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STUDY ON MULTI-OBJECTIVE OPTIMIZATION OF X12M STEEL MILLING PROCESS BY REFERENCE IDEAL METHOD

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Abstract

For all machining cutting methods, surface roughness is a parameter that greatly affects the working ability and life of machine elements. Cutting force is a parameter that not only affects the quality of the machining surface but also affects the durability of cutter and the level of energy consumed during machining. Besides, material removal rate (MRR) is a parameter that reflects machining productivity. Workpiece surface machining with small surface roughness, small cutting force and large MRR is desirable of most machining methods. Milling is a popular machining method in the machine building industry. This is considered to be one of the most productive machining methods, capable of machining many different types of surfaces. With the development of the cutting tool and machine tool manufacturing industries, this method is increasingly guaranteed with high precision, sometimes used as the final finishing method. Milling using a face milling cutter is more productive than using a cylindrical cutter because there are multiple cutter s involved at the same time. This article presents a study of multi-objective optimization of milling process using a face milling cutter. The experimental material used in this study is X12M steel. Taguchi method has been applied to design an orthogonal experimental matrix with 27 experiments (L27). In which, five parameters have been selected as the input parameters of the experimental process including insert material, tool nose radius, cutting speed, feed rate and cutting depth. The Reference Ideal Method (RIM) is applied to determine the value of input parameters to ensure minimum surface roughness, minimum cutting force and maximum MRR. Influence of the input parameters on output parameters is also discussed in this study.

Keywords: surface milling, multi-objective optimization, surface roughness, cutting force, Reference Ideal Method, RIM.

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1. Introduction

Milling is one of the most common machining methods in mechanical machining. This method can be applied on various types of surfaces and materials in the process of machining many different products. Conducting surface milling by a face milling cutter is considered to be the most productive method due to its large number of inserts and cutting time. In recent years, with the development of cutting tool technology and machine tools, product quality when machining by milling method using face milling cutters is also increasingly improved. In some cases, it is selected as the final machining method. In most milling processes, small surface roughness, small cutting force and large MRR are the objectives to be achieved. Therefore, many authors have studied how to determine the value of the processing parameters to ensure small surface roughness, small cutting force and large MRR.

The Taguchi method has been widely applied to design the experimental matrix in milling. Designing experimental matrices according to the Taguchi method allow multiple input parameters to be tested through the minimal number of experiments. On the other hand, the experimental design according to the Taguchi method is known to be the only method that allows the selection of input parameters that are parameters in a qualitative (not quantitative) form. A significant number of studies have applied the Signal-to-Noise (S/N) ratio analysis method to determine the optimal values of some cutting parameters in combination with the Taguchi method [1–16]. In **Table 1** the optimal values of some cutting mode parameters during milling in specific cases are presented.

The above studies show that the Taguchi method is a very successful technique to solve optimization problems of milling process. However, if only the Taguchi method is used to design the experimental matrix, the only method to achieve optimum values of input parameters was to conduct S/N ratio analysis. In this case, the application is limited to solving single objective optimization problem. To overcome this limitation of the Taguchi method, there have been a number of studies combining Taguchi method with a certain algorithm to optimize the objective of the milling process.

Table 1

Milling experiment studies applying the Taguchi method & S/N ratio analysis

No.	Ref.	Condition	Optimized Output Parameter	Optimized Input Parameters
1	2	3	4	5
1	[1]	Milling Al7075 aluminum alloy with carbide cutting tool	Surface roughness (minimum)	Spindle speed: 4800 rpm. Feed rate: 165 mm/min. Cutting depth: 0.8 mm
			MRR (maximum)	Spindle speed: 4800 rpm. Feed rate: 230 mm/min. Cutting depth: 1 mm
2	[2]	Milling AISI 304 steel with carbide cutting tool	Surface roughness (minimum)	Spindle speed: 3000 rpm. Feed rate: 200 mm/min. Cutting depth: 0.5 mm
3	[3]	Milling nickel based Waspaloy material in Minimum quantity lubrication (MQL) condition	Surface roughness (minimum)	Cutting fluid: vegetable oil. Flow rate of cutting fluid (Flow rate): 100 ml/h. Milling type: up milling. Distance from the nozzle to the cutting tool: 50 mm. Nozzle length is 32 mm
4	[4]	Milling Inconel 718 steel with hard alloy cutting tool	Surface roughness (minimum)	Cutting speed: 55 m/min. Feed rate: 0.12 mm/rev. Cutting depth: 1.2 mm
5	[5]	Milling carbon fiber reinforced plastics with diamond coated cemented carbide cutting tool	Surface roughness (minimum)	Cutting speed: 500 m/min. Feed rate: 0.03 mm/tooth. Cutting depth: 0.1 mm
6	[6]	Milling 1040 MS steel with hard alloy cutting tool	Surface roughness (minimum)	Spindle speed: 2500 rpm. Feed rate: 800 mm/min. Cutting depth: 0.8 mm. Flow rate: 30 liters/min
7	[7]	Milling EN8 steel with carbide cutting tool	Surface roughness (minimum)	Spindle speed: 4000 rpm. Feed rate: 1000 mm/min. Cutting depth: 0.1 mm
8	[8]	Milling EN31 steel with a hard alloy coated cutting tool	Surface roughness (minimum)	Spindle speed: 1150 rpm. Feed rate: 175 mm/min. Cutting depth: 1 mm. Flow rate: 20 liters/min
9	[9]	Milling AISI H3 steel with a TiAlN coating cutting tool (Cooling lubrication: dry, nanofluid and MQL)	Surface roughness (minimum)	Cooling lubrication: nanofluid. Cutting speed: 80 m/min. Feed rate: 0.01 mm/tooth. Cutting depth: 0.2 mm
10	[10]	Milling Ultra-high molecular weight polyethylene (UHMWPE) with a SECO-93060F cutting tool	Surface roughness (minimum)	Spindle speed: 7219 rpm. Feed rate: 1636 mm/min. Step over: 0.069 mm
11	[11]	Milling AL 6351-T6 material with a 15HP type cutting tool (Tool diameter: 10 mm, 12 mm and 16 mm)	Surface roughness (minimum)	Tool diameter: 12 mm. Spindle speed: 5000 rpm. Feed rate: 2500 mm/min. Cutting depth: 0.7 mm
12	[12]	Dry milling H13 steel by PVD coated carbide inserts	Surface roughness (minimum)	Cutting speed: 200 m/min. Feed rate: 0.05 mm/tooth. Radial depth of cut: 0.3 mm. Axial depth of cut: 1.5 mm

