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Optimization of milling parameters to increase surface quality and machining time of the bohler m303 extra

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Abstract. Bohler M303 Extra is a material commonly used in plastic injection molds. Improving the surface quality of molded products through the CNC process can reduce production costs by eliminating the polishing and finishing process. Reduction of production costs can also be achieved by decreasing machining time. This paper deals with surface quality optimization and machining time optimization from a variety of toolpath strategies, feed rates, and depth of cut. The machine parameters experiments were based on the L9 orthogonal array of taguchi method. The NC program was generated from the MasterCAM® software and experiments using a Sinumeric 802S/C CNC milling machine. The tool used was Carbide End Mill with TiAlN Coat 12 mm in diameter, with a total of 4 Flutes. The ANOVA results show that the parameters of the toolapth strategy, feed rate, and depth of cut do not have a significant effect on surface quality, but the feed rate parameters have a significant effect on the value of machining time. The result of the S/N ratio calculation places the toolpath strategies parameter as the 1st rank which affects the surface quality while the feed rate parameter is the 1st rank which affects the machining time. The calculation of the s/n ratio also shows that the lower the feed rate value is, the better the surface quality, but the greater the machining time value. Machine parameter setting that gets the optimum surface quality is not the one that produces the lowest or highest machining time values.

1. Introduction

Plastic injection molds are widely used for producing very complex parts and it is possible to produce multiple parts in one cycle [1]. The product result of the plastic injection molding has a good surface roughness, which is 2-63 µin or 0.05-1.6 µm (N2-N7) [2]. The surface roughness 2-63 µin is obtained because the cavity surface on the molding has been finished using the grinding/etching/lapping/stone hand tool before the polishing process. Mold finishing is very important to produce good surface quality, but the it is very costly. The cost of poles finishing for most of the mold components takes 5 to 30% of the mold [2]. A high level difficulty of mold making is done by a CNC machine. Surface roughness is an important measure of product quality because it greatly affects the performance of mechanical parts as well as production costs [3]. There have been many studies on the effects of cutting speed, depth of cut, and feed rate on the surface roughness of CNC machining. Machine parameter has a significant effect on surface roughness [4-9]. The most important parameters are the feed rate, then cutting speed and depth of cut. The feed rate is the most important factor that affects the machine surface roughness of the alloy steel. Furthermore, coolant flow and cutting material are also found to significantly affect surface roughness. The determination of the cutting step and the cutting

method affect the time [10-11]. Setting the stepover and cutting method in roughing is necessary to make the CNC machining process more efficient.

Many studies use the taguchi method in order to find the best surface quality and machining time from machine parameter experiments. The Taguchi method is often used for optimization due to reasons of cost, time and material savings [12]. The Taguchi method is an efficient tool in designing experiments to produce qualified manufactured products [8]. It is a statistical method that can improve the quality of manufactured products and reduce the types of trial and error trials using a matrix design [13]. Optimization using the Taguchi method to determine that the optimum CNC milling parameters to be more efficient is studied at three different levels and the optimal speed is 1094rpm, feed rate is100 m min^{-1}, and 1mm of depth of cut [14].

CNC parameters that influence machining time are spindle rate, feed rate, stepover and toolpath strategies [15]. Studies on the influence of pocket geometry and toolpath strategies on machining time pocket milling on the UNS A96063 alloy found that the contour-parallel strategy resulted in lower machining times [10]. Toolpath strategies can be generated from the CAD/CAM tool. The advantage of computer-assisted manufacturing technology is that it allows a simulation of a work environment. Simulation of a computer-assisted manufacturing process on a CNC machine allows visualization of the toolpath and correctness checking of NC programs before they are implemented [16].

Optimization of machining time on a machine parameter and toolpath strategies variation in various cross-sections demonstrates a zigzag tool path strategy and 80% cutting width results in a short machining time [15]. Optimization of feed rates to minimize machining times was studied and resulted in approximately 35% reduction in machining times [17]. A study of design and optimization of machining parameters for the effective AISI P20 removal rate during milling operations found that a proper process design and control of milling parameters reduce total production time and increase metal removal rate which is a function of productivity [18].

