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Optimization Of Cutting Regimes For Milling AISI-1045 Steel

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***Abstract*—This paper presents an experimental study to determine the influence of cutting regime parameters on surface roughness when milling AISI-1045 steel. Three cutting regime parameters were considered in this study, including cutting speed, feed rate, and depth of cut. Surface roughness was chosen as the evaluation criterion for the milling process in this research. The experiment was carried out on a vertical milling machine. The Box-Behnken experimental matrix was used to design the experiments with a total of 14 tests. The problem-solving process found the optimal values of the input parameters to ensure the smallest surface roughness value. The optimization results were verified by the experimental process. Finally, directions for further research are also mentioned in this paper.**

Keywords—milling, AISI-1045 steel, surface roughness, cutting regime, optimization

1. INTRODUCTION

Milling is a prevalent machining method, known for its high productivity and wide-ranging applications in mechanical processing. It can be employed to machine various surface types across a multitude of materials. Surface roughness significantly impacts product lifespan and is frequently selected as a key metric for evaluating the effectiveness of milling, and cutting processes in general [1-4].

Numerous researchers have investigated milling processes to identify solutions for minimizing surface roughness. Typically, studies focus on the effects of cutting regime parameters on surface roughness, which is understandable since these parameters are more easily controlled by machine operators than other variables. The outcomes of these studies establish a foundation for selecting cutting regime parameters under specific conditions. Experimental milling of AISI 304 steel, as documented in reference [5], concluded that both cutting speed and feed rate significantly influence surface roughness, with cutting speed having a more substantial impact than feed rate. Reference [6] examined the milling of Al-1Fe-1V-1Si and Al-2Fe-1V-1Si alloys, observing that cutting regime parameters had minimal effect on surface roughness for Al-1Fe-1V-1Si. For Al-2Fe-1V-1Si, these parameters notably affected the Rz index but had little impact on the Ra index. In reference [7], milling AISI 316L SS with WC-coated tools indicated that feed rate and cutting speed significantly affected surface roughness. Feed rate had a more substantial impact than cutting speed. The relationship between feed rate, depth of cut, and surface roughness was complex, with increases in these parameters sometimes increasing and sometimes decreasing surface roughness. Research presented in reference [2] concluded that feed rate had the greatest impact on surface roughness, followed by cutting speed. Depth of cut had a lesser effect. The interaction between feed rate and depth of cut had the strongest influence, followed by the interaction between cutting speed and feed rate. The interaction between cutting speed and depth of cut had minimal impact. A study on milling Ti-6242S alloy [8] found that all three cutting regime parameters significantly affected surface roughness. Increasing feed rate and depth of cut increased surface roughness, while increasing cutting speed decreased it. Reference [9] examined milling 6061 aluminum alloy under Minimum Quantity Lubrication (MQL) using high-speed steel tools, noting that the interaction between cutting speed and feed rate had a significant impact on surface roughness. Cutting speed had a greater effect than feed rate. Research on milling SKD61 steel [10] showed that cutting speed, feed rate, depth of cut, and workpiece hardness all significantly affected surface roughness. Reference [3] experimented with milling 42CrMo4 steel using TiN-coated tools, concluding that cutting speed had a minimal effect on surface roughness. Feed rate had a greater impact on surface roughness at a fixed depth of cut than at a variable depth of cut. Reference [11] found that feed rate significantly affected surface roughness when milling AA2014 (T4) alloy, while cutting speed had minimal impact. Increasing feed rate increased surface roughness, while the effect of cutting speed was more complex, sometimes increasing and sometimes decreasing surface roughness.

These studies indicate that while much research has explored the effects of cutting regime parameters on surface roughness, the degree and nature of these effects vary with specific machining conditions. Therefore, applying research findings to production requires experimental studies tailored to specific conditions, including workpiece and tool materials. This paper investigates the influence of cutting regime parameters on surface roughness when milling AISI-1045 steel.

