Multi-objective optimization of SKD11 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. 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 SKD11 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. 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, SKD11 steel, Multi-objective optimization, Surface roughness, Cutting force, MRR, Taguchi, RIM

I. INTRODUCTION

Milling is one of the most common machining methods in mechanical machining. This method can be applied on many types of surfaces, many materials and is used in the process of machining many different products. When conducting surface milling by a face milling cutter, it 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 the development of 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. Similar to other machining methods, workpiece surface machining with small surface roughness, small cutting force and large MRR is always the objective that needs to be achieved in most milling processes. Therefore, the study on determining the value of the processing parameters to ensure small surface roughness, small cutting force and large MRR have been carried out by many authors.

Taguchi method has been applied to design the experimental matrix when milling Al7075 aluminum alloy [1]. The cutting tool material used in this study is carbide. Signal-to-Noise (S/N) ratio analysis method has been applied to determine the optimal values of some cutting parameters. The results showed that in order to achieve the minimum value of surface roughness, values of spindle speed, feed rate and cutting depth are 4800 rpm, 165 mm/min and 0.8 mm, respectively. The MRR will have the maximum value when the spindle speed is 4800 rpm, the feed rate is 230mm/min and the cutting depth is 1 mm.

Taguchi method is also applied to design AISI 304 steel milling experimental matrix [2]. The cutting tool used in this study is made from carbide. The S/N ratio analysis method has also been used to optimize the milling process. The results showed that in order to achieve the minimum value of surface roughness, the values for spindle speed, feed rate and cutting depth are 3000 rpm, 200 mm/min and 0.5 mm, respectively.

In [3] has optimized the Nickel Based Waspaloy material milling process in Minimum quantity lubrication (MQL) condition. This study used H13A Sandvik uncoated carbide as cutting tool. Five parameters have been selected as the input parameters for the experiment including type of cutting fluid, flow rate of cutting fluid, milling type, distance from nozzle to cutting tool and nozzle length. This study has shown that in order to achieve the minimum value of surface roughness, it is necessary to use vegetable oil as cutting fluid, flow rate is 100 ml/h, milling type is up milling, the distance from the nozzle to the cutting tool is 50 mm and the nozzle length is 32 mm. The experiments in this study are also designed according to the Taguchi method and the optimization method in this study is also the S/N ratio analysis method.

Taguchi method is also applied to design the experimental matrix when milling Inconel 718 steel with hard alloy cutting tools [4]. The S/N ratio analysis method has also been applied to perform the optimization. The results have shown that in order to achieve the minimum value of surface roughness, cutting speed is 55 m/min, feed rate is 0.12 mm/rev and cutting depth is 1.2 mm.

Using diamond coated cemented carbide as cutting tool for milling carbon fiber reinforced plastics (CFRP) has shown that in order to achieve the minimum value of surface roughness, cutting speed is 500 m/min, feed rate is 0.03 mm/tooth and cutting depth is 0.1 mm [5]. In this study, the experiments were also designed according to the Taguchi method, and to determine the optimum values of the cutting parameters as mentioned above, the S/N ratio analysis method was also applied.

Taguchi method has also been applied to design the experimental matrix when milling 1040 MS steel with hard alloy cutting tool [6]. S/N ratio analysis method has also been applied to solve the optimal problem in this study. The results showed that in order to achieve the minimum value of surface roughness, spindle speed is 2500 rpm, feed rate 800 mm/min, cutting depth is 0.8 mm and flow rate of cutting fluid is 30 liters/min.

Taguchi method has been applied to design the experimental matrix when milling EN8 steel with a carbide cutting tool [7]. In this study, S/N ratio analysis method has also been applied to determine the optimal values of some cutting parameters. The results showed that in order to achieve the minimum value of surface roughness, the spindle speed, feed rate and cutting depth are 4000 rpm, 1000 mm/min and 0.1 mm, respectively.

When milling EN31 steel with a hard alloy coated cutting tool, in order to achieve the minimum value of surface roughness, values of the spindle speed, feed rate, cutting depth and flow rate of cutting fluid are 1150 rpm, 175 mm/min, 1 mm and 20 liters/min, respectively [8]. In this study, the experimental matrix was also designed according to the Taguchi method, and the S/N ratio analysis method was also applied to determine values of input parameters as above.

In [9], the research on optimization of AISI H3 steel milling process with a TiAlN coating cutting tool was performed. This study designed the Taguchi method test matrix with four input parameters including cooling lubrication condition (dry, nanofluid and MQL), cutting speed, feed rate and cutting depth. Analysis of the S/N ratio has shown that in order to achieve the minimum value of surface roughness, it needs to be machined under cooling lubrication of nanofluid, cutting speed of 80 m/min, feed rate of 0.01 mm/tooth and cutting depth of 0.2 mm.

