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MULTI-OBJECTIVE OPTIMIZATION OF THE CYLINDRICAL GRINDING PROCESS OF SCM440 STEEL USING PREFERENCE SELECTION INDEX METHOD

This paper presents a study to ensure the minimum values of *Ra and Rz*, and the maximum value of MRR when external cylindrical grinding by the *PSI* method. The experiments were performed according to the orthogonal Taguchi L9 matrix with the input parameters including workpiece speed, feed rate, and depth of cut in the conventional grinding machine. Analysis of experimental results by Pareto chart showed that the feed rate and the depth of cut most influence on *Ra* and *Rz*, respectively. Feed rate and depth of cut all have a great influence on MRR. Meanwhile, the workpiece speed has a negligible effect on all three output parameters. The research results showed that to obtain the minimum values of *Ra* and *Rz*, and maximum of MRR, the workpiece speed, feed rate, and depth of cut were 400 rev/min 37.7 mm/min, 0.09 mm/rev, and 0.02 mm, respectively.

NOMENCLATURE

Ra: The arithmetical mean deviation of the assessed profile
Rz: The minimum value of the profile maximum height
n: Workpiece speed
f: Feed rate
a_r: Depth of cut
PSI: The preference selection index method
MRR: Material removal rate
GRA: Gray relational analysis method
MOORA: Multi-objective Optimization on the basis of ratio analysis
DEAR: The data envelopment analysis-based ranking
TOPSIS: Preference by similarity to the ideal solution
COPRAS: Complex proportional assessment
VIKOR: Vlsekriterijumska optimizacija i kompromisno resenje in Serbian

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1. INTRODUCTION

Grinding is often chosen as a finish machining for the surface with a high requirement for accuracy and with small surface roughness [1]. Therefore, the parameters of the surface quality of the machine parts when grinding are especially interested. Several parameters of the surface properties of the part, such as wear resistance, fatigue strength, chemical corrosion resistance, and joint strength (for tight joints), are directly affected by surface roughness. Therefore, surface roughness is a very important parameter.

Many experimental studies have been carried out by many authors to determine the values of process parameters to ensure the small value of surface roughness. In all the studies as analysed below, the authors have built the experimental matrix according to the Taguchi method and then used the S/N ratio analysis method to determine the optimal value. of the input parameters. When grinding Al/SiC materials with aluminium oxide wheels, the authors of the study [2] selected cutting speed, workpiece velocity, feed rate and depth of cut as input parameters of the experimental process. experience. They have shown that to ensure minimum surface roughness, and the cutting speed is 2639 m/min, the part velocity is 26.72 m/min, the feed rate is 0.06 m/min, and the depth of cut is 0.3 mm.

Reference [3] presented the optimization process of the cylindrical grinding of the EN353 steel by aluminium oxide grinding wheel. The authors of this study selected input parameters including wheel speed, feed rate and depth of cut. They have shown that, for minimum surface roughness, the wheel speed is 2000 rev/min (41.88 m/s), the feed rate is 125 mm/min, and the depth of cut is 0.14 mm. The aluminium oxide wheel has also been used to grinding AISI 4150 steel [4]. In this study, the input parameters including wheel speed, abrasive grain size and depth of cut were selected. This study has shown that in order to have the minimum surface roughness when workpiece speed of 600 rev/min (43.35 m/min), the grain size of 100, and depth of cut of 0.02 mm.

In reference [5], the cylindrical grinding process of EN 19 steel was conducted by an aluminium oxide grinding wheel. The wheel repair depth, feed rate (drag angle of the dresser) and the number of movements of the wheel repair head were selected as variables during the experiment. The obtained results showed that to achieve the minimum surface roughness value, the values of dressing depth of cut, dressing cross feed rate, drag angle of the dresser, and the number of passes was 20 μm, 80 mm/min, 500, and 4, respectively. When using the aluminium oxide grinding wheel to cylindrical grind the C40E steel, the optimal values of input parameters that were determined were workpiece velocity of 210 m/min, feed rate of 0.11 mm/rev, and depth of cut of 0.04 mm. When machining with this set of optimal values, the surface roughness was the smallest [6].

