Improving Surface Roughness of CNC Milling Machined Aluminum Samples Due to Process Parameter Variation

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Abstract

The objective of this research was to study the effects of CNC machining processes on Aluminum alloy 6061 samples for its surface roughness. This research investigated the effects of the most significant parameters such as spindle speed, depth of cut, feed rate and tool size on the surface roughness. Each parameter that would have an influence on the surface roughness of the machined parts was taken into consideration. The classical method of Design of Experiments (DOE) was chosen for the research. A statistically designed experiment was used to determine the processing factors that affected the surface roughness of the aluminum samples made by the CNC milling machine. A two-level, four-factor full factorial experiment was used to select the best combination of factors level that would minimize the surface roughness. The significant factors, their interactions, optimum setting and the physical interpretation of the effects of the process parameters on surface roughness are presented in this research.

Introduction

Computer numerical control (CNC) milling machine is used to fabricate solid parts worldwide. Manufacturing engineers from around the world use CNC machine to produce high quality precise parts for different applications [1-4]. Especially when it comes to manufacturing high precision parts like aerospace components and parts with critical dimensions, it becomes imperative to check for surface finish. One answer to the quest for six sigma quality and performance may be hidden in the surface of a product. The microscopic features of a part's surface may hold the reasons behind a product's failure reveal the effectiveness of a new process or validate specifications.

Many different factors (parameters) go into the manufacturing of a machine. When several factors affect the response (y), then the best strategy of experimentation is to vary all the factor combinations together. The data is then statistically analyzed to determine the effects of the factors and their interactions on the response. The method known as design of experiments (DOE) is utilized in this project and intended to help improve the quality of a design and processes by using statistical analysis [5]. Improving an experiment is to optimize the average response value and minimize the affects of variability on process or product performance.

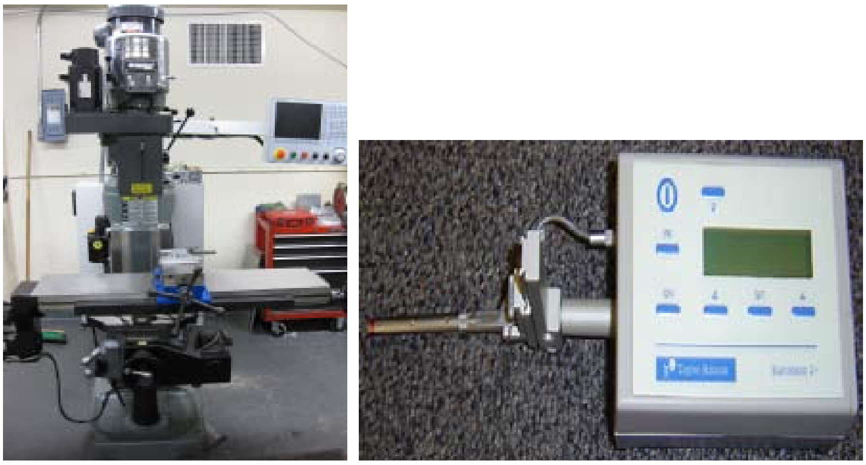
Design of experiments has provided documented substantial savings to thousands of companies by solving difficult quality problems, reducing product and process variation, and optimizing product/process performance and consistency [6]. DOE is a very powerful analytical method that can be taught to industry professionals at a very practical level, providing a cost-effective and organized approach to conducting industrial experiments. A major benefit of DOE is that multiple product design and/or process variables can be studied at the same time with these efficient designs, instead of a hit-and-miss approach, providing very reproducible results.

Previous work has used design of experiments (DOE) as a method to minimize surface roughness of CNC machined parts [7]. However, many of the factors used for influencing the surface roughness are different. In addition, these statistically designed experiments on CNC processes have not been physically interpreted in terms of the material properties and microstructure. This paper will use the quality engineering tool to design, analyze and physically interpret our selection of the CNC processing factors and their levels.

Experimental Methods

The equipments used in this experiment are listed as follows: Bridgeport CNC Milling Machine, Surtronic 3+ Surface Roughness Measuring Machine, MicroXAM Surface Mapping Microscope, Carbide Endmill C230 Drill bits of _ inch and _ inch diameter, and 3 Aluminum Alloy 6061 bars of 1 feet long. The experimental setup is shown in Figure 1.

Figure 1: Experimental Setup (a) CNC milling machine; (b) Surface roughness instrument



(a) (b)

Four factors were selected for this experiment: Spindle Speed (A), Depth of Cut (B), Feed Rate (C), and Tool Size (D) with two levels, as shown in Table 1.