Optimization when milling Ultra-high molecular weight polyethylene (UHMWPE) with a SECO-93060F cutting tool was carried out [10]. The experimental matrix was designed in this study according to Taguchi method with three input parameters including spindle speed, feed rate and step over. S/N ratio analysis method was applied to determine the optimal values of the input parameters. The results have shown that in order to achieve the minimum value of surface roughness, spindle speed must be 7219 rpm, feed rate must be 1636 mm/min and step over must be 0.069 mm.

In [11], research on optimization of milling AL 6351 –T6 material with a 15HP type cutting tool was presented. Taguchi method has been applied to design the experimental matrix with four input parameters including spindle speed, feed rate, cutting depth and tool diameter (including 3 values of 10mm, 12mm and 16mm). By applying S/N ratio analysis method, this study has determined that in order to achieve the minimum value of surface roughness, it requires a tool with a diameter of 12 mm, a spindle speed of 5000 rpm, a feed rate of 2500 mm/min and a cutting depth of 0.7 mm.

Optimization process when dry milling H13 steel (cutting fluid is not used) by PVD coated carbide inserts was performed [12]. In this study, the experimental matrix according to the Taguchi method has been designed with four input parameters including cutting speed, feed rate, radial depth of cut, and axial depth of cut. S/N ratio analysis method was applied and determined that in order to achieve the minimum value of surface roughness, cutting speed is 200 m/min, feed rate is 0.05 mm/tooth, radial depth of cut is 0.3 mm and axial depth of cut is 1.5mm.

Taguchi method has been applied to design test matrix when milling EN19 steel [13]. TiN coating cutting tool was used in this study. S/N ratio analysis method is used as optimization method. The results showed that in order to achieve the maximum value of MRR, cutting speed, feed rate and cutting depth are 19.22 m/min, 50 mm/min and 1.2 mm, respectively.

In [14], it presented the optimization of aluminum milling by SECO R220.69-12 cutting tool. In this study, experimental matrix was designed according to Taguchi method and S/N ratio analysis method was used to solve the optimization problem. The results have shown that in order to achieve the minimum value of surface roughness, spindle speed is 1800 rpm, feed rate is 400 mm/min, cutting depth is 0.7 mm; in order to achieve minimum value of cutting force, spindle speed, feed rate and cutting depth must be 2600 rpmn, 400 mm/min and 0.7 mm, respectively.

In [15], it presented the optimization when milling Nimonic C-263 alloy with TiAlN coating cutting tool. Taguchi method was used to design the experimental matrix, and the analytical method of S/N ratio was also applied to perform optimization. The results have been determined that in order to achieve the minimum value of surface roughness, spindle speed is 2000 rpm, feed rate is 5 mm/min, cutting depth is 0.6 mm. In order to achieve minimum value of cutting force, values of spindle speed, feed rate and cutting depth are 1500 rpm, 5 mm/min and 0.4 mm, respectively.

Taguchi method has been applied to construct experimental matrix when milling Ti-6Al-4V alloy with TiN coating cutting tool [16]. S/N ratio analysis method has been applied to solve the optimization problem. The results have shown that in order to achieve the minimum value of surface roughness, cutting speed is 180 m/min and feed rate is 250 mm/min. An interesting thing happened in this study is that when the surface roughness is minimum, the cutting force also achieves minimum value.

The above studies show that matrix design according to Taguchi method has been successfully applied in many optimization problems of milling process. This is also easy to explain because when designing matrices according to the Taguchi method it is possible to select many input parameters while not having too many 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. However, the above studies show that, 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 single objective optimization problem is only solved. To overcome this limitation of Taguchi method, there have been a number of studies combining Taguchi method with a certain algorithm to optimize the objective of the milling process.

Taguchi method has been combined with Grey Relational Analysis (GRA) method to optimize the milling process of AISI 304 stainless steel [17]. Cutting tool material used in this study is tungsten carbide. This study has shown that 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 Taguchi method has also been combined with the GRA method to maximize the goals of 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 for 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.

Multi-objective optimization of ASSAB XW-42 tool steel milling has been carried out [19]. Tool made of hard alloy was used in this study. 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. Taguchi and GRA methods have been combined to solve optimal problem in this study.

In [20], multi-objective optimization of 465 steel milling process was conducted. Cutting tool used in this study was a TiAlN coating cutting tool. This study has determined that in order to ensure the purposes of minimum surface roughness, minimum cutting temperature and maximum MRR, cutting speed must be 150 m/min, feed rate must be 0.1 mm/min, cutting depth must be 0.2 mm. In this study, Taguchi method and GRA method were also combined.