In reference [7], the type of steel, workpiece speed, and depth of cut were selected as the input parameters to design the experimental matrix. Three steel types that were used in this study were EN19, EN24, and EN21, with the hardness of 40 HRC, 47 HRC, and 55 HRC, respectively. This study showed that the surface roughness was smaller when grinding the EN19 steel with the workpiece speed of 414 rev/min and depth of cut of 1 mm. In another study, when grinding EN19 steel, the authors studied the minimum surface roughness when the cutting parameters were cutting velocity of 560 m/min, feed rate of 0.12 mm/rev, and cutting depth of 0.4 μm [8]. In the grinding process of EN21 steel, if the grinding wheel speed was 1000 rev/min, the feed rate was 0.12 mm/rev, and the depth of cut was 0.04 mm, the surface roughness would be the smallest [9].

In reference [10], the workpiece velocity, depth of cut, and workpiece material (EN24 steel, EN31 steel, and EN353 steel) were chosen as the input parameters to design the experimental matrix. The obtained results showed that the surface roughness was smaller when grinding the EN353 steel with a cutting depth of 0.02 mm and a workpiece speed of 120 rev/min (workpiece diameter of 32 mm). In this study, an aluminium oxide grinding wheel was also used in the experimental process. In addition to surface texture, MRR is also a parameter, is commonly chosen by the authors as an indicator to evaluate the efficiency of the grinding process in particular and the mechanical machining processes in general. This parameter was used to evaluate the productivity of a machining process [11].

The experimental studies to determine the machining parameters to ensure the maximum value of MRR has also been carried out by many authors. Some of the studies shown below also used the Taguchi method to design the experimental matrix, and then the S/N ratio analysis method was also used to solve the optimization problem. [12] The study has selected the wheel speed, workpiece speed, feed rate and depth of cut as input parameters when grinding EN15AM steel. Aluminium oxide grinding wheels were also used in this study. They eventually determined that if they wanted the maximum MRR, then the grinding wheel speed, workpiece speed, feed rate, and depth of cut were 1800 rev/min, 155 rev/min, 275 mm/rev, and 0.04 mm, respectively. The optimization process when cylindrical grinding the AISI 316 steel using an aluminium oxide grinding wheel was performed and presented in reference [13]. The workpiece velocity, feed rate, and depth of cut is input parameters. In this study, the MRR was largest when the values of workpiece velocity, feed rate, and depth of cut were 560 m/min, 0.13 mm/rev, and 0.005 mm, respectively.

In reference [14], the optimization process was performed when the cylindrical grinding process of the AISI 1045 steel. The input parameters of grinding wheel speed, workpiece speed, grinding grain types (including Black aluminium oxide – A 60B, White aluminium oxide – A60W, and Green silicon carbide – SIC 60G), depth of cut, the concentration of the lubricant, and the number of passes. The results showed that *MRR* was the largest value when using the A 60W grinding grain, and the values of grinding wheel speed, workpiece speed, depth of cut, the concentration of the lubricant, and the number of passes were 2640 rev/min, 250 rev/min, 0.025 mm, 5%, and two times, respectively. When cylindrical grinding the OHNS steel (equivalent to AISI 0-1 steel) by aluminium oxide grinding wheel, to achieve the maximum value of MRR, the workpiece speed, depth of cut, number of passes were 150 rev/min, 0.02 mm, and one time, respectively [15]. When cylindrical grinding the IS319 Brass material by aluminium oxide grinding wheel, to achieve the maximum value of MRR, the grinding process need to be performed with the grinding wheel of 11000 rev/min (grinding wheel diameter of 300 mm), workpiece speed of 40 rev/min (workpiece diameter of 35 mm), and cutting depth of 0.2 mm [16]. The optimal values of several parameters of grinding wheel dressing when using aluminium oxide grinding wheel to machine the 9CrSi steel were presented in reference [17]. This study showed that to achieve the maximum *MRR* then the dressing feed rate was 1.4 m/min, the coarse dressing depth was 0.025 mm, coarse dressing times was 1, fine dressing depth was 0.005 mm, fine dressing times was 3, and non-feeding dressing times was 5.