Continuation of the Table 1

1	2	3	4	5
13	[13]	Milling EN19 steel with TiN coated cutting tool	MRR (maximum)	Cutting speed: 19.22 m/min. Feed rate: 50 mm/min. Cutting depth: 1.2 mm
14	[14]	Milling aluminum with a SECO R220.69-12 cutting tool	Surface roughness (minimum)	Spindle speed: 1800 rpm. Feed rate: 400 mm/min. Cutting depth: 0.7 mm
			Cutting force (minimum)	Spindle speed: 2600 rpm. Feed rate: 400 mm/min. Cutting depth: 0.7 mm
15	[15]	Milling Nimonic C-263 alloy with TiAlN coated cutting tool	Surface roughness (minimum)	Spindle speed: 2000 rpm. Feed rate: 5 mm/min. Cutting depth: 0.6 mm
			Cutting force (minimum)	Spindle speed: 1500 rpm. Feed rate: 5 mm/min. Cutting depth: 0.4 mm
16	[16]	Milling Ti-6Al-4V alloy with TiN coating cutting tool	Surface roughness (minimum)	Cutting speed: 180 m/min. Feed rate: 250 mm/min
			Cutting force (minimum)	Cutting speed: 180 m/min. Feed rate: 250 mm/min

The Taguchi method has been combined with Grey Relational Analysis (GRA) method to optimize the milling process in a number of studies [17–20]. [17] used this method to optimize the milling of AISI 304 stainless steel with tungsten carbide cutting tool: In order to achieve the minimum value of surface roughness and maximum value of MRR at the same time, cutting speed is 95 m/min, feed rate is 800 mm/min and cutting depth is 0.8 mm. The similar method has been applied to optimize the AISI O2 steel milling process [18]. Four parameters have been selected as the input parameters of the experiment including cutting tool coating material (including 3 types: AlTiN/TiN, TiN/TiAlN and TiAlSiN/TiSiN/TiAlN), cutting speed, feed rate and cutting depth. This study has determined that to achieve small surface roughness, small cutting energy and large MRR, it is necessary to use AlTiN/TiN tool coating material, cutting speed of 150 m/min, feed rate of 0.5 mm/tooth and cutting depth of 1 mm. [19] has optimized the milling process of ASSAB XW-42 tool steel with hard alloy tool. Four experimental parameters were selected including cutting fluid flow rate (using Liquid nitrogen oil), cutting speed, feed rate and axial depth of cut. The results showed that in order to ensure the purposes of minimum surface roughness, minimum tool wear and maximum MRR, it is necessary to work with values of cutting fluid flow rate of 0.5 liter/min, cutting speed of 109.9 m/min, feed rate of 94.2 mm/min and axial depth of cut of 0.9 mm. [20] has optimized the milling process of 465 steel with a TiAlN coating cutting tool: In order to ensure the purposes of minimum surface roughness, minimum cutting temperature and maximum MRR, the suggested cutting speed is 150 m/min, feed rate is 0.1 mm/min, and cutting depth is 0.2 mm.

The Taguchi method has also been combined with the Desirability Function Analysis (DFA) for the purpose of multi-objective optimization of glass-fiber reinforced plastic (GFRP) composites milling process [21]. The cutting tool used in this study is solid carbide. This study has determined that in order to ensure minimum surface roughness, minimum cutting force and maximum delamination factor, the input parameters are as follow: fiber orientation angle is 15°, helix angle is 25°, and spindle speed is 400 rpm, and feed rate is 0.7123 mm/min.

Another method that has been combined with the Taguchi method to solve optimization problem in milling process is the Principal Component Analysis (PCA) method. [22] has used this method for the purpose of multi-objective optimization of the GFRP composites milling process. A hard alloy of type K10 cutting tool was used in this study. To achieve minimum surface roughness, minimum cutting force and maximum material separation ability, the input parameters are as follow: helix angle is 35°, cutting speed is 4000 m/min, feed rate is 750 mm/rev, and cutting depth is 2 mm.

Finally, the Taguchi method has also been used together with the weighting method for the purpose of multi-objective optimization of AISI 4140 steel milling process [23]. TiAlN+TiN coating cutting tool was used in this study. This study has shown that all three surface roughness parameters, including arithmetic average roughness (R_a), root mean square average roughness (R_q) and average maximum height of the profile (R_z) have the lowest value when cutting speed is 325 m/min, feed rate is 0.08 mm/rev, cutting depth is 1 mm, and number of insert is 1.

From the analysis above, it can be seen that the optimization of the milling process (both single-objective and multi-objective) has been studied extensively by many authors. However, for each specific processing material and type of cutting tool, the optimum values of the input parameters found in those studies vary widely. On the other hand, in the studies listed above, different cutting parameters dominate cutting tool parameters as the selected input parameters. This is understandable as the value of the cutting parameters can be adjusted quickly and simply by the operator who operates the machine. These studies have given the impression that in order to ensure one or several of the criteria of the milling process, the simplest choice is to determine optimal values of cutting parameters and cutting tool parameters under each particular condition.

X12M steel is a steel with high abrasion resistance, high tensile strength and high hardenability. This type of steel is popularly used to fabricate parts in various fields such as steel cutters, rolling pins, rollers, gears, dies, etc. Study on milling this steel has been done by a number of authors, such as: Investigation of the effect of nanoparticle concentration, cutting speed and hardness of the workpiece on cutting force when milling in MQL conditions [24]; Simultaneous optimization of two, which are surface roughness and milling vibration [25]; study on the effects of cooling lubricating parameters on surface roughness when milling under MQL condition and minimum quantity cooling lubrication (MQCL) condition [26]; investigation of cutting force, surface roughness and tool wear while milling with laser support [27]; study on improving the efficiency of milling process in MQLC conditions, cutting fluid of MoS2 Nanofluid [28]; study on effect of cutting parameters and cooling lubrication parameters on surface roughness [29], etc. However, no studies have been published to determine type of cutting tool, tool nose radius, cutting speed, cutting depth to simultaneously ensure the criteria of minimum surface roughness, minimum cutting force and maximum *MRR* when milling this steel up to now. In this study, this problem will be solved in order to supplement the research results on this steel processing technology.