Bohler M303 Extra is a stainless martensitic chromium steel which is commonly used as a plastic mold material. Injection mold finishing to obtain a surface finish that complies to Society of the Plastics Industry, Inc (SPI) standard requires additional costs. The good surface roughness of the injection mold from the CNC production can reduce the cost of finishing the mold. In addition, the low machining time also contributes to reduce the costs of mold manufacturing. The CNC milling machine parameter for injection mold manufacturing contributes to the value of surface quality and machining time. Literature review have been studied a great deal about the optimization of surface quality but not with the optimization of machining time, or otherwise. In addition, the parameters of the tool path strategies have been widely studied for their influence on the value of machining time, but not on surface quality. This paper deals optimization of surface quality and machining time to obtain optimal machine parameters and toolpath strategies. Machine parameters tested is feed rate and depth of cut.

2. Method
Optimization method for surface quality (surface roughness) and machining time uses the Taguchi method. The program is generated from the CADCAM device while the cutting experiment uses a 802S sinumeric milling CNC machine. CAD-CAM program that is used to design and simulate products can reduce production time and contribute to lower product manufacturing costs [19-20].

The specimen used in this study is Bohler M303 Extra which its chemical composition is shown in table 1. The specimen size is 50 mm long, 50 mm wide, and 25 mm thick is shown in figure 1. Bohler M303 Extra (DIN 1.2316/AISI 422) is a martensitic stainless steel chromium steel, which has excellent toughness, corrosion and wear resistance. The machinability of the Bohler M303 Extra can be enhanced and polished.

Table 1. Chemical composition (%) of Bohler M303 Extra material

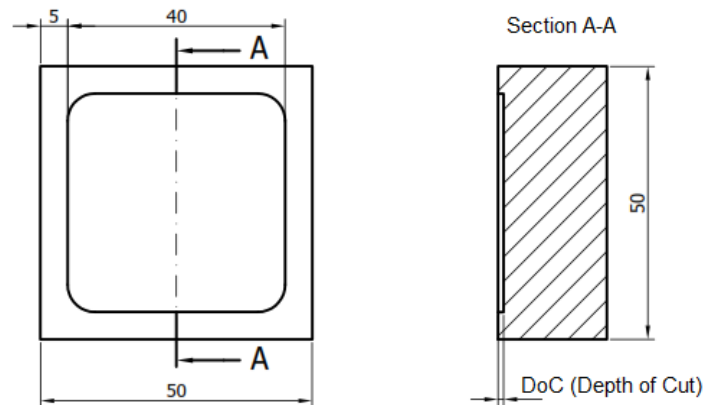| C	Si	Mn	Cr	Ni	Mo	N	Additional
0.27	0.30	0.65	14.50	0.85	1.00	+	Others

Figure 1. Geometry specimen

The end mill used is a flat type end mill with a diameter of 12mm and 4 flutes of Carbide coating materials for TiAN (Titanium Aluminum Nitride). The SFM value of the M303 Extra bohler material is 225 [21] which is then converted to 1819 RPM. Conversion of the SFM cutting speed to RPM spindle speed uses equation (1) and the calculation of the feed rate *Fr* of the IPT value uses equation (2).

$$S = \frac{SFM}{d1} \ x \ 3.82 \tag{1}$$

$$Fr = z \ x \ IPT \ x \ RPM \ x \ 25.4 \ x \ MF \tag{2}$$

Where *SFM* is Surface Feet minutes, *S* is Spindle speed in Rotations Per Minutes, d1 is tool diameter, *Fr* is feed rate in mm per min, z is number of flutes, *IPT* is Inch per teeth, and *Mf* is multiplied by factor.