The authors of the study [18] performed the grinding of AISI 316 L steel with silicon carbide grinding wheel. In this study they chose cutting speed, feed rate and depth of cut as variables that varied in each experiment. The analysed results showed that to achieve the maximum value of MRR, the values of cutting velocity, feed rate, and depth of cut were 200 m/min, 0.3 mm/rev, and 0.3 mm, respectively. And to achieve the minimum value of *Ra*, the values of cutting velocity, feed rate, and depth of cut were 150 m/min, 0.3 mm/rev, and 0.2 mm, respectively.

The silicon carbide has been used to experiment with grinding EN19 steel [19]. The input parameters including workpiece speed, feed rate, depth of cut, and the workpiece hardness (30 HRC, 40 HRC, and 50 HRC). The obtained results showed that to achieve the maximum value of MRR, the workpiece speed, feed rate, depth of cut, and workpiece hardness were 247 rev/min, 0.18 mm/rev, 0.04 mm, and 30 HRC, respectively. And to achieve the minimum value of *Ra*, the workpiece speed, feed rate, depth of cut, and workpiece hardness were 145 rev/min, 0.06 mm/rev, 0.02 mm, and 50 HRC, respectively. The experience of grinding EN8 steel with aluminium oxide wheels has also been studied [20]. Three input parameters including cooling lubricant oil types (water-soluble oil, pure oil, and pure water), workpiece speed, and depth of cut. The workpiece diameter was 100 mm. The analysed results showed that to achieve the maximum value of MRR then the grinding process needs to be performed with the water-soluble oil, and the values of workpiece speed and depth of cut were 120 rev/min and 0.5 mm, respectively. This set of optimal values was the same as the case the optimization criterion was the surface roughness.

The SCM440 steel is capable of withstanding large loads, good wear resistance, and high impact resistance. This steel type is often used to fabricate the components with variable loads such as motor drives, gears, plastic injection moulds, rolls, etc. These products are often required a cylinder grinding process as the final machining method for some surfaces. Equivalent symbols of this steel according to some standards as follows: JIS (Japan) – SCM440; AISI (USA) – 4140; DIN (Germany) – 10083-3; GB (China) – 42CrMo; BS (UK) – 42CrMo4; NF (France) – 42CrMo4.

Several studies have been published on cylindrical grinding processes of this steel (or equivalent steel), such as determination of the values of the grinding wheel speed, workpiece speed, grind size, cutting depth, and concentration of coolant solution when grinding the AISI 4140 steel to ensure the minimum surface roughness [21]; determine the value of the workpiece speed, cutting depth and the number of slot when grinding AISI 4140 steel for minimum surface roughness [22]; Analysis of surface roughness when grinding the AISI 4140 steel [23], analysis of surface roughness when grinding SCM440 steel [24], analysis of surface roughness when grinding 42CrMo steel [25], etc. However, so far, the authors of this paper have not found any published research on the simultaneously optimizing process of the surface roughness and MRR when grinding this steel. Through the analysis of the above studies shows that:

First: the Taguchi method has been used a lot to design the experimental matrix. This is understandable as this method may only need to conduct a small number of experiments but allows for a wide selection of input parameters. In particular, this method that is the only experimental design method allows the selection of input parameters that are qualitative ones. However, the above studies also showed that if only using the Taguchi method, it is only possible to perform the single-objective optimization problem (through the analysis of the ratio *S/N*).

In order to overcome this limitation, there have been some studies combining Taguchi with another method to solve the multi-objective optimization problem in cylindrical grinding processes, such as combining the Taguchi method and Gray relational analysis method (*GRA*) for solving the multi-objective Optimization in the grinding process of stainless steel [26], multi-objective Optimization in grinding process of aluminium alloy 6061-T4 [27], etc. In terms of the optimization method, up to now, there have been many multi-objective optimization methods that were introduced as in the above studies, such as the GRA method, MOORA method, DEAR method, TOPSIS method, COPRAS method, VIKOR method, PSI method, etc. In particular, the PSI method has been used to solve the multi-objective optimization problem in some studies such as multi-objective optimizing in the design of production systems [28]. Optimize the criteria of the computer software to serve human resource management [29], determine the best factors in choosing the positions to sell the used computers (premises rentals, location, number of customers) [30], multi-objective optimizing the turning process of AA7075 material [31], etc. However, up to now, there have not been any studies that have applied the PSI method to solving the multi-objective optimization problem in the grinding process in general and the cylindrical grinding process in particular.