In terms of optimization algorithm, there are currently many optimization algorithms that have been combined with the Taguchi method and have been successful in solving the multi-objective optimization problem in many different cases. For example: combining Taguchi method and Topsis method for multi-objective optimization of DIN 1.2379 steel milling by segmented grinding wheel [30]; combining Taguchi method and Dear method for multi-objective optimization of AISI 1055 steel turning process [31]; combining Taguchi method with Moora and Copras method for multi-objective optimization of SKD11 steel milling process [32], etc.

Reference Ideal Method (RIM) is a method used for multi-objective optimization, which was first introduced in 2014 [33]. This method has been applied for multi-objective optimization in the selection of military aircraft for the Spanish army forces [34], and for optimization of turning process [35]. However, up to now, there have been no published studies on the application of this method for multi-objective optimization of milling process.

Based on some of the above analysis, this study will apply the RIM method for multi-objective optimization of X12M steel milling process. Taguchi method will be applied to design the experimental matrix with input parameters including cutting parameters and cutting tool parameters. Three parameters including surface roughness, cutting force and *MRR* will be selected as the output parameters.

2. Materials and Methods

2. 1. RIM method

Reference Ideal Method (RIM) is a method to solve the problem of multi-objective optimization. This method is based on the concept of «ideal solution», which is performed according to the following steps [33].

Step 1. Normalization process:

This phase will determine the ideal reference interval according to (1):

$$d_{\min}(x,[C,D]) = \min(|x-C|,|x-D|), \qquad (1)$$

in which:

– x is the value of a criterion at a certain option;

– $[C, D]$ is ideal reference interval.

The next stage of normalization process is to determine normalization value using the following equation:

$$f\left(x,[A,B],[C,D]\right) = \begin{bmatrix} 1 \ \text{ if}: x \in [C,D], \\ 1-\dfrac{d_{\min}\left(x,[C,D]\right)}{[A-C]} \ \text{ if}: x \in [A,C], \text{and}: A \neq C, \\ 1-\dfrac{d\min\left(x,[C,D]\right)}{[D-B]} \ \text{if}: x \in [A,C], \text{and}: B \neq D, \end{bmatrix} \qquad (2)$$

in which, $[A, B]$ is the range of values from minimum to maximum of a certain criterion.

Step 2. Normalize the valuation matrix X with the reference ideal:

$$Y = \begin{bmatrix} f\left(x_{11},t_1,S_1\right) \ldots \ f\left(x_{1n},t_n,S_n\right) \\ f\left(x_{21},t_1,S_1\right) \ldots \ f\left(x_{2n},t_n,S_n\right) \\ \ldots \quad \ldots \quad \ldots \\ f\left(x_{m1},t_1,S_1\right) \ldots f\left(x_{mn},t_n,S_{1n}\right) \end{bmatrix}, \qquad (3)$$

in which, function f has been calculated according to (2), n is the number of criteria, m is the number of options.

Step 3. Determine the weight for each criterion, where i is the number of criteria:

$$\sum_{i=1}^{n} w_i = 1. \qquad (4)$$

Step 4. Calculate the weighted normalized matrix Y':

$$Y' = \begin{bmatrix} f\left(x_{11},t_1,S_1\right) \ldots \ f\left(x_{1n},t_n,S_n\right) \\ f\left(x_{21},t_1,S_1\right) \ldots \ f\left(x_{2n},t_n,S_n\right) \\ \ldots \quad \ldots \quad \ldots \\ f\left(x_{m1},t_1,S_1\right) \ldots f\left(x_{mn},t_n,S_{1n}\right) \end{bmatrix}. \qquad (5)$$

Step 5. Calculate the variation to the normalized reference ideal for each alternative:

$$Ii^{+} = \sqrt{\sum_{j=1}^{m}\left(y'_{ij}-w_j\right)^2}. \qquad (6)$$

$$Ii^{-} = \sqrt{\sum_{j=1}^{m}\left(y'_{ij}\right)^2}, \qquad (7)$$

in which:

– $i = 1, 2, \ldots, m$ (number of options);

– $j = 1, 2, \ldots, n$ (number of criteria).

Step 6. Calculate the relative index:

$$Ri = \frac{Ii^-}{Ii^+ + Ii^-}, \tag{8}$$

in which: $0 < R_i < 1$, $i = 1, 2, \ldots, m$.

Step 7. Rank options according to R_i value. The option with maximum R_i is the best one.

2. 2. Experimental materials

Experimental material used in this study is X12M steel. The sample is heat-treated to reach 62HRC hardness. The length, width and height of the steel model are all 45 mm.

2. 3. Experimental machine and cutting tools

Experimental machine used in this study is a 3-axis CNC milling machine. The brand of the machine is HAAS and the machine uses SINUMERIK S840DSB operating system.

Three types of inserts used during the experiment with tool nose radius are 0.3 mm, 0.5 mm and 0.8 mm, denoted as R390-11T303M, R390-11T305M and R390-11T308M, respectively. Each type of insert is used with three different materials, including TiN coating, TiCN coating and TiAlN coating. The handle used in this study is 14 mm in diameter, on which two inserts are attached symmetrically. Some parameters for insert are shown in **Table 2**.

Table 2

Some parameters of insert

Parameter	Cutting insert		
	R390-11T303M-PM1025	**R390-11T305M-PM1025**	**R390-11T308M-PM1025**
Tool nose radius (mm)	0.3	0.5	0.8
Back edge length (mm)	0.8	0.9	1.2
Weight (kg)	0.0022	0.0026	0.003
Coating material	TiN; TiCN; TiAlN		
Cutting thickness (mm)	3.59		
Main cutting angle (degree)	90		
Maximum cutting depth (mm)	10		
Shape style of cutting piece	L		
Edge width (mm)	6.8		
Effective length of edge (mm)	10		

2. 4. Design the experiment

The five parameters selected are the input parameters of the experimental including insert material, tool nose radius, cutting speed, feed rate and cutting depth. Three levels of each input parameter are selected as shown in **Table 3**. Values of the cutting parameters in this table are selected according to the cutting tool manufacturer's recommendation.