The Taguchi method has been combined with Desirability Function Analysis (DFA) for purpose of multi-objective optimization of glass-fiber reinforced plastic (GFRP) composites milling process [21]. 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, fiber orientation angle is 15°, helix angle is 25°, and spindle speed is 400 rpm, and feed rate is 0.7123 mm/min.

Taguchi method has been combined with Principal Component Analysis (PCA) method for purpose of multi-objective optimization of the GFRP composites milling process [22]. Cutting tool is a hard alloy of type K10 that was used in this study. The purpose of this study is to ensure minimum surface roughness, minimum cutting force and maximum material separation ability. This study has determined that to achieve the above goals, helix angle is 35°, cutting speed is 4000 m/min, feed rate is 750 mm/rev, and cutting depth is 2 mm.

Taguchi method has been combined with the weighting method for 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 (*Ra*), root mean square average roughness (*Rq*) and average maximum height of the profile (*Rz*) 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 has been shown that the optimization of the milling process (both single-objective and multi-objective) has been done by many authors. However, for each specific case of the processing material and type of cutting tool, the optimum values of the input parameters found in those studies were not the same. These studies have also shown that many types of parameters have been selected as input parameters in experimental studies, of which cutting parameters have been chosen as the input parameters in most of the studies listed above. This is understandable as the adjustment of the value of the cutting parameters will be done quickly and simply by the operator who operates the machine. From these analyzes, it gives an orientation that in order to ensure one or several of the criteria of the milling process, the simplest task is to determine optimal values of cutting parameters and cutting tool parameters under each particular condition.

SKD11 steel is a steel with high abrasion resistance, high tensile strength, high hardenability, etc. 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 effect of nanoparticle concentration, cutting speed and hardness of the workpiece on cutting force when milling, milling process which is done 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], ect.

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.

From some of the above analysis, this study will apply the RIM method for multi-objective optimization of SKD11 steel milling process. Taguchi method will be applied to design the experimental matrix with input parameters as cutting parameters and cutting tool parameters. Three parameters including surface roughness, cutting force and *MRR* will be selected as the output parameters.

II. REFERENCE IDEAL METHOD (RIM)

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 formula (1).

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

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:

$$f(x,[A,B],[C,D]) = \begin{cases} 1 & if\ x \in [C,D] \\ 1-\dfrac{d_{min}(x,[C,D])}{|A-C|} & if\ x \in [A,C] and\ A \\ 1-\dfrac{d_{min}(x,[C,D])}{|D-B|} & if\ x \in [D,B]\ and\ D \end{cases} \quad (2)$$

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

$$Y = \begin{bmatrix} f(x_{11},t_1,s_1) & \dots & f(x_{1n},t_n,s_n) \\ f(x_{21},t_1,s_1) & \dots & f(x_{2n},t_n,s_n) \\ \dots & \dots & \dots \\ f(x_{m1},t_1,s_1) & \dots & f(x_{mn},t_n,s_{1n}) \end{bmatrix} \quad (3)$$

In which, function *f* has been calculated according to equation (2), *n* is number of criteria, *m* is number of options

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

$$\sum_{i=1}^{n} w_i = 1\ and\ 0 < w_i < 1 \quad (4)$$

Step 4. Calculate the weighted normalized matrix Y'.

$$Y' = Y.W = \begin{bmatrix} y_{11}.w_1 & \dots & y_{1n}.w_n \\ y_{21}.w_1 & \dots & y_{2n}.w_n \\ \dots & \dots & \dots \\ y_{m1}.w_1 & \dots & y_{mn}.w_n \end{bmatrix} \quad (5)$$

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

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

$$I_i^- = \sqrt{\sum_{j=1}^{n}\left(y'_{ij}\right)^2} \quad (7)$$

In which:

i = 1, 2, ….*m* (number of options)

j = 1, 2, ….*n* (number of criteria)

Step 6. Calculate the relative index

$$R_i = \frac{I_i^-}{I_i^+ + I_i^-} \quad (8)$$

In which: $0 < R_i < 1$, i = 1, 2, ….*m*

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

III. MILLING PROCESS EXPERIMENT

A. Experimental materials

Experimental material used in this study is SKD11 steel. The sample is heat-treated to reach 62HRC hardness. The length, width and height of the steel model are all 45 mm.

B. Experimental machine and cutting tools

Experimental machine used in this study is a 5-axis CNC milling machine. The brand of the machine is DMU 50 ECOLINE and the machine uses SINUMERIK S840DSB operating system.