Second: there are many parameters affecting surface roughness and MRR, such as cutting parameters, machining material type parameters, processing parameters, the grinding wheel dressing parameters, etc. In which cutting parameters are often chosen by the authors as input parameters when doing experimental research. This is also easily understood because the adjustment of the cutting parameters will be made simply by the operator who operates the machine.

Third: Aluminum oxide grinding wheel has been used a lot in the experimental processes. This is understandable because it is a low-cost grinding wheel, and it can be used to machine a variety of workpiece materials. However, through the above-mentioned studies, it also has been shown that the optimal values of the cutting parameters when grinding different materials are not the same. Thence, it shows that for each different material, there should be specific experimental and optimization studies. So, the optimal values of the cutting parameters can be determined to ensure the minimum value of surface roughness and maximum value of MRR.

In order to inherit the advantages of the published studies, as well as fill the several gaps in the contents that have not been implemented in the published studies. In this paper, the multi-objective optimization study in the cylindrical grinding process of SCM440 steel was carried out using an aluminium oxide grinding wheel. The experimental matrix was designed according to the Taguchi method, and the PSI method was used to solve multi-objective optimization problems. The goal of this study is to determine the values of the cutting parameters to ensure the minimum value of surface roughness and maximum value of MRR. The obtained results in this study are not only directly applied to production when using the aluminium oxide grinding wheel to grind the steel SCM440, but the methodology that was presented in this study can also be applied when studying the multi-objective optimization of other machining processes.

2. PSI METHOD

PSI is a multi-objective optimization method that was first introduced in 2010. This is an approach based on the concept of *"overall preference value of attributes"*. The outstanding feature of this method is the Optimization of the objectives without assigning weights to the criteria. This method is performed according to the following steps [32]:

Step 1: Determine the objectives.
Step 2: Create a decision matrix based on the available information.
Step 3: Normalize the attributes.

$$N_{ij} = \frac{x_{ij}}{x_j^{\max}} \quad \text{for criterion as large as better} \tag{1}$$

$$N_{ij} = \frac{x_j^{\min}}{x_{ij}} \quad \text{for criterion as small as better} \tag{2}$$

Where *i* is the ordinal number of the row in the matrix (*i = 1 ÷ n*), *j* is the ordinal number of the column in the matrix (*j = 1 ÷ m*), x_{ij} is the value of the criterion in row *i* and column *j*.
Step 4: Calculate the average values of normalized data.

$$N = \frac{1}{n}\sum_{i=1}^{n} N_{ij} \tag{3}$$

Step 5: Determine the preferred values from the average values.

$$\varphi_j = \sum_{i=1}^{n}\left[N_{ij} - N\right]^2 \tag{4}$$

Step 6: Determine the deviation in the preferred value.

$$\emptyset_j = \left[1 - \varphi_j\right] \tag{5}$$

Step 7: Determine the overall preferred value for the criteria.

$$w_j = \frac{\emptyset_j}{\sum_{j=1}^{m} \emptyset_j} \tag{6}$$

Step 8: Calculate the Preference Selection Index (*PSI*) of each solution.

$$\theta_j = \sum_{j=1}^{m} x_{ij} \,.\, w_j \tag{7}$$

Step 9: Rank the solutions. Which solution has the largest value of θ_i is the best solution?

3. EXPERIMENTAL METHOD

3.1. WORKPIECE MATERIAL

The SCM440 workpieces were used in this study. The percentage of chemical components of some major elements of workpiece steel is determined by analysis on a spectrophotometer and presented in Table 1. These workpieces have the diameter and length of 30 mm and 250 mm, respectively. And these workpieces were heat-treated to reach 52HRC hardness.