Table 3

Value of input parameters at different levels

Parameter	Symbol	Unit	Value at level		
			1	**2**	**3**
Insert material	*IM*	–	TiN	TiCN	TiAlN
Tool nose radius	r	mm	0.3	0.5	0.8
Cutting speed	V_c	m/min	100	125	150
Feed rate	V_f	mm/min	300	400	500
Depth of cut	a_p	mm	0.25	0.35	0.45

Experimental matrix is designed according to Taguchi method, which is an orthogonal matrix consisting of 27 experiments (L27) as shown in **Table 4**.

Table 4

Orthogonal matrix L27

No.	Code value					Actual value				
	IM	*r*	V_c	V_f	a_p	*IM*	*r* (mm)	V_c (m/min)	V_f (mm/min)	a_p (mm)
1	1	1	1	1	1	TiN	0.3	100	300	0.25
2	1	1	1	1	2	TiN	0.3	100	300	0.35
3	1	1	1	1	3	TiN	0.3	100	300	0.45
4	1	2	2	2	1	TiN	0.5	125	400	0.25
5	1	2	2	2	2	TiN	0.5	125	400	0.35
6	1	2	2	2	3	TiN	0.5	125	400	0.45
7	1	3	3	3	1	TiN	0.8	150	500	0.25
8	1	3	3	3	2	TiN	0.8	150	500	0.35
9	1	3	3	3	3	TiN	0.8	150	500	0.45
10	2	1	2	3	1	TiCN	0.3	125	500	0.25
11	2	1	2	3	2	TiCN	0.3	125	500	0.35
12	2	1	2	3	3	TiCN	0.3	125	500	0.45
13	2	2	3	1	1	TiCN	0.5	150	300	0.25
14	2	2	3	1	2	TiCN	0.5	150	300	0.35
15	2	2	3	1	3	TiCN	0.5	150	300	0.45
16	2	3	1	2	1	TiCN	0.8	100	400	0.25
17	2	3	1	2	2	TiCN	0.8	100	400	0.35
18	2	3	1	2	3	TiCN	0.8	100	400	0.45
19	3	1	3	2	1	TiAlN	0.3	150	400	0.25
20	3	1	3	2	2	TiAlN	0.3	150	400	0.35
21	3	1	3	2	3	TiAlN	0.3	150	400	0.45
22	3	2	1	3	1	TiAlN	0.5	100	500	0.25
23	3	2	1	3	2	TiAlN	0.5	100	500	0.35
24	3	2	1	3	3	TiAlN	0.5	100	500	0.45
25	3	3	2	1	1	TiAlN	0.8	125	300	0.25
26	3	3	2	1	2	TiAlN	0.8	125	300	0.35
27	3	3	2	1	3	TiAlN	0.8	125	300	0.45

The experiments were carried out with constant values of the following parameters: cutting fluid of Caltex Aquatex 3180 with concentration of 12 %, using flow of 9 liters/min. In order to eliminate the effect of tool wear on the output parameters, each insert is used only for one experiment.

2. 5. Measuring equipment

Surface roughness is measured with a MITUTOYO-Surftest SJ-210 roughness tester (Japan). The standard length of the set measurement is 0.8 mm. Each experimental sample will be measured at least three times, the roughness value in each experiment is the average value of successive measuring time.

Cutting force measuring device to be used is a Kistler force sensor, brand 9139AA. **Fig. 1** shows the experimental system. During the experiment, the cutting force components in the three directions x, y, z will be measured simultaneously (F_x, F_y, F_z). Data processor is used to connect dynamometer and computer. Cutting force value at each experiment is calculated by the following (9):

$$F_c = \sqrt{F_x^2 + F_y^2 + F_z^2}. \quad (9)$$

Fig. 1. Experimental system

MRR is calculated using the following (10):

$$MRR = a_p \cdot w \cdot V_f, \tag{10}$$

in which:

– a_p is cutting depth;
– w is cutting width;
– V_f is the amount of feed rate per minute.

3. Results

The experiment is conducted in the order of the experiments in **Table 4**, the results are presented in **Table 5**.

Table 5
Experimental results

No.	*IM*	*r* (mm)	V_c (m/min)	V_f (mm/min)	a_p (mm)	R_a (µm)	F_c (N)	*MRR* (mm^3/min)
1	TiN	0.3	100	300	0.25	0.653	63.075	1050
2	TiN	0.3	100	300	0.35	1.235	76.766	1470
3	TiN	0.3	100	300	0.45	1.438	193.094	1890
4	TiN	0.5	125	400	0.25	1.303	128.370	1400
5	TiN	0.5	125	400	0.35	0.767	116.328	1960
6	TiN	0.5	125	400	0.45	0.836	121.044	2520
7	TiN	0.8	150	500	0.25	1.869	144.006	1750
8	TiN	0.8	150	500	0.35	1.341	155.534	2450
9	TiN	0.8	150	500	0.45	0.731	176.236	3150
10	TiCN	0.3	125	500	0.25	0.247	162.604	1750
11	TiCN	0.3	125	500	0.35	0.303	177.232	2450
12	TiCN	0.3	125	500	0.45	0.679	148.560	3150
13	TiCN	0.5	150	300	0.25	0.912	121.840	1050
14	TiCN	0.5	150	300	0.35	2.464	175.440	1470
15	TiCN	0.5	150	300	0.45	0.859	59.280	1890
16	TiCN	0.8	100	400	0.25	0.835	72.720	1400
17	TiCN	0.8	100	400	0.35	2.619	138.436	1960
18	TiCN	0.8	100	400	0.45	1.313	161.820	2520
19	TiAlN	0.3	150	400	0.25	0.31	104.856	1400
20	TiAlN	0.3	150	400	0.35	0.175	162.960	1960
21	TiAlN	0.3	150	400	0.45	0.293	118.880	2520
22	TiAlN	0.5	100	500	0.25	0.737	191.360	1750
23	TiAlN	0.5	100	500	0.35	1.635	162.351	2450
24	TiAlN	0.5	100	500	0.45	0.444	157.815	3150
25	TiAlN	0.8	125	300	0.25	0.462	194.991	1050
26	TiAlN	0.8	125	300	0.35	1.313	148.157	1470
27	TiAlN	0.8	125	300	0.45	1.357	58.590	1890

The surface roughness value at the experiments has been measured at least three times per sample. The surface roughness value at each experiment is the average value of the successive measurements. Three cutting force components (F_x, F_y and F_z) are measured during the time the cutter enters the workpiece, the cutting force value (F_c) at each experiment is calculated according to (9). MRR was calculated for each experiment using (10).