Three types of inserts used during the experiment with tool nose radius are 0.3mm, 0.5mm and 0.8mm, denoted by 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 1.

C. 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 2. Values of the cutting parameters in this table are selected according to the cutting tool manufacturer's recommendation. Experimental matrix is designed according to Taguchi method, which is an orthogonal matrix consisting of 27 experiments (L27) as shown in Table 3.

Table 1. Some parameters of insert

Parameter	Cutting piece		
	R390-11T303M-PM1025	R390-11T305M-PM1025	R390-11T305M-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		

Table 2. 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

Table 3. 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

D. Experimental conditions

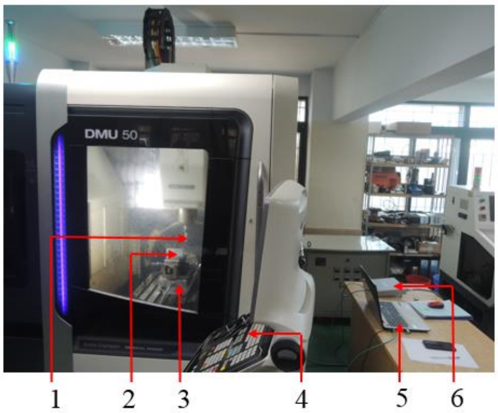
The experiments were carried out with constant values of the following parameters: cutting fluid of Caltex Aquatex 3180 with concentration of 12%, using flow of 9 liters/min. In order to eliminate the effect of tool wear on the output parameters, each insert is used only for one experiment.

E. 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. Figure 1 shows the mounting of the dynamometer and the components supporting the measurement and processing of force components. During the experiment, the cutting force components in the three directions x, y, z will be measured simultaneously (*Fx*, *Fy*, *Fz*). Data processor is used to connect dynamometer and computer. Cutting force value at each experiment is calculated by the following equation.

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



1 - cutting tool, 2 - workpiece, 3 - dynamometer, 4 - console, 5 - computer and software; 6 - data processor

Fig. 1 Experimental system setting

MRR is calculated using the following equation.

$$MRR = a_p . w . V_f \quad (10)$$

In which:

a_p is cutting depth;

w is cutting width.

V_f is the amount of feed rate per minute.

IV. Results and Discussion

The experiment is conducted in the order of the experiments in Table 3, measuring surface roughness, measuring cutting force components and calculating *MRR* for each experiment according to formula (10), the results are presented in Table 4.

Table 4. Experimental results

No.	*IM*	*r* (mm)	V_c (m/min)	V_f (mm/min)	a_p (mm)	*Ra* (µm)	*Fc* (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

From the data in Table 4, the graph of the influence of input parameters on surface roughness and cutting force has been established as shown in Figures 2 and 3. As for *MRR* when calculated by the equation (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*.

From Figure 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.

Figure 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.

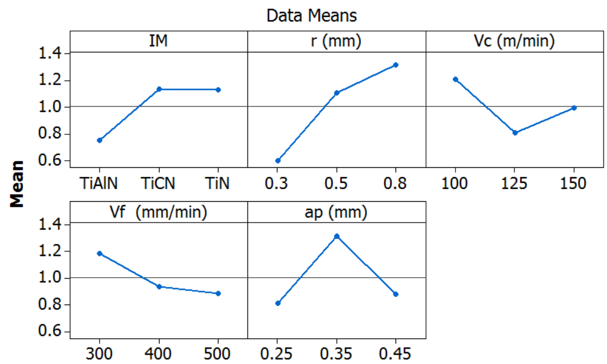


Fig. 2. *Main effects plot for Ra*

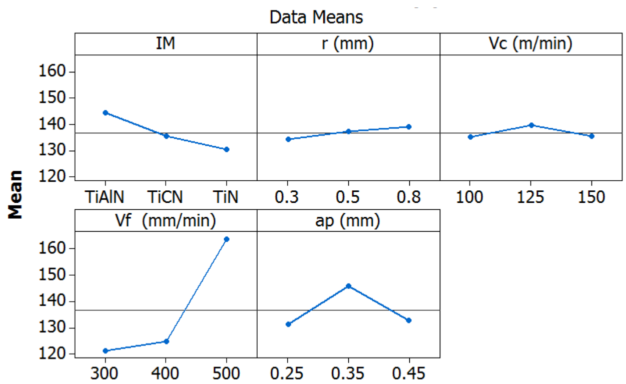


Fig. 3 Main effects plot for Fc

If influence of each input parameter on each output parameter is only considered, Figure 2 and Figure 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.

