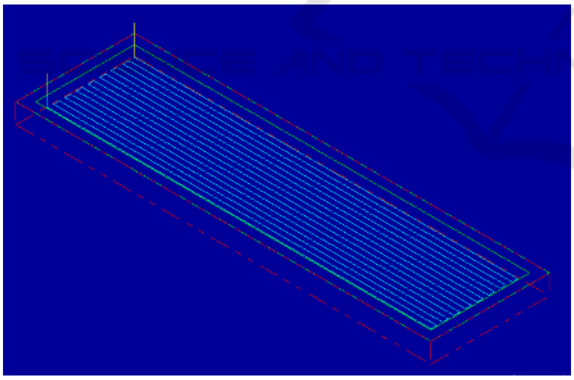

Figure 11: Zigzag toolpath on W5 workpiece.

The cross section of the W5 workpiece is a rectangular with a sizes of 400 mm x 100 mm as shown Figure 11. The results of the simulation Machining time of the W5 workpiece are shown Table 11.

Machining Time simulation results in the cross section of the W5 workpiece show that the fastest Machining Time is 80% WoC and TS1 (Zigzag) which is 12 minutes 19 seconds. The longest Machining Time is 50% WoC with TS6 (true spiral) which is 50 minutes 09 seconds.

Table 11: Machining time of W5 workpiece.

Variation	Machining Time (minute, seconds)		
	WoC 30%	WoC 50%	WoC 80%
W5TS1	17,15	17,38	12,19
W5TS2	16,24	16,51	13,25
W5TS3	17,23	17,50	13,06
W5TS4	17,46	18,13	13,23
W5TS5	45,53	46,29	30,13
W5TS6	30,44	41,18	38,02
W5TS7	20,04	19,42	13,40
W5TS8	49,24	50,09	32,36

The constraint of machining time optimization on W5 workpiece is 17 min, 27 sec. The constraint value is obtained from CNC milling machining time calculations with size of W2 workpieces is 100 mm and 200 mm, width of cut 50%, feed rate 361 mm/min, D endmill 12 mm. L is 388 x ((100-12)/6+1)+ 88 = 6296 mm.

Table 12: Machining time calculation of W5.

Size		L (mm)	A=O (mm)	Fr (mm/min)	Tm (min, sec)
a (mm)	b (mm)				
100	100	6296	0	361	17,27

The plot of machine time with the machine parameters and toolpath variations is shown in Figure 8, and the machine time constraint, Tm ≤ 17min, 27sec.

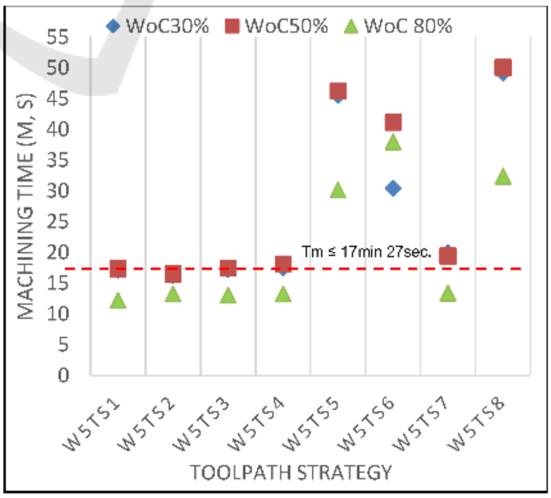

Figure 12: Plot Machine Time vs toolpath strategy on W5.

Result from optimization of machine time show machine parameters and toolpath strategies that produce machine time data less than Tm (≤ 17min 27sec) namely W5TS1 on WoC 30% and 80%; W5TS2 on WoC30%, 50% and 80%; W5TS3 on WoC30% and 80%; W5TS4 on WoC80%; and W3TS7 on WoC80%. Machine parameters and toolpath strategies that produce an optimum machine time is W3TS1 (zigzag toolpath strategy) on WoC 80% with time of 12 min, 19 sec.

The optimization results in each cross section of the workpiece (W1-W5) obtained that the fastest (optimal) machining time is a parameter zigzag toolpath strategy and width of Cut 80%. The zigzag toolpath uses the shortest cutting path compared to other toolpath strategies, while WoC 80% allows achieving the largest area cuts compared to WoC30% and 50%. The spindle rate and feed rate are the same for WoC 50% and 80% This results in 80% smaller WoC machining time compared to 50%. Using the same value for speed and feed rate refers to catalog data from the guhring tool.