From the data in **Table 5** the graph of the influence of input parameters on surface roughness has been established as shown in **Fig. 2.**

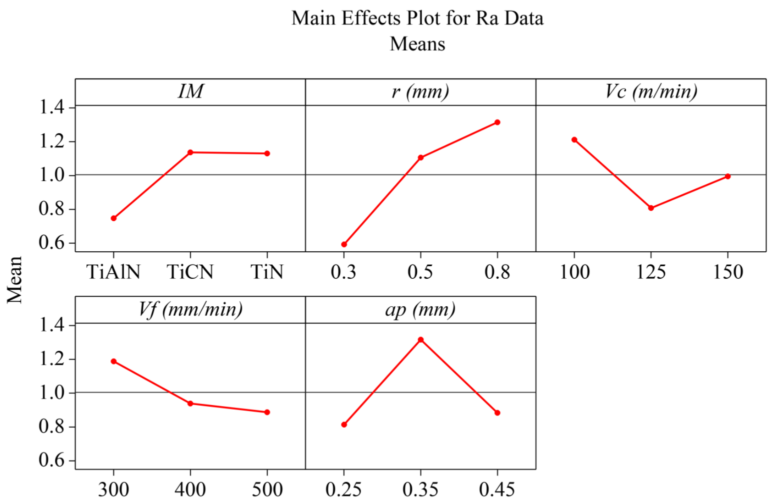

Fig. 2. Main effects plot for *Ra*

From the data in **Table 5**, the graph of the influence of input parameters on cutting force has been established as shown in **Fig. 3**.

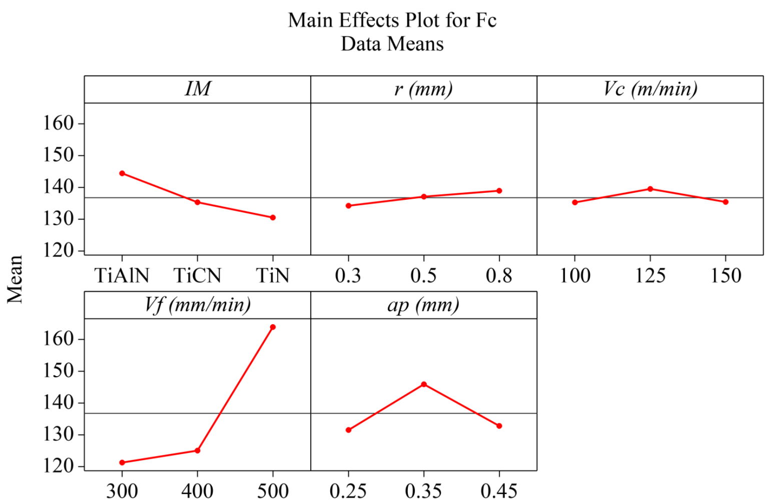

Fig. 3. Main effects plot for F_c

Fig. 4 show diagram on effects of the interaction between input parameters on surface roughness.

The influence of the interaction between the input parameters to the surface roughness is extremely complex. It is necessary to conduct analysis of these figures to see more clearly the statement just mentioned.

Fig. 5 show diagram on effects of the interaction between input parameters on cutting force. From **Fig. 5** shows, the influence of the interaction between the input parameters to the cutting force is extremely complex.