2. MILLING PROCESS EXPERIMENTATION

2.1. Experimental Setup

The experimental material used was AISI-1045 steel (USA standard). Table 1 presents the equivalent designations of this steel type according to various international standards. Table 2 details the chemical composition of the steel. The dimensions of the experimental samples were 80mm in length, 40mm in width, and 30mm in height.

Table 1. Equivalent Designations of AISI-1045 Steel in Various Countries

Country	USA	Germamy	Japan	China	Italy
Standard	AISI	DIN	JIS	BS	UNI
Symbols	1045	CK45	S45C	060A4	C45

Table 2. Chemical Composition of AISI-1045 Steel

Composition (%)									
C	Si	Mn	Cr	Ni	Mo	V	Ti	B	Cu
0.42	0.23	0.68	0.19	0.11	0.02	0.01	0,0005	0.006	0.16

The experimental machine employed in this study was a vertical milling machine, model JL-VH320B. A surface roughness tester, SJ201 (Mytutoyo – Japan), was utilized during the experiment. Each sample underwent at least three measurements. The surface roughness value for each experiment was determined by averaging these successive measurements. During the measurement process, the machine was set with a standard length of 0.8mm and a stylus tip diameter of 0.005mm.

2.2. Experimental Design

The Box-Behnken design of experiments (DOE) matrix was used to structure the experiments in this research. The input parameters for each experiment were the cutting regime parameters, including cutting speed, feed rate, and depth of cut. Each parameter had three levels. The values of the parameters at each level were selected based on practical experience, as shown in Table 3. The experimental matrix consisted of 14 experiments, as presented in Table 4.

Table 3. Cutting Parameters

Parameter	Unit	code	Values at different levels		
			-1	0	1
Cutting speed	m/min	v	120	200	280
Feed rate	mm/tooth	f	0.1	0.2	0.3
Depth of cut	mm	a_p	0.5	0.6	0.7

Table 4. Experimental Matrix

No.	Code value			Actual values			Surface roughness
	v	f	a_p	v (m/min)	f (mm/tooth)	a_p (mm)	Ra (µm)
1	0	0		200	0.2	0.6	0.868
2	-1	0	-1	120	0.2	0.5	1.885
3	-1	0	1	120	0.2	0.7	0.625
4	1	0	1	280	0.2	0.7	0.803
5	0	1	1	200	0.3	0.7	1.139
6	0	-1	-1	200	0.1	0.5	0.644
7	0	0	0	200	0.2	0.6	0.765
8	-1	-1	0	120	0.1	0.6	0.672
9	-1	1	0	120	0.3	0.6	0.812
10	1	1	0	280	0.3	0.6	0.672
11	0	1	-1	200	0.3	0.5	0.579
12	0	0	0	200	0.2	0.6	1.111
13	1	-1	0	280	0.1	0.6	0.765
14	0	-1	1	200	0.1	0.7	0.775

3. Results and Discussion

The experiments were conducted in the order presented in Table 4, and the surface roughness values for each experiment were also included in this table. The statistical software Minitab 16 was employed to generate graphs illustrating the influence of input parameters on surface roughness, as shown in Figure 1. The interaction effects between input parameters on surface roughness are depicted in Figure 2.