Table 1: Parameters for the experiment

Parameter (Factor)	**Description**	**Level**	
		Low	**High**
		-	**+**
A	Spindle Speed	2300 rpm	2800 rpm
B	Depth of Cut	0.03 in	0.075 in
C	Feed Rate	10 in/min	20 in/min
D	Tool Size	0.25 in	0.5 in

These four process control parameters were identified as being the most likely to affect the surface roughness of the aluminum CNC machined parts [8]. Discussed below is a brief description of each parameter.

Factor A: Spindle Speed - is the rotational frequency of the spindle of the machine, measured in revolutions per minute(RPM). The preferred speed is determined based on the material being cut. Excessive spindle speed will cause premature tool wear, breakages, and can cause tool chatter, all of which can lead to potentially dangerous conditions. Using the correct spindle speed for the material and tools will greatly affect tool life and the quality of the surface finish.

Factor B: Depth of Cut - This is how deep the tool is under the surface of material being cut. This will be the height of the chip produced. Typically, the depth of cut will be less than or equal to the diameter of the cutting tool. The unit for depth of cut is usually inches.

Factor C: Feed Rate - is the velocity at which the cutter is fed, that is, advanced against the workpiece. It is expressed in units of distance per time for milling machine (typically inches per minutes). Feed rate is dependent on the surface finish desired, power available at the spindle, rigidity of the machine and tooling setup, strength of the workpiece and characteristics of the material being cut. Chip flow depends on material type and feed rate.

Factor D: Tool Size - is the different sizes of the drill bits that have been used to mill the aluminum parts. The size of the tool is usually measured in inches

An orthogonal design matrix was utilized as shown in Table 2 using classical notation. A full factorial experiment was conducted which included sixteen trials. The trials were randomized to improve the statistical response. Three replications were conducted for each run.

Table 2: Randomized Table for DOE

No.	**N**	**I**	**A**	**B**	**C**	**D**
13	cd	+	-	-	+	+
16	abcd	+	+	+	+	+
3	b	+	-	+	-	-
8	abc	+	+	+	+	-
12	abd	+	+	+	-	+
2	a	+	+	-	-	-
15	bcd	+	-	+	+	+
6	ac	+	+	-	+	-
4	ab	+	+	+	-	-
14	acd	+	+	-	+	+
5	c	+	-	-	+	-
1	(I)	+	-	-	-	-
11	bd	+	-	+	-	+
7	bc	+	-	+	+	-
10	ad	+	+	-	-	+
9	d	+	-	-	-	+

The Bridgeport CNC milling machine was used to create the test samples. The samples were manufactured very carefully using the combination of factors and their levels as per Table 2. The design of the test specimen was in the shape of a rectangular bar. The length was 4.5 inch (11.4 cm) and a consistent thickness of 0.4 inch (1 cm).

Analysis of Data

Table 3 below shows the results obtained for the surface roughness measured using the surface roughness measuring instrument for all the replications of 16 trials. The Y(average) is the total average of all the Y responses from each trial measured. The average results are also verified by using a system equation whose function is to minimize the surface roughness Ymin [7],

$$\begin{aligned} Y_{min} &= \overline{\overline{Y}} + c_A A + c_B B + c_C C + c_D D + c_{AB}(AB) + c_{AC}(AC) + c_{AD}(AD) \\ &+ c_{BC}(BC) + c_{BD}(BD) + c_{CD}(CD) + c_{ABC}(ABC) + L + \text{Error} \\ &\text{where } \overline{\overline{Y}} = \ddot{A} \text{ value of I column, and all c values are } \ddot{A}/2 \text{ values} \end{aligned} \tag{1}$$

The last column of Table 3 shows the results from the system equation.

Table 3: Results for the Y responses

Sample No.	N	Std. Deviation [_m]	Y (Average) [_m]	Y (From System Equation) [_m]
13	cd	0.282	2.533	0.708
16	abcd	0.068	2.058	-0.232
3	b	0.055	1.208	7.56
8	abc	0.020	3.182	3.81
12	abd	0.143	1.482	-1.49
2	a	0.123	1.105	0.295
15	bcd	0.040	2.198	9.99
6	ac	0.130	2.960	2.47
4	ab	0.159	0.877	-1.90
14	acd	0.142	2.297	-1.04
5	c	0.068	3.470	5.52
1	(I)	0.299	1.757	2.87
11	bd	0.121	1.653	-2.81
7	bc	0.095	4.078	-0.392
10	ad	0.156	1.320	6.41
9	d	0.0632	1.522	1.91

The key goal of this experiment is to see which factor(s) contributes to surface roughness by looking at their interactions [7]. From **Figures 2-3**, graphs of the AD and BD show no interaction. However, **Figure 4** shows a strong interaction between these, as the two lines intersect.