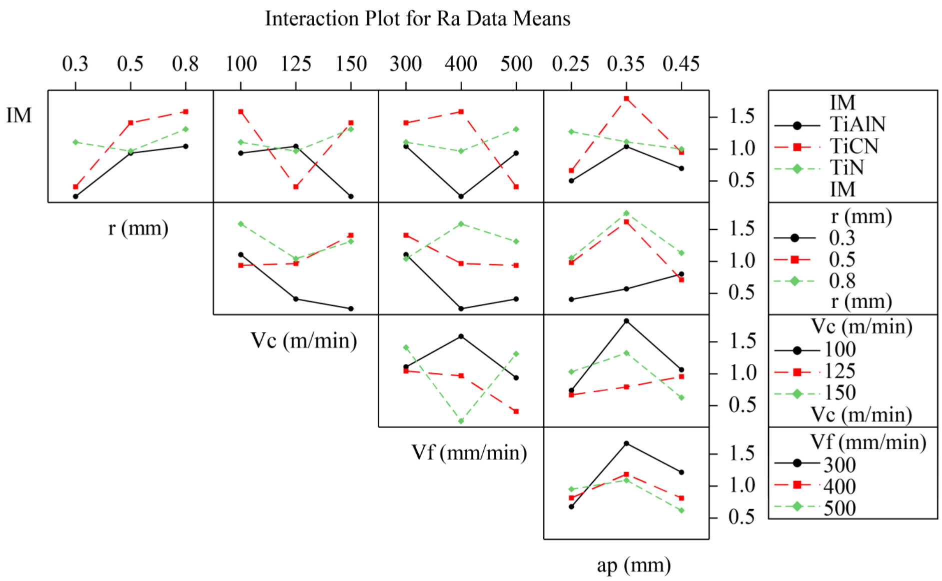

Fig. 4. Interaction plot for R_a

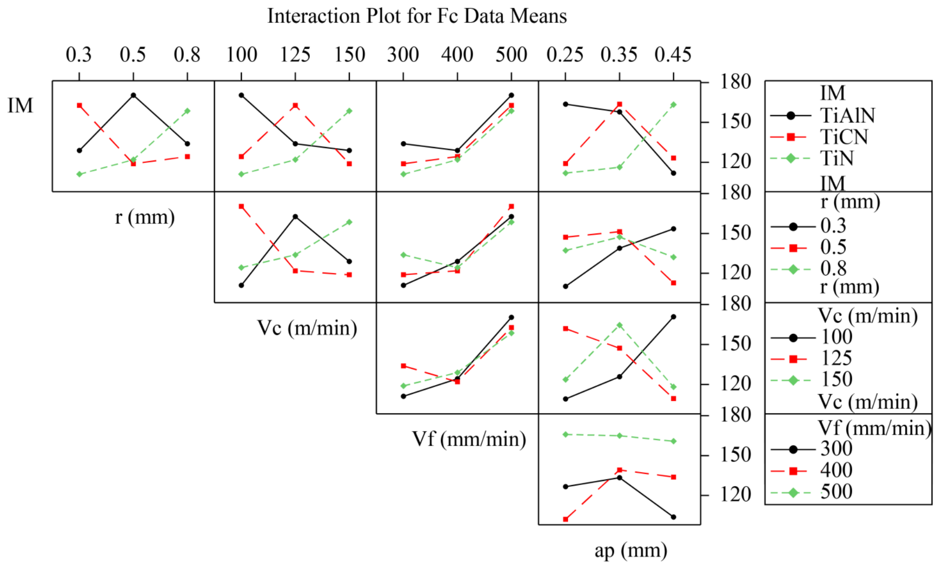

Fig. 5. Interaction plot for F_c

4. Discussion of experimental results

From **Fig. 2**, it shows that tool nose radius is the parameter that has the greatest influence on surface roughness, followed by influence of the insert material. The influence of feed rate on the surface roughness ranked at position 3 out of the 5 input parameters, cutting speed affects the surface roughness is in position 4, while cutting depth has negligible influence on surface roughness.

Fig. 3 also shows that feed rate is the parameter that has the greatest influence on cutting force, followed by influence of insert material. Meanwhile, three parameters including tool nose radius, cutting speed and cutting depth have negligible influence on cutting force.

As for *MRR* when calculated by the eq. (10), it is obvious that MRR will increase when increasing cutting depth, feed rate and cutting width. Meanwhile, insert material, tool nose radius and cutting speed do not affect the *MRR*.

If influence of each input parameter on each output parameter is only considered, **Fig. 2, 3** show that the surface roughness will be of small value when insert material is TiAlN, while the cutting force will be of small value when selected insert material is TiN. When tool nose radius is 0.3 mm, both surface roughness and cutting force have small values. When speed is at 125 m/min, surface roughness will be of a smaller value when speed is 100 m/min and 150 m/min; however, when cutting speed is also at the value of 125 m/min, cutting force is greater when the cutting speed is 100 m/min and 150 m/min. Surface roughness will be of a small value when feed rate is 500 mm/min; however, cutting force is maximum at this value of feed rate. Surface roughness and cutting force are both small when the cutting depth is 0.25 mm. From some analysis above, it shows that although independent effect of each input parameter on the output parameters is only considered, it showed the complexity and difficulty in determining the value of the input parameters to ensure that both surface roughness and cutting force were of small value. On the other hand, in practice, the output parameters not only depend on the individual input parameters, but it also depends on the same parameters as well as the interaction between them.

Analysis of results in **Fig. 4** shows that:

– when using insert material of TiCN and TiAlN, surface roughness increases if the tool nose radius increases. If using a TiN insert material, surface roughness decrease when increasing tool nose radius from 0.3 mm to 0.5 mm; however, surface roughness increases if tool nose radius continues to increase;

– when using insert material of TiAlN, surface roughness increases slowly if cutting speed increases from 100 m/min to 125 m/min; however, surface roughness will decrease rapidly if cutting speed continues to increase. For TiCN insert material, surface roughness will decrease quickly when increasing cutting speed from 100 m/min to 125 m/min; however, surface roughness will increase rapidly if cutting speed continues to increase. In the case of using TiN as insert material, surface roughness decreases slowly when increasing cutting speed between 100 m/min and 125 m/min; however, surface roughness will increase when increasing cutting speed from 125 m/min to 150 m/min;

– for TiN insert material and TiAlN insert material, when feed rate increases from 300 mm/min to 400 mm/min, surface roughness will decrease; however, surface roughness will increase if the feed rate continues to increase. When using TiCN insert material, if feed rate increases from 300 mm/min to 400 mm/min, surface roughness increases slowly; however, if feed rate continues to increase, surface roughness will increase rapidly;

– for both inserts material of TiAlN and TiCN, surface roughness will increase when cutting depth increases from 0.25 mm to 0.35 mm and surface roughness will decrease if cutting depth continues to increase. In the case of using TiN insert material, surface roughness will decrease if cutting depth increases;

– when tool nose radius are 0.5 mm and 0.8 mm, surface roughness will decrease if cutting speed increases from 100 m/min to 125 m/min; however, surface roughness will increase if cutting speed continues to increase. In the case tool nose radius is 0.3 mm, surface roughness will decrease if cutting speed increase;

– for insert with tool nose radius of 0.8 mm, surface roughness will increase if the feed rate increases from 300 mm/min to 400 mm/min; however, surface roughness will decrease if feed rate continues to increase. In the case of using a 0.3 mm tool nose radius, surface roughness will decrease rapidly when feed rate increases in the feed rate from 300 mm/min to 400 mm/min; however, surface roughness increases slowly if feed rate continues to increase. In the case tool nose radius has a value of 0.5 mm, surface roughness will decrease if feed rate value increases;

– when tool nose radius are 0.5 mm and 0.8 mm, surface roughness will increase quickly if cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease quickly if cutting depth continues to increase. When using the tool nose radius of 0.3 mm radius, surface roughness increases if cutting depth increases;

– when cutting speed is 100 m/min, surface roughness will increase if feed rate continues to increases from 300 mm/min to 400 mm/min. If feed rate continues to increase, surface roughness will decrease. When cutting speed is 125 m/min, surface roughness will decrease if feed rate increases. In case cutting speed is 150 m/min, surface roughness will decrease quickly if feed rate increases from 300 mm/min to 400 mm/min; however, surface roughness will increase rapidly if feed rate continues to increase;

– when cutting speeds are 100 m/min and 150 m/min, surface roughness will increase if the cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease if cutting depth continues to increase. When the cutting speed is 125 m/min, surface roughness will increase slowly if cutting depth increases;

– in all three cases of feed rate, if cutting depth increases from 0.25 mm to 0.35 mm, it will increase surface roughness. If cutting depth of continues to increase, surface roughness will decrease.