The variation of machine parameters is designed using L9 orthogonal array. Table 2 is the variable of machine parameter, the number of levels and the values used in roughing cuts with a width of cut of 50% or 6mm. Table 3 displays the L9 orthogonal array of machine parameter. L9 Orthogonal arrays are in accordance with the case of three factors and three levels used for planning experiments. The machining time of experimental results based on Table 3 was analyzed using ANOVA and the calculation of the S/N ratio. Identification of the level influence and factors on surface quality and machining time is done 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 characteristic of smaller is better calculated by the equation (3). The measurement of specimen surface roughness data used the SE300 Surface Roughness tester Surfcorder. The machining time data was collected by recording the cycle time value on the CNC screen panel display.

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

The calculation of CNC milling machining time uses equation (4). Where *Tm* is machining time (min) and *L* is length of cut (mm).

$$Tm = \frac{L}{Fr} \tag{4}$$

Table 2. Independent variabel and level setting

Factor	1	2	3
Toolpath strategies, "*TS*"	TS1	TS2	TS3
Feed rate, "*Fr*" (mm min^{-1})	566	346	314
Depth of cut, "*DoC*" (mm)	0.1	0.2	0.3

In which TS1 is a zig zag, TS2 is a constant overlap spiral, and TS3 is a true spiral. Figure 2 shows the toolpath strategies of the zig zag model, constant overlap spiral, and true spiral generated from the MasterCAM® software.
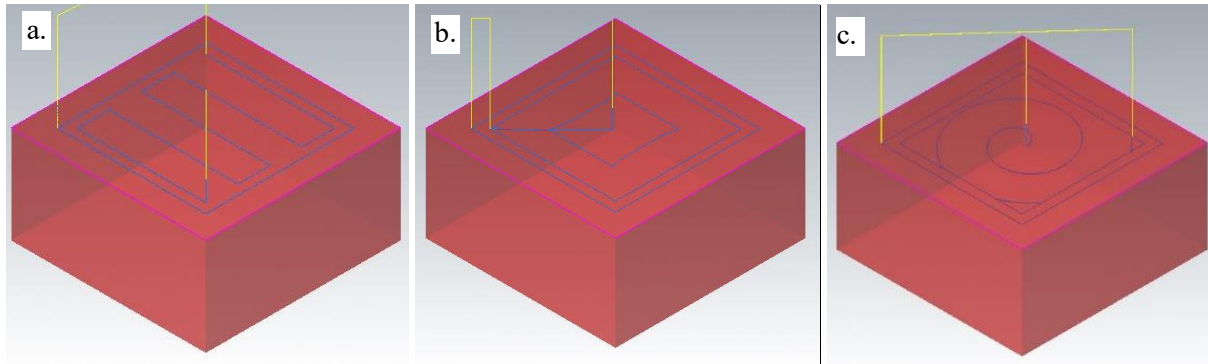

Figure 2. Toolpath strategy: (a) zig zag; (b) constant overlap spiral; (c) true spiral

Table 3. The orthogonal array of variation of L9 machine parameters (3^3)

No	Toolpath strategies, *TS*	Feed rate, *Fr*	Depth of cut, *DoC*
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. Optimization on surface roughness

The result of the specimen surface roughness test according to variation in machine parameters are shown in table 4. The surface roughness values measured are in the range 0.27 to 0.82 μm. The values are included in the roughness category of N4 to N6. The smallest surface roughness value, 0.27 μm, is the parameter setting no.3, which is TS1, the feed rate is 314 mm min^{-1}, with a Depth of cut of 0.3 mm. The highest roughness value (0.82 μm) is the parameter setting no 7, which is TS3 toolpath strategies, a feed rate of 566 mm min^{-1}, and a depth of cut of 0.3 mm.

Analysis of variance (Anova) is used to determine the effect of each factor (machine parameter) on the resulting roughness value. Table 5 is the analysis result of the variance of each factor at each level tested on surface roughness. The analysis result (see table 5) shows that the three machine parameters do not have a significant effect on surface roughness because the analysis value is greater than the specified P value (0.05). The largest F value (1.66) is on the toolpath strategies factor, thus it is the most influencing factor on surface roughness compared to the feed rate and Depth of cut factors. The calculation result of S/N ratio is shown in the table 6.

Table 4 Surface roughness value of l_9 machine parameter (3^3)

No	Factor			Surface Roughness, μm			
	TS	*Fr*	*DoC*	*R1*	*R2*	*R3*	*Ra* mean
1	1	1	1	0.379	0.335	0.321	0.35
2	1	2	2	0.462	0.411	0.327	0.40
3	1	3	3	0.251	0.312	0.242	0.27
4	2	1	2	0.369	0.671	0.641	0.56
5	2	2	3	0.437	0.549	0.589	0.53
6	2	3	1	0.419	0.692	0.499	0.54
7	3	1	3	1.227	0.474	0.751	0.82
8	3	2	1	0.429	0.485	0.507	0.47
9	3	3	2	0.347	0.414	0.34	0.37

Table 5. Analysis of Variance on Surface Roughness

Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Toolpath strategies	2	0.08749	0.043743	1.66	0.377
Feed rate	2	0.05107	0.025533	0.97	0.509
Depth of cut	2	0.01625	0.008125	0.31	0.765
Error	2	0.05284	0.026420		
Total	8	0.20764			

Table 6. S/N Ratio on surface roughness

Level	Toolpath strategies	Feed Rate	Depth of Cut
1	9.543	5.342	7.047
2	5.345	6.682	7.232
3	5.650	8.513	6.258
Delta	4.198	3.171	0.974
Rank	1	2	3

Table 6 shows the S/N ratio value of the surface roughness value of each factor. The calculation result shows the toolpath strategies to be ranked 1 or as the factor that has the most significant influence on the surface roughness value. The data from the S/N ratio calculation is plotted in figure 3.

Figure 3 shows that each factor affects each level. The toolpath strategies factor at level 1 gives a greater influence therefore it can be said that TS1 gives a less roughness grade, or has a better fineness value. For the feed rate factor, it is known that the level 3 of feed rate has a high influence compared to level 1 and 2. Smaller feed rates give less impact on surface roughness. The level 2 of Depth of cut factor has a higher effect than level 1 and 3. The Depth of cut factor in this process has a small depth of 0.1 to 0.3 mm, so the Depth of cut factor has no significant effect on surface roughness. Based on this plot, it can be concluded that the biggest influence on surface roughness is the parameter of the zig zag toolpath, with the smallest feed rate, and the Depth of cut of 0.2 mm.
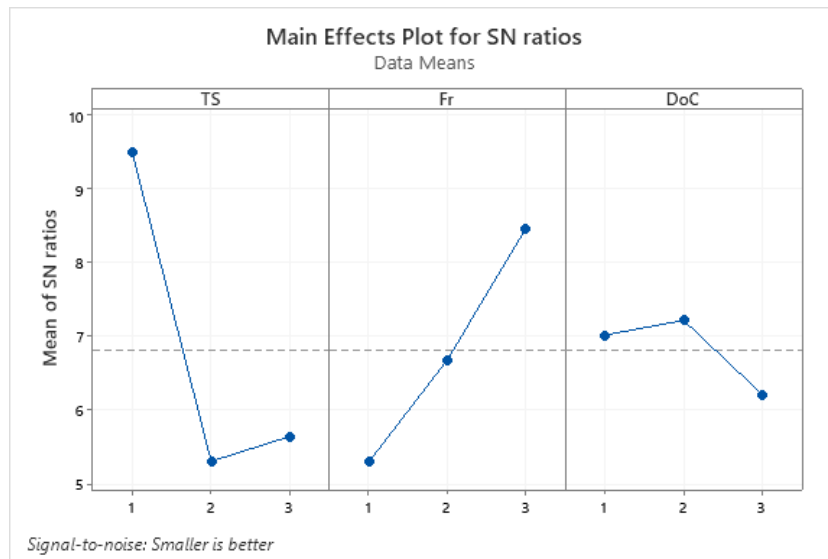
Figure 3. S/N ratio plot on surface roughness