Figure 2: AD Interaction

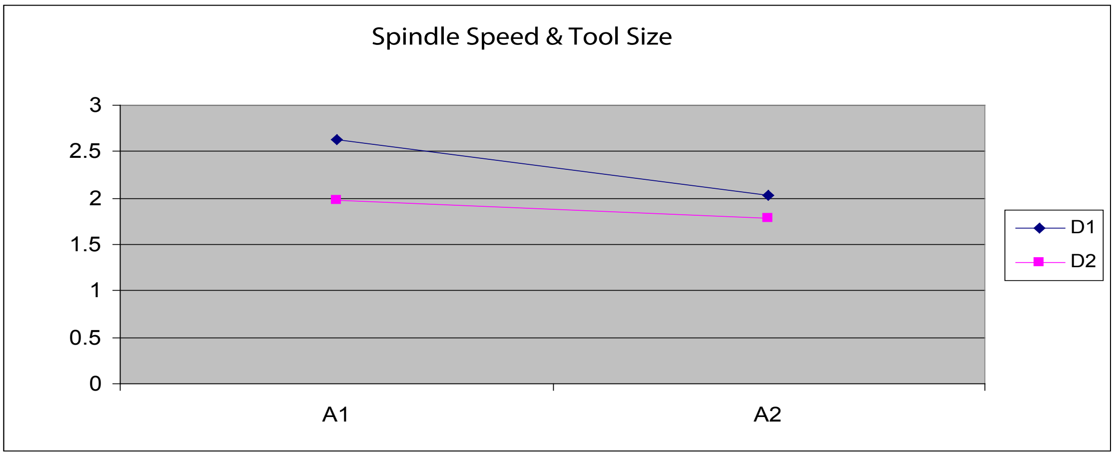


Figure 3: BD Interaction

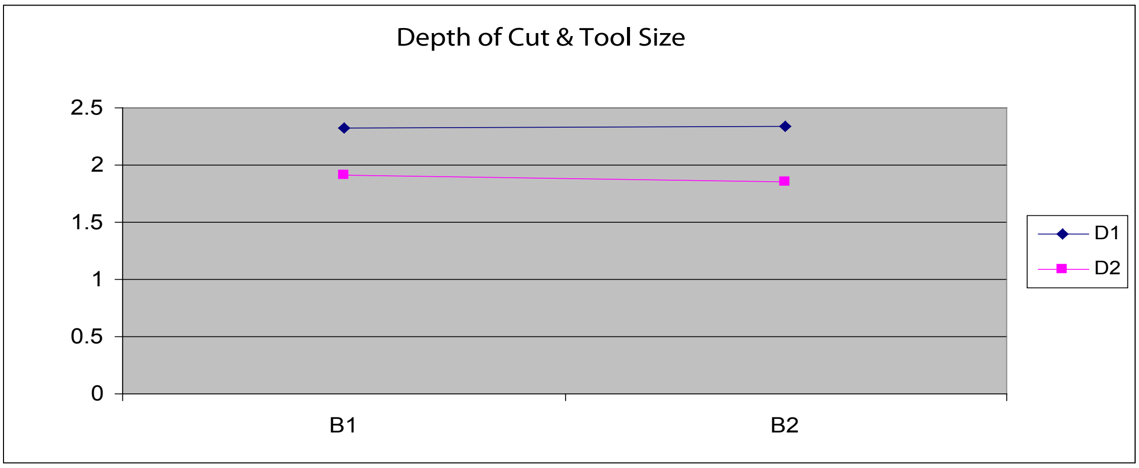
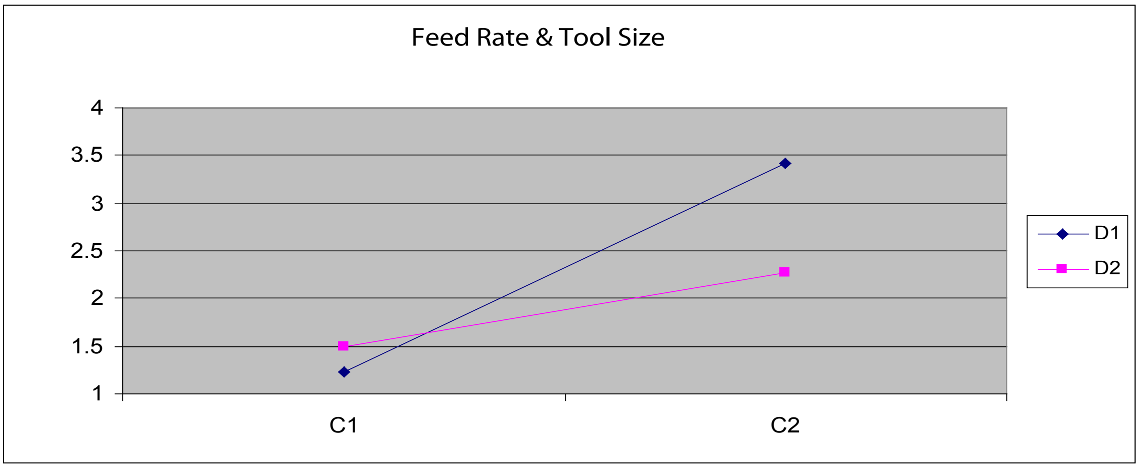