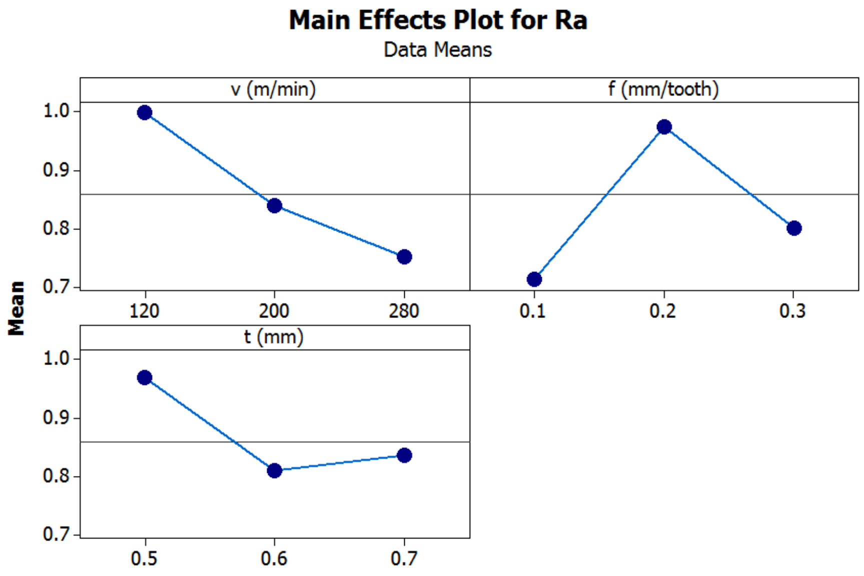

Figure 1. Effect of Cutting Parameters on Surface Roughness

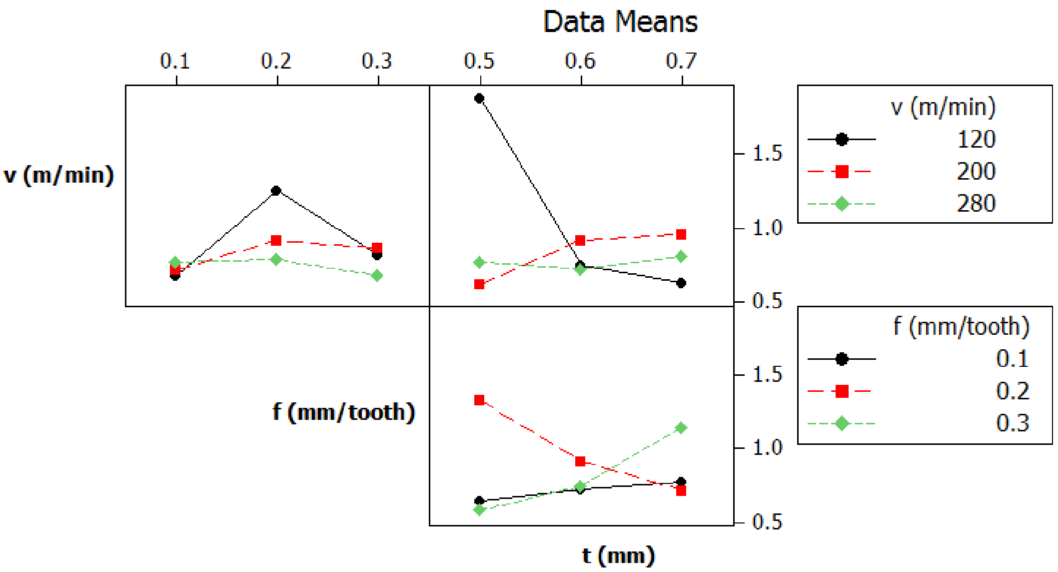

Figure 2. Interaction Effects Between Parameters on Surface Roughness

The observation of Figure 1 reveals a complex relationship between cutting parameters and surface roughness. However, some clear trends can be identified: (1) Among the three parameters studied, cutting speed has the most significant impact on surface roughness, followed by feed rate, and lastly, depth of cut; (2) As cutting speed increases, surface roughness tends to decrease, which aligns with findings from published milling studies [12, 13].

Figure 2 demonstrates a highly intricate interaction effect between the parameters on surface roughness. The following points elaborate on this observation:

- When the cutting speed is 120 (m/min), increasing the feed rate from 0.1 (mm/tooth) to 0.2 (mm/tooth) increases surface roughness. However, further increases in feed rate lead to a decrease in roughness. At a cutting speed of 200 (m/min), surface roughness increases with increasing feed rate. Conversely, at 280 (m/min), increasing feed rate reduces surface roughness.

- At a cutting speed of 120 (m/min), raising the depth of cut from 0.5 (mm) to 0.6 (mm) rapidly decreases surface roughness; further increases result in a slower decrease. At 200 (m/min), increasing depth of cut increases surface roughness. At 280 (m/min), increasing depth of cut from 0.5 (mm) to 0.6 (mm) slightly decreases roughness, but further increases lead to a slight increase.