Table 1. Compositions of SCM440 steel

Element	C	Si	Mn	Cr	Mo	S	P
%	0.42	0.26	0.68	1.02	0.22	0.022	0.018

3.2. GRINDING MACHINE AND GRINDING WHEEL

The experiments were conducted in the conventional grinding machine (GU32x100S of Palmary Brand, Taiwan) as described in Fig. 1. Grinding wheels that were made in Hai Duong grinding wheel factory (Hai Duong grinding wheel company, Vietnam) was used in this study. The grinding wheel has the designation *Cn80-G-V-280-40-115-35 m/s*, where *Cn* reflects the grinding wheel grain material as aluminium oxide, *G* reflects the binder as ceramic, *V* reflects the grinding wheel type as cylinder grinding wheel, 280 is the outer diameter of the grinding wheel, 40 is the thickness of the grinding wheel, 115 is the hole diameter of the grinding wheel. According to the manufacturer's recommendation, for this type of grinding wheel, the maximum usable cutting velocity is 35 m/s. The grinding wheel with grinding wheel grain material (*Cn*) and binder (*G*) as the one used in this study is one of the most common grinding wheel types is used for grinding steel in a variety of grinding methods such as cylinder, surface, centreless grinding, etc. [33].

Fig. 1. Grinding machine

3.3. EXPERIMENTAL DESIGN

In this study, three parameters that were selected as the input parameters were workpiece speed (n), feed rate (f), and depth of cut (a_r). Each parameter has three values corresponding to the three coding levels of –1, 0, and 1. The values of the input parameters were chosen according to the recommended range of the grinding wheel type using in this study for grinding the alloy steel [34], as presented in Table 2. The experimental matrix that was designed according to the Taguchi method was the orthogonal L_9 matrix, as listed in Table 3.

Table 2. Input parameters and values at their level

Parameter	Symbol	Unit	Value at level		
			1	2	3
Workpiece speed	n	rev/min	400	600	800
Feed rate	f	mm/rev	0.05	0.075	0.09
Depth of cut	a_r	mm	0.01	0.015	0.02

Table 3. Orthogonal matrix L_9

No.	Code value			Actual value		
	n	f	a_p	n (rev/min)	f (mm/rev)	a_r (mm)
1	1	1	1	400	0.05	0.01
2	1	2	2	400	0.075	0.015
3	1	3	3	400	0.09	0.02
4	2	1	2	600	0.05	0.015
5	2	2	3	600	0.075	0.02
6	2	3	1	600	0.09	0.01
7	3	1	3	800	0.05	0.02
8	3	2	1	800	0.075	0.01
9	3	3	2	800	0.09	0.015

3.4. MEASUREMENT SYSTEM

The machining surface roughness (*Ra* and *Rz*) were measured using SJ-301 surface tester of Mitutoyo (Japan). The machine code is 178-953-2, the stylus tip code is 178-390, and the stylus tip radius is 5 μm. The standard length of each measurement was fixed at 0.8 mm. Each experimental piece was measured at least three times. Surface roughness at each experiment is calculated by the average of the successive measurements. The reason for this study to choose both *Ra* and *Rz* to evaluate surface roughness is because *Ra* and *Rz* are two of the most popular parameters to evaluate surface roughness. However, since there is no mathematical relationship between *Ra* and *Rz*, it is possible that some surface has large *Ra*, but *Rz* is small and vice versa. Therefore, to have a more comprehensive view of surface roughness, it is necessary to examine both of these parameters [35, 36]. *MRR* is calculated as the material removal per minute. This parameter is calculated by subtracting the volume of the workpiece before grinding to the volume from the workpiece after grinding and dividing it by the grinding time. Where the grinding time is calculated by the length of the grinding divided by the displacement speed of the grinding wheel (the feed rate).

3.5. GRINDING CONDITIONS

The experiments were performed in machining conditions as follows: The spindle speed was 1750 rev/min (corresponding to 25.65 m/s); the grinding wheel is dressed by a dressing tool with one diamond grain, the dressing depth is 0.01 mm, the dressing feed rate is 120 mm/min; the cooling lubricant that is used in the experimental process is industrial oil N-600 (made in Vietnam) with the concentration of 12% and the flow of 16 litres/min. These values have been selected