Analysis of results in **Fig. 5** shows that:

– if insert material is TiAlN, surface roughness will increase when tool nose radius increases from 0.3 mm to 0.5 mm; however, surface roughness will decrease when tool nose radius continues to increase. If the insert material is TiCN, surface roughness will decrease when tool nose radius increases from 0.3 mm to 0.5 mm. In the case of using TiN insert material, the surface roughness will increase when tool nose radius increase;

– when insert material is TiAlN, surface roughness will decrease if cutting speed increases. When using TiCN insert material, surface roughness will increase rapidly if cutting speed increases from 100 m/min to 125 m/min; however, surface roughness will decrease rapidly if cutting speed continues to increase. When using TiN as insert material, surface roughness will increase if cutting speed increases;

– for all three types of inserts to be used, surface roughness will increase if feed rate increases;

– when insert material is TiAlN, surface roughness will decrease if cutting depth increases. For insert material of TiCN, surface roughness increase quickly if cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease quickly if cutting depth continues to increase. In case of using insert material of TiN, surface roughness increases if cutting depth increases;

– when tool nose radius is 0.3 mm, surface roughness will increase if cutting speed increases from 100 m/min to 125 m/min; however, surface roughness will decrease if the cutting speed continues to increase. When tool nose radius is 0.5 mm, surface roughness will decrease if cutting speed increases. Meanwhile, surface roughness will increase if cutting speed increases when tool nose radius is 0.8 mm;

– with all three values of tool nose radius, all surface roughness will increase if feed rate increases;

– when tool nose radius is 0.3 mm, surface roughness will increase if cutting depth increases. When the tool nose radius are 0.5 mm and 0.8 mm, surface roughness increases slowly if cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease if cutting depth increases;

– in all three cases of cutting speeds (100 m/min, 125 m/min and 150 m/min), surface roughness will increase if feed rate increases;

– when cutting speed is 100 m/min, surface roughness will increase if cutting depth increases. When cutting speed is 125 m/min, surface roughness will decrease if cutting depth increases. In case of cutting speed of 150 m/min, surface roughness will increase if cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease if cutting depth continues to increase;

– when feed rates are 300 mm/min and 400 mm/min, surface roughness will increase if cutting depth increases from 0.25 mm to 0.35 mm; however, surface roughness will decrease if cutting depth continues to increase. In the case of a feed rate of 500 mm/min, surface roughness will decrease if cutting depth increases.

The above analysis shows that the influence of the input parameters as well as the interaction between them on the output parameters is extremely complex. From there, it shows that if only the above diagrams are observed, it is not possible to determine the values of the input parameters to ensure simultaneously minimum surface roughness and minimum cutting force.

On the other hand, data in **Table 5** shows that surface roughness has the smallest value in experiment No. 20 (R_a = 0.175 μm), while cutting force has the smallest value in experiment No. 27 (F_c = = 58.590 N) and *MRR* has the maximum value in experiment No. 9, No. 12 and No. 24 (*MRR* = = 3150 mm^3/min). From there, it can also be confirmed that it is impossible to determine the value of the input parameters in order to satisfy the set criteria through observation on the experimental results in this table. This work can only be determined by solving the multi-objective optimization problem, where all three parameters including surface roughness, cutting force and *MRR* are selected as the criteria to evaluate the milling process. This is why it is necessary to perform the optimization in this study.

The experimental data in **Table 5** shows that the minimum and maximum values of R_a are 0.175 µm and 2.619 µm, respectively; minimum and maximum value of F_c are 58.59 N and 194.991 N respectively; minimum and maximum values of *MRR* are 1050 mm^3/min and 3150 mm^3/min, respectively. From there, it can be deduced as follow:

$$[A, B] = [0.175\ 2.619\ 58.59\ 194.991\ 1050\ 3150].$$

It can also be seen from the data in **Table 5** that surface roughness has minimum value of 0.175 µm, F_c has minimum value of 58.59 N, while the *MRR* has maximum value of 3150 mm^3/min. These are the three best indicators of the ideal plan. So:

$$[C, D] = [0.175\ 0.175\ 58.59\ 58.59\ 3150\ 3150].$$

By applying (1), it can determine ideal reference interval of R_a, F_c and *MRR*. By applying (2), it can determine normalized values of R_a, F_c and *MRR*. By applying (3) to (7), it can calculate values of the parameters of I_i^+ and I_i^-, where weights of R_a, F_c and *MRR* have equal values, which means that: $w_1 = w_2 = w_2 = 1/3$. All these values are shown in **Table 6**.

Table 6
Parameters in the RIM

No.	$d_{\min}(R_a, [C, D])$	$d_{\min}(F_c, [C, D])$	$d_{\min}(MRR, [C, D])$	$f(R_a)$	$f(F_c)$	$f(MRR)$	I_i^+	I_i^-
1	0.478	4.485	–2100.0	0.804	0.967	2.000	1.844	2.363
2	1.060	18.176	–1680.0	0.566	0.867	1.800	1.578	2.077
3	1.263	134.504	–1260.0	0.483	0.014	1.600	1.315	1.671
4	1.128	69.780	–1750.0	0.538	0.488	1.833	1.522	1.972
5	0.592	57.738	–1190.0	0.758	0.577	1.567	1.327	1.833
6	0.661	62.454	–630.0	0.730	0.542	1.300	1.065	1.586
7	1.694	85.416	–1400.0	0.307	0.374	1.667	1.334	1.735
8	1.166	96.944	–700.0	0.523	0.289	1.333	1.019	1.461
9	0.556	117.646	0.000	0.773	0.137	1.000	0.822	1.271
10	0.072	104.014	–1400.0	0.971	0.237	1.667	1.481	1.943
11	0.128	118.642	–700.0	0.948	0.130	1.333	1.191	1.641
12	0.504	89.970	0.000	0.794	0.340	1.000	0.810	1.321
13	0.737	63.250	–2100.0	0.698	0.536	2.000	1.718	2.185
14	2.289	116.850	–1680.0	0.063	0.143	1.800	1.503	1.807
15	0.684	0.690	–1260.0	0.720	0.995	1.600	1.480	2.017
16	0.660	14.130	–1750.0	0.730	0.896	1.833	1.651	2.167
17	2.444	79.846	–1190.0	0.000	0.415	1.567	1.280	1.621
18	1.138	103.230	–630.0	0.534	0.243	1.300	0.991	1.426
19	0.135	46.266	–1750.0	0.945	0.661	1.833	1.653	2.166
20	0.000	104.370	–1190.0	1.000	0.235	1.567	1.405	1.873
21	0.118	60.290	–630.0	0.952	0.558	1.300	1.169	1.705
22	0.562	132.770	–1400.0	0.770	0.027	1.667	1.436	1.836
23	1.460	103.761	–700.0	0.403	0.239	1.333	1.007	1.413
24	0.269	99.225	0.000	0.890	0.273	1.000	0.871	1.366
25	0.287	136.401	–2100.0	0.883	0.000	2.000	1.786	2.186
26	1.138	89.567	–1680.0	0.534	0.343	1.800	1.480	1.909
27	1.182	0.000	–1260.0	0.516	1.000	1.600	1.443	1.956