3.2. Optimization of machining time

The machining time of experiment result based on the L9 orthogonal array parameter is presented in table 7. The lowest machining time (0.87) is obtained from the machine parameter setting no.1, which is TS1, feed rate 566 mm min^{-1}, and Depth of cut 0.1 mm.
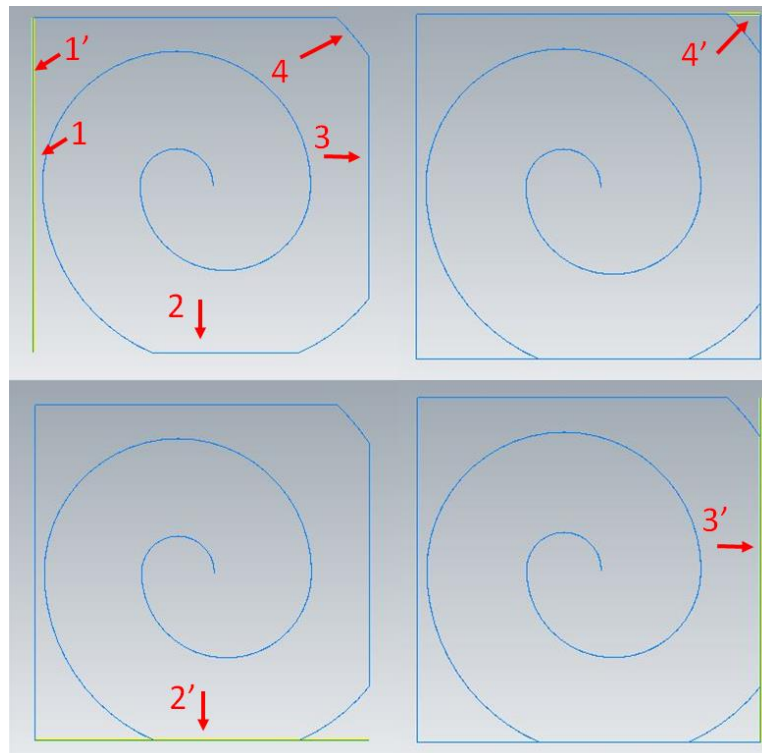

Figure 4. Path repetition on true spiral toolpath

TS1 and TS2 have a path with no movement repetition, so the length of cut is shorter than TS3. True spiral is very suitable for circular workpieces. On the other hand, for rectangles, there will be repetition of the tool movement which causes the length of cut to be large. Figure 4 shows the repetition of the tool movement in the outermost cutting area, which is the toolpath line 1, 2, 3, 4 with

the toolpath line 1', 2', 3', 4'. The repetition causes the length of cut to be large and the machining time to be high.

Table 7. Machining time value from L_9 machine parameter (3^3)

No.	Factor			Machining time (min)
	TS	Fr	DoC	
1	1	1	1	0.87
2	1	2	2	1.25
3	1	3	3	1.47
4	2	1	2	0.92
5	2	2	3	1.33
6	2	3	1	1.43
7	3	1	3	1.00
8	3	2	1	1.48
9	3	3	2	1.62

Table 8 is the analysis result of each factor variant at each level tested on finishing cutting with 50% WoC and 1819 RPM speed. The analysis shows that the feed rate parameter significantly affects the machining time, because the P value is less than P (0.05). The feed rate factor has the most significant influence on machining time compared to tool path strategies and depth of cut.

Table 8. Analysis of Variance on Machining time

Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Toolpath strategies	2	2.3267	1.1633	15.87	0.059
Feed Rate	2	29.3615	14.6807	200.25	0.005
Depth of Cut	2	0.0545	0.0272	0.37	0.729
Error	2	0.1466	0.0733		
Total	8	31.8893			

Table 9 presents the value of the S/N machining time ratio for each factor. The result shows that the feed rate is ranked 1 or is the most significant factor affecting machining time. The 2nd influential factor is the toolpath strategies and the third is the depth of cut. The data of S/N ratio calculation is plotted in Figure 5.

Table 9. S/N Ratio on machining time

Level	Toolpath strategies	Feed Rate	Depth of Cut
1	-1.3406	0.6662	-1.7696
2	-1.6233	-2.6206	-1.7849
3	-2.5324	-3.5420	-1.9418
Delta	1.1918	4.2082	0.1722
Rank	2	1	3

Figure 5 shows the factors (machine parameters) that influence each level. The toolpath strategies (TS) factor at level 1 has a major influence on the value of Tm. The feed rate at level 1 has the greatest effect on the value of Tm because the value of L divided by a large fr will result in a low value of Tm. The smaller the value of Fr, the greater the value of Tm. The DoC factor has little effect on the value of Tm.
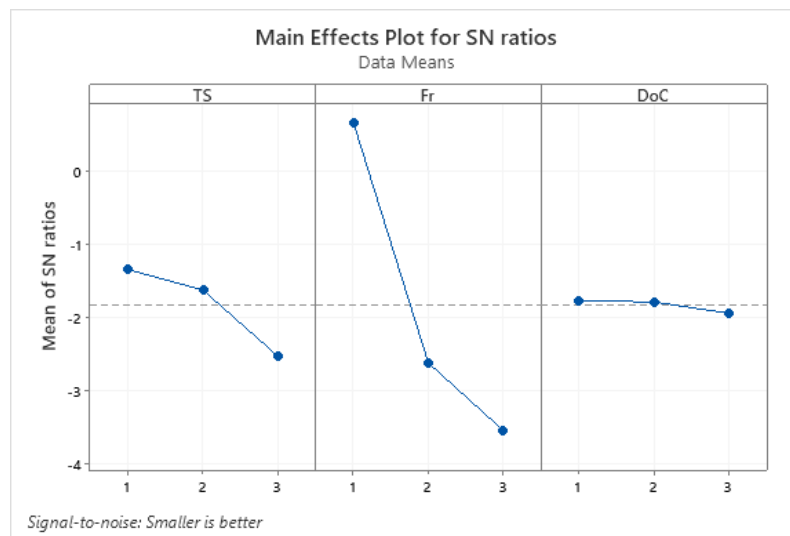
Figure 5. S/N Ratio plot on machining time

4. Conclusions

Optimization of surface roughness in setting toolpath strategies, feed rate, and depth of cut ensures that zigzag toolapth strategies, feed rate level 1 and depth of cut level 3 are the optimum values for surface roughness (0.27 μm). Anova result shows that the three parameters has no significant effect because the P value is more than P (0.05). Toolpath strategies are the rank 1 factor that influence consecutively the surface roughness then the feed rate, and finally the depth of cut. The smaller the feed rate, the smaller the surface roughness value (the surface quality is getting better).

Optimization of the machining time of the three factors obtains the optimum value in experiments with zig zag toolpath strategies, the largest feed rate (level 1) 566 mm min^{-1}, and the depth of cut level 1 (0.1 mm). Feed rate is the most significant influencing factor based on ANOVA analysis and is ranked 1 based on S/N ratio analysis. The higher the feed rate, the smaller the machining time. The zig zag toolpath strategies are compatible with square workpieces where there are no repeating paths thus the length of cut is shorter than the other two toolpath strategies. True Spiral produces the largest length of cut because there is toolpath movement repetitions in the final step which causes high machining time values. Parameter setting that produces optimum surface quality (0.27 μm) is not the parameter that produces the lowest machining time value. Based on the s/n ratio calculation, the lower the feed rate value, the better the surface quality, but the greater the machining time value.

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