The parallel spiral toolpath produces the second lowest machining time after zigzag. While the toolpath with the biggest machining time values is true spirals and high speed. True spirals toolpath has the longest cutting path in the form of W3 and W5 resulting in the largest machining time value.

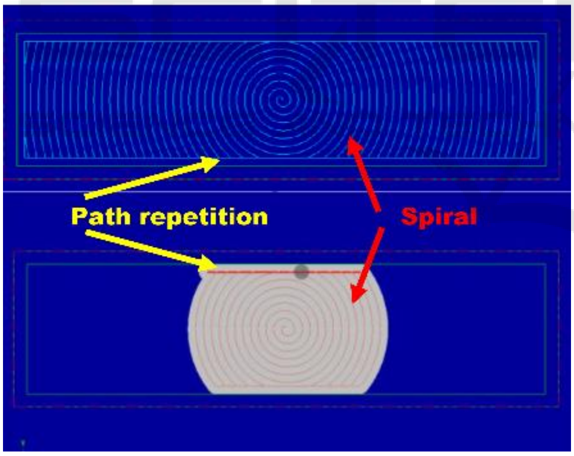

Figure 13: True spirals toolpath on W5 workpieces.

The longest path is generated from repetition of paths on the X axis for W3 objects and, repetition of paths on the Y axis for W4 workpiece. W3workpieces has a longitudinal size on the Y axis, while W5 has a longitudinal size on the X axis. The occurrence of path repetition due to the movement of a rotating cutting device (spiral). True spiral toolpath on W5 workpiece shown on figure 13.

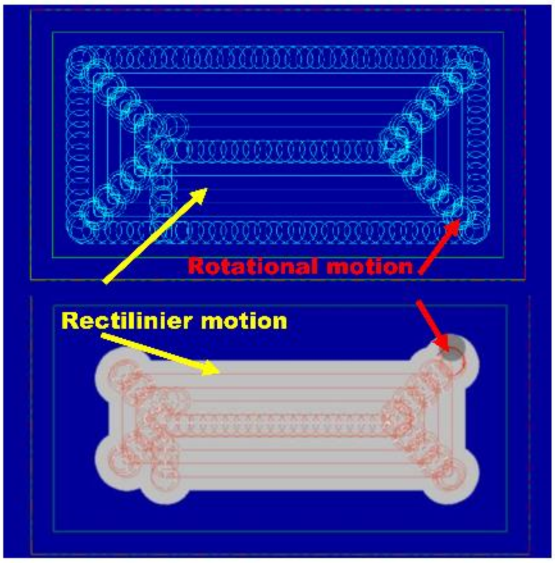

Figure 14: High speed toolpath on W5 workpieces.

The biggest machining time on the workpiece W1, W2, and W4 is generated from high speed toolpath. The high speed toolpath uses a rotation and straight cut path. Rotational movement is a long movement of the cutting path so as to produce a large machining time.

4 CONCLUSIONS

The optimal machining time with the lowest / fastest value in each workpiece cross section is generated from the zigzag toolpath setting and 80% width of cut. The optimal value of the fastest machining time is affected by the length of the planned cutting path. The Zigzag toolpath has the shortest cutting path compared to other toolpath strategies. The optimum machining time value on a square cross section (W1) is 3 minutes, 11 seconds; W2 is 5 minutes 55 seconds; W3 is 12 minutes 25 seconds; W4 is 5 minutes 18 seconds; and W5 is 12 minutes 19 seconds. The greater the width of cut value, the greater the area cut at one time the movement path.

The toolpath strategy produces the largest values of machining time is true spirals and high speed. True spirals toolpath has the longest cutting path on W3 and W5 workpiecs resulting the largest machining time value. The longest path is generated from repetition of paths in longitudinal direction of workpieces. Path repetition occure due to the movement of a rotating cutting (spiral).

The largest machining time on the W1, W2, and W4 workpiece is generated from high speed toolpath.

Rotational movement on high speed toolpath has a long movement of the cutting path that produce a large machining time.

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