Figure 4 and Figure 5 show diagram on effects of the interaction between input parameters on surface roughness and cutting force. From these figures shows, the influence of the interaction between the input parameters to the output parameters is extremely complex. It is necessary to conduct analysis of these figures to see more clearly the statement just mentioned.

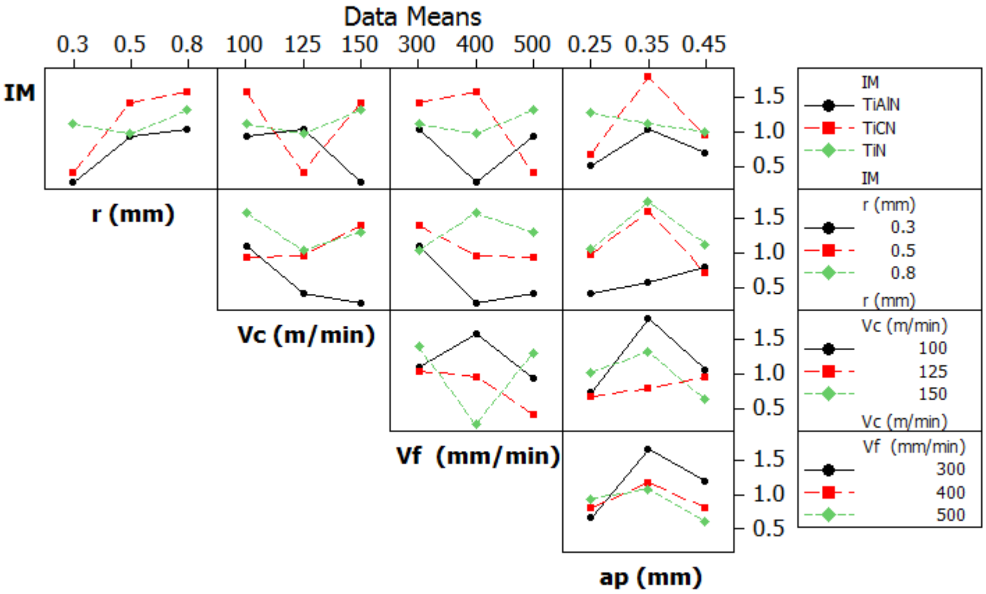


Fig. 4 Interaction plot for Ra

Analysis of results in Figure 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 0.3mm to 0.5mm; 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.

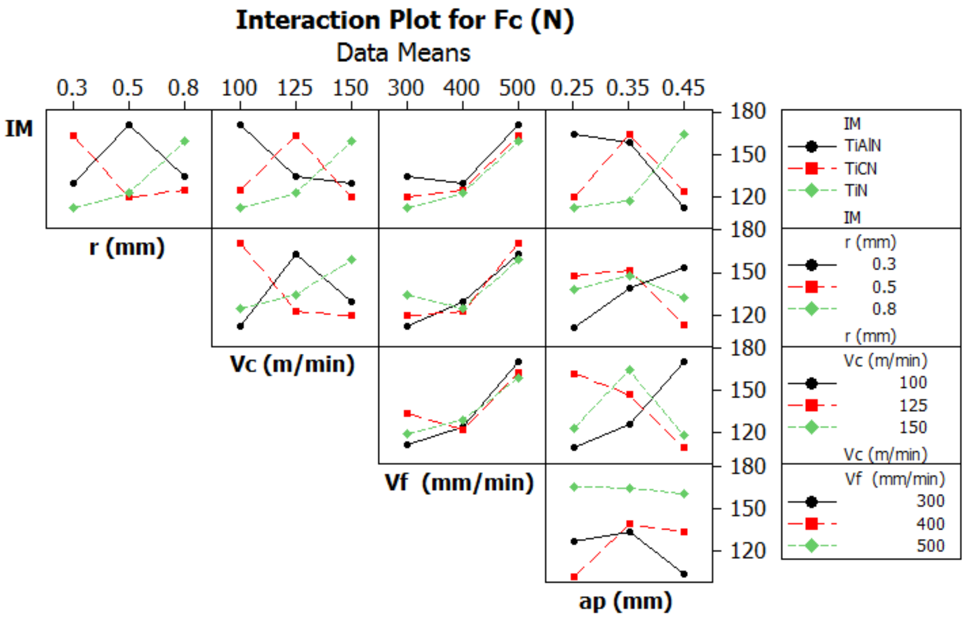


Fig. 5 Interaction plot for Fc

Analysis of results in Figure 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 0.25mm to 0.35mm; 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 4 shows that surface roughness has the smallest value in experiment #20 ($Ra = 0.175\ \mu m$), while cutting force has the smallest value in experiment #27 ($Fc = 58.590\ N$) and *MRR* has the maximum value in experiment #9, #12 and #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.

V. Multi-objective optimization by RIM

From the experimental data in Table 4, it shows that the minimum and maximum values of *Ra* are 0.175 µm and 2.619 µm, respectively; Minimum and maximum value of *Fc* 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]

From the data in Table 4, it also shows that surface roughness has minimum value of 0.175 µm, *Fc* 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 we have:

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

By applying equation (1), it can determine ideal reference interval of *Ra*, *Fc* and *MRR*. By applying equation (2), it can determine normalized values of *Ra*, *Fc* and *MRR*. By applying equations (3) to (7), it can calculate values of the parameters of I_i^+ and I_i^-, where weights of *Ra*, *Fc* and *MRR* have equal values, which mean that: $w_1 = w_2 = w_2 = 1/3$. All these values are shown in Table 5.

By applying equation (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 6.

Table 5. Parameters in the RIM

No.	d_{min} (Ra, [C, D])	d_{min} (Fc, [C, D])	d_{min} (MRR, [C, D])	f (Ra)	f (Fc)	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

Table 6. Ranking of the options

No.	IM	r (mm)	V_c (m/min)	V_f (mm/min)	a_p (mm)	Ra (µm)	Fc (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

Results in Table 6 show that experiment #12 is the best of the 27 experiments that have been performed, while experiment #14 is the worst. Value of *MRR* in experiment #12 (equal to value of *MRR* in experiment #9 and #24) equal to 3150 mm^3/min is the maximum value out of a total of 27 experiments. Value of cutting force *Fc* in experiment #12 is 148,560 N, ranked 14^{th} out of 27 experiments. Value of *Ra* in Experiment #12 is 0.679µm, which is quite a small value of the 27 conducted experiments (ranked 9^{th}). Although *Ra* and *Fc* in experiment #12 are not minimum values among the 27 experiments. But for the purpose of finding that experiment with *Ra* is considered "minimum", *Fc* is considered "minimum" and *MRR* is considered "maximum", it can also be said that experiment #12 is the best option. Therefore, optimum values of the input parameters are: 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.

VI. Conclusion

This study conducted the SKD11 steel milling experiment. Insert material type, tool nose radius, cutting speed, feed rate and cutting depth were selected as the input parameters of the experiment. Three parameters were selected as the output parameters of experimental process including surface roughness, cutting force and *MRR*. From the experimental results, it is determined the influence of the input parameters on the output parameters. RIM has been applied to solve multi-objective problem. Some of the conclusions drawn from this study are as follows:

- For surface roughness: tool nose radius is the most influential parameter, followed by influence of insert material, feed rate, 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 influence of insert material. 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 purpose of multi-objective optimization of SKD11 steel milling process in this study. This method also promises to be successful when applied for multi-objective optimization of milling other materials or when being applied of multi-objective optimization of other machining methods.

REFERENCES

[1]. Sunilkumar S. Panshetty, Parag V. Bute, Rohit R. Patil, Jitendra B. Satpute, *Optimization of Process Parameters in Milling Operation by Taguchi's Technique using Regression Analysis*, International Journal of Science Technology & Engineering, Vol. 2, No. 11, 2016, pp. 130-136.

[2]. Pratyusha J, Ashok kumar.U, Laxminarayana .P, *Optimization of Process Parameters for Milling Using Taguchi Methods*, International Journal of Advanced Trends in Computer Science and Engineering, Vol. 2, No. 6, 2013, pp. 129-135.

[3]. Çağrı Vakkas Yildirim, Turgay Kivak, Fehmi Erzincanli, İlyas Uygur, Murat Sarikaya, *Optimization of MQL Parameters Using the Taguchi Method in Milling of Nickel Based Waspaloy*, Gazi University - Journal of Science, Vol. 30, No. 2, 2017, 173-186

[4]. Sourabh Kuamr Soni, Dr S.K.Moulick, *Optimization of Milling Process Parameter for Surface Roughness of Inconel 718 By Using Taguchi Method*, International Journal for Scientific Research & Development, Vol. 2, No. 11, 2015, pp. 57-63.

[5]. ZHOU Jingwen, CHEN Yan, FU Yucan, XU Jiuhua, HU Andong, LIU Siqi, *Optimization of milling parameters of CFRP for surface roughness using Taguchi design method*, Advanced Materials Research, Vol. 4, 2014, pp. 76-79, doi:10.4028/www.scientific.net/AMR.1027.76

[6]. Avinash A. Thakre, *Optimization of Milling Parameters for Minimizing Surface Roughness Using Taguchi's Approach*, International Journal of Emerging Technology and Advanced Engineering, Vol. 3, No. 6, 2013, pp. 226-230.