- With feed rates of 0.1 (mm/tooth) and 0.3 (mm/tooth), increasing depth of cut increases surface roughness. Conversely, at a feed rate of 0.2 (mm/tooth), increasing depth of cut reduces roughness.

Therefore, the analysis of Figures 1 and 2 highlights the difficulty in determining optimal cutting speed, feed rate, and depth of cut values to ensure minimal surface roughness. This necessitates solving an optimization problem.

4. MILLING PROCESS OPTIMIZATION

The statistical software Minitab 16 was again utilized to solve the milling process optimization problem. The optimization graph is presented in Figure 3.

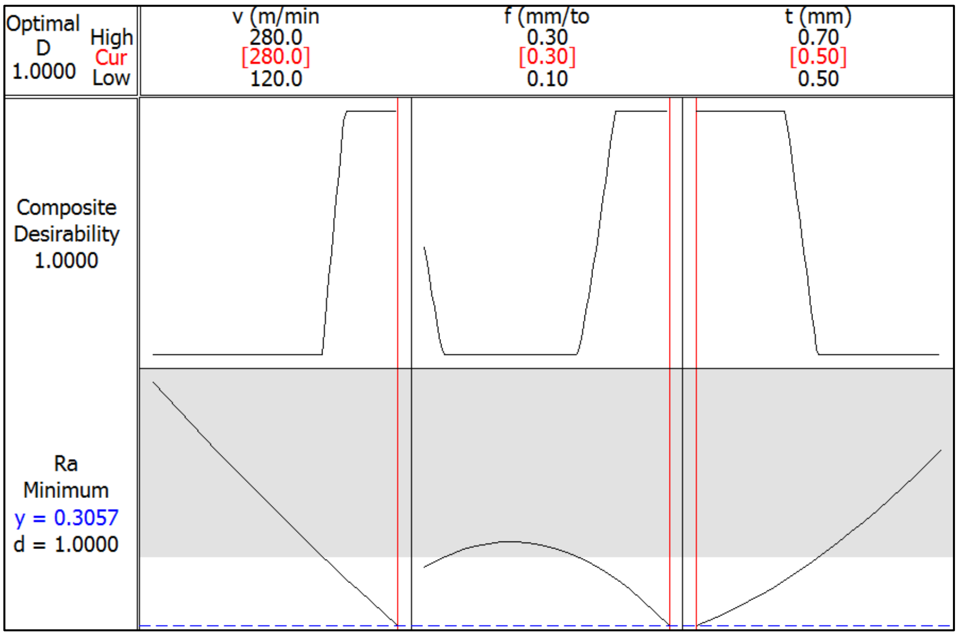

Figure 3. Optimization Graph

The results in Figure 3 indicate that the optimal values for cutting speed, feed rate, and depth of cut are 280 m/min, 0.3 mm/tooth, and 0.5 mm, respectively. The desirability function achieved a value of 1, meaning there is a 100% probability of achieving the minimum surface roughness when machining with this optimal set of cutting regime parameters. This optimal set of parameters was then used to conduct milling experiments on 5 steel samples. The average surface roughness value from these 5 experiments was 0.318 mm.

Therefore, the deviation between the experimental and predicted results is only approximately 3.86%.

5. CONCLUSION

The milling experiments on AISI-1045 steel were conducted in this study. The determination of the optimal values for the cutting regime parameters was also performed. Several conclusions can be drawn as follows:

The optimal values for cutting speed, feed rate, and depth of cut are 280 m/min, 0.3 mm/tooth, and 0.5 mm, respectively. Machining with these values of the cutting regime parameters resulted in the smallest surface roughness value, approximately 0.318 mm.

Determining the values of cutting regime parameters to simultaneously ensure objectives such as minimum surface roughness, minimum cutting force, maximum material removal rate, etc., are directions for further research.

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