By applying (8), R_i can be calculated for 27 options. Then, values of R_i are used to rank options in **Table 6** with the results presented in **Table 7**.

Results in **Table 7** show that experiment No. 12 has the best performance of the 27 experiments that have been performed, while experiment No. 14 is the worst. Value of *MRR* in experiment No. 12 (equal to value of *MRR* in experiment No. 9 and No. 24) equal to 3150 mm^3/min, is the maximum value out of a total of 27 experiments. Value of cutting force F_c in experiment No. 12 is 148,560 N, ranked 14th out of 27 experiments. Value of R_a in experiment No. 12 is 0.679 µm, which is quite a small value of the 27 conducted experiments (ranked 9th). Although R_a and F_c in experiment No. 12 are not the minimum values among those of the 27 experiment, but for the purpose of this study (minimizing R_a and F_c while simultaneously maximizing *MRR*), it can be concluded that experiment No. 12 is the most optimized option.

Therefore, the optimum values of the input parameters are suggested as follow: insert material of TiCN, tool nose radius of 0.3 mm, cutting speed of 125 m/min, feed rate of 500 mm/min and cutting depth of 0.45 mm.

Table 7

Ranking of the options

No.	*IM*	*r* (mm)	V_c (m/min)	V_f (mm/min)	a_p (mm)	R_a (µm)	F_c (N)	*MRR* (mmm^3/s)	R_i	*Ranking*
1	TiN	0.3	100	300	0.25	0.653	63.075	1050	0.5616	21
2	TiN	0.3	100	300	0.35	1.235	76.766	1470	0.5682	14
3	TiN	0.3	100	300	0.45	1.438	193.094	1890	0.5597	24
4	TiN	0.5	125	400	0.25	1.303	128.370	1400	0.5644	19
5	TiN	0.5	125	400	0.35	0.767	116.328	1960	0.5801	9
6	TiN	0.5	125	400	0.45	0.836	121.044	2520	0.5982	4
7	TiN	0.8	150	500	0.25	1.869	144.006	1750	0.5654	18
8	TiN	0.8	150	500	0.35	1.341	155.534	2450	0.5892	7
9	TiN	0.8	150	500	0.45	0.731	176.236	3150	0.6073	3
10	TiCN	0.3	125	500	0.25	0.247	162.604	1750	0.5675	16
11	TiCN	0.3	125	500	0.35	0.303	177.232	2450	0.5794	10
12	TiCN	0.3	125	500	0.45	0.679	148.560	3150	0.6199	1
13	TiCN	0.5	150	300	0.25	0.912	121.840	1050	0.5598	23
14	TiCN	0.5	150	300	0.35	2.464	175.440	1470	0.5458	27
15	TiCN	0.5	150	300	0.45	0.859	59.280	1890	0.5767	11
16	TiCN	0.8	100	400	0.25	0.835	72.720	1400	0.5677	15
17	TiCN	0.8	100	400	0.35	2.619	138.436	1960	0.5587	25
18	TiCN	0.8	100	400	0.45	1.313	161.820	2520	0.5899	6
19	TiAlN	0.3	150	400	0.25	0.31	104.856	1400	0.5672	17
20	TiAlN	0.3	150	400	0.35	0.175	162.960	1960	0.5714	13
21	TiAlN	0.3	150	400	0.45	0.293	118.880	2520	0.5932	5
22	TiAlN	0.5	100	500	0.25	0.737	191.360	1750	0.5611	22
23	TiAlN	0.5	100	500	0.35	1.635	162.351	2450	0.5840	8
24	TiAlN	0.5	100	500	0.45	0.444	157.815	3150	0.6108	2
25	TiAlN	0.8	125	300	0.25	0.462	194.991	1050	0.5503	26
26	TiAlN	0.8	125	300	0.35	1.313	148.157	1470	0.5632	20
27	TiAlN	0.8	125	300	0.45	1.357	58.590	1890	0.5755	12

This study has identified which experiment was considered the «best» of the experiments performed. However, in practice, the best set of input parameters may not coincide with this experiment, which is the limitation of this study. The construction of regression functions to serve as the basis for multi-goal optimization with the aim of finding the best set of parameters will actually overcome the limitations of this study. This is the direction for the next research.

5. Conclusion

For surface roughness: tool nose radius is the most influential parameter, followed by influence of insert material type, feed rate, and cutting speed. Cutting depth has a negligible effect on surface roughness.

Feed rate is the parameter that has the greatest influence on cutting force, followed by the influence of insert material type. Tool nose radius, cutting speed and cutting depth have a negligible effect on the cutting force.

In order for the milling process to simultaneously ensure the parameters including the minimum surface roughness, minimum cutting force, and maximum *MRR*, it is recommended to use TiCN as insert material, tool nose radius of 0.3 mm, cutting speed of 125 m/min, feed rate of 500 mm/min and cutting depth of 0.45 mm.

RIM has been successfully applied for the first time for the purpose of multi-objective optimization of X12M steel milling process in combination with the Taguchi method in this study. This method is also promising for multi-objective optimization of the milling process of other materials or other machining methods.

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