[7]. Tasleem Ahmad, Noor Zaman Khan, Zahid A. Khan, *Optimization Of End Milling Process Parameters On Surface Roughness Using Taguchi Method*, International Journal of Scientific & Engineering Research, Vol. 8, No. 7, 2017, pp. 190-194.

[8]. Prachi Londhe, Chilwant, *Optimization of cutting parameters in milling operation to improve surface finish of EN 31*, International journal of engineering sciences & management research, Vol. 3, No. 9, 2016, pp. 1-9, doi: 10.5281/zenodo.61609

[9]. The-Vinh Do, Ngoc-Chien Vu, Quoc-Manh Nguyen, *Optimization of cooling conditions and cutting parameters during hard milling of AISI H13 steel by using Taguchi method*, IEEE International Conference on Advanced Manufacturing, 2018, pp. 396-398, doi: 10.1109/AMCON.2018.8615057

[10]. W. D. Lestari, R. Ismail, J. Jamari, A. P. Bayuseno, *Optimization of CNC milling parameters through the Taguchi and RSM methods for surface roughness of UHMWPE acetabular cup*, International Journal of Mechanical Engineering and Technology, Vol. 10, No. 2, 2019, pp. 1762–1775.

[11]. Pinki Maurya, Dr. Pankaj Sharma, Bijendra Diwaker, *Implementation of Taguchi methodology to Optimization of CNC end milling process parameters of AL6351–T6*, International Journal of Modern Engineering Research, Vol. 2, No. 5, 2012, pp-3530-3533.

[12]. S. Zhang, Y. B. Guo, *Design Optimization of Cutting Parameters using Taguchi Method and ANOVA During High-speed Machining Hardened H13 Steel*, Materials Science Forum, Vol. 626-627, 2009, pp. 129-134, doi:10.4028/www.scientific.net/MSF.626-627.129

[13]. Vishal Parashar, Rajesh Purohit, *Investigation of the effects of the Machining Parameters on Material Removal Rate using Taguchi method in End Milling of Steel Grade EN19*, Materials Today: Proceedings, Vol. 4, 2017, pp. 336–341.

[14]. Anil Antony Sequeira, Ravikantha Prabhu, N.S.Sriram, Thirumaleshwara Bhat, *Effect of Cutting Parameters on Cutting Force and Surface Roughness of Aluminium Components using Face Milling Process - a Taguchi Approach*, IOSR Journal of Mechanical and Civil Engineering, Vol. 3, No. 4, 2012, pp. 7-13.

[15]. P Giridhar Reddy, S Gowthaman, T Jagadeesha, *Optimization of Cutting Parameters Based on Surface Roughness and Cutting Force During End Milling of Nimonic C-263 Alloy*, IOP Conf. Series: Materials Science and Engineering, Vol. 912 , 2020, 032020, doi:10.1088/1757-899X/912/3/032020

[16]. Mustafa Günay, Alaattin Kaçal, Yakup Turgut, *Optimization of machining parameters in milling of Ti-6Al-4V alloy using Taguchi method*, Journal of New World Sciences Academy, Vol. 6, No. 1, 2011, pp. 428-440.

[17]. B. Vijaya Krishna Teja, N. Naresh, K. Rajasekhar, *Multi-Response Optimization of Milling Parameters on AISI 304 Stainless Steel using Grey-Taguchi Method*, International Journal of Engineering Research & Technology, Vol. 2, No. 8, 2013, pp. 2335-2341

[18]. Djordje CICA, Halil CALISKAN, Peter PANJAN, Davorin KRAMAR, *Multi-objective Optimization of Hard Milling Using Taguchi Based Grey Relational Analysis*, Tehnički vjesnik, Vol. 27, No. 2, 2020, pp. 513-519, doi: 10.17559/TV-20181013122208

[19]. Rachmadi Norcahyo, Bobby O.P Soepangkat, *Optimization of Multi Response in End Milling Process of ASSAB XW-42 Tool Steel with Liquid Nitrogen Cooling Using Taguchi-Grey Relational Analysis*, AIP Conference Proceedings, Vol. 1855, 2017, doi :10.1063/1.4985456

[20]. Kanchana J, Prasath V, Krishnaraj V, Geetha Priyadharshini B, *Multi response optimization of process parameters using grey relational analysis for milling of hardened Custom 465 steel*, Procedia Manufacturing, Vol. 30, 2019, pp. 451–458, doi: 10.1016/j.promfg.2019.02.064

[21]. M.P. Jenarthanan, R. Jeyapaul, *Optimisation of machining parameters on milling of GFRP composites by desirability function analysis using Taguchi method*, International Journal of Engineering, Science and Technology, Vol. 5, No. 4, 2013, pp. 23-36, doi: 10.4314/ijest.v5i4.3

[22]. M.P. Jenarthanan, R Gokulakrishnan, B Jagannaath, P Ganesh Raj, *Multi objective optimization in endmilling of GFRP composites using taguchi techniques with principal component analysis*, Multidiscipline Modeling in Materials and Structures , Vol. 13, No. 1, 2017, doi: 10.1108/MMMS-02-2016-0007

[23]. Yusuf Fedai, Funda Kahraman, Hediye Kirli Akin, Gokhan Basar, *Optimization of machining parameters in face milling using multi-objective Taguchi technique*, Technical journal, Vol. 12, No. 2, 2018, pp. 104-108, doi: 10.31803/tg-20180201125123

[24]. Tran Minh Duc, Pham Quang Dong, Tran The Long, Dang Van Thanh, Evaluation of MQCL Technique Using MoS2 Nanofluids During Hard Milling Process of SKD 11 Tool Steel, International Journal of Mechanical Engineering and Applications, Vol. 7, No. 4, 2019,pp. 91-100, doi: 10.11648/j.ijmea.20190704.11

[25]. Thi-Bich Mac, Banh Tien Long, Duc-Toan Nguyen, Optimization of Surface Roughness and Vibration During Thermal-Assisted Milling SKD11 Steel Using Taguchi Method, Advanced Materials, Springer Proceedings in Materials, Vol. 6, 2020, pp. 271-282, doi: 10.1007/978-3-030-45120-2_23

[26]. Tran Minh Duc, Tran The Long, Effects of MQL and MQCL Parameters on Surface Roughness in Hard Milling of SKD 11 Tool Steel, SSRG International Journal of Mechanical Engineering, Vol. 7, No. 10, 2020, pp.28-31, doi:10.14445/23488360/IJME-V7I10P106

[27]. Xavierarockiaraj.S, Kuppan.P, Investigation of cutting forces, surface roughness and tool wear during Laser assisted machining of SKD11 tool steel, Procedia Engineering, Vol. 97, 2014, pp.1657 – 1666, doi: 10.1016/j.proeng.2014.12.316

[28]. Pham Quang Dong, Tran Minh Duc and Tran The Long, *Performance Evaluation of MQCL Hard Milling of SKD 11 Tool Steel Using MoS2 Nanofluid*, Metal, Vol. 9, No. 658, 2019, pp.1-16, doi:10.3390/met9060658

[29]. Apichad Inkhamnoi, Komson Jirapattarasilp, *Effect of Milling Parameters and Coolants on Surface hardness of Tool Steel: SKD 11*, Advanced Materials Research, Vol 650, 2013, pp. 596-601, doi:10.4028/www.scientific.net/AMR.650.596

[30]. D.D. Trung, N.V. Thien, N.-T. Nguyen, *Application of TOPSIS Method in Multi-Objective Optimization of the Grinding Process Using Segmented Grinding Wheel*, Tribology in Industry, 2021, doi: 10.24874/ti.998.11.20.12

[31]. S. Nguyen Hong, U. Vo Thi Nhu, *Multi-objective Optimization in Turning Operation of AISI 1055 Steel Using DEAR Method*, Tribology in Industry, 2021, doi: 10.24874/ti.1006.11.20.01

[32]. Nhu-Tung Nguyen, Do Duc Trung, *Combination of Taguchi method, Moora and Copras technique in multi-objective optimization of surface grinding process*, Journal of Applied Engineering Science, 2021, doi:10.5937/jaes0-28702

[33]. E. Cables Perez , M.T. Lamata , J.L. Verdegay, *RIM-Reference Ideal Method in Multicriteria Decision Making*, Information Sciences, vol. 337-338, No. 10, pp. 1-10, 2016, doi: 10.1016/j.ins.2015.12.011

[34]. J.M. Sánchez-Lozano, O. Naranjo Rodríguez, *Application of Fuzzy Reference Ideal Method (FRIM) to the military advanced training aircraft selection*, Applied Soft Computing Journal, Vol. 88, No. 106061, 2020, pp. 1-12, doi: 10.1016/j.asoc.2020.106061

[35]. Mehmet Alper SOFUOĞLU, R. Aykut ARAPOĞLU, Sezan ORAK, *Multi objective optimization of turning operation using hybrid decision making analysis*, Anadolu University Journal of Science and Technology A- Applied Sciences and Engineering, Vol. 18, No. 3, 2017, pp. 595- 610.