Figure 4: CD Interaction



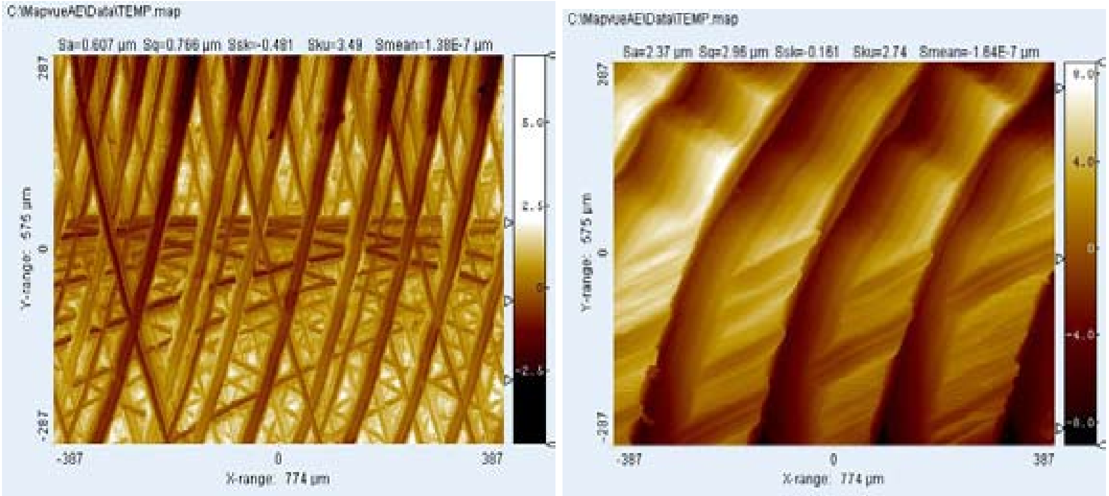
The strong interaction between C and D is shown in **Table 4**.

Table 4: Average responses for factor C and D

		C:Feed Rate	
		1	2
D:Tool Size	1	1.236667	3.4225
	2	1.494167	2.271667

The MicroXAM Surface Mapping Microscope is a machine that shows the detailed surface profile of the test samples. Figure 5, below, shows the surface roughness characteristics of sample numbers four and seven. The images were captured using the MicroXAM machine.

Figure 5: (a) 2-D Surface Profile for Sample No.4 (b) 2-D Surface Profile for Sample No.



(a) (b)

Conclusions

Based on the findings from the research, the following conclusion and recommendations can be made:

1. The two factors highly responsible for the surface roughness are feed rate and tool size.

2. Sample No. 7 had the most surface roughness when the feed rate was high in combination with the highest depth of cut and the lowest spindle speed but it was not consistent with the system response.

3. Sample No. 4 provided the least roughness amongst all given samples. The combination for achieving this type of surface finish is best when the spindle speed is running at its highest i.e.,2800 rpm, depth of cut was adjusted to its maximum value of 0.075 in with a low feed rate of 10 in/min.

4. The tool size of 0.5 inches in diameter used for this experiment did not show much variability in the surface roughness when compared to the tool size of 0.25 inches dia. The 0.25 inch tool size did give the highest and the lowest surface roughness when in combination with the other three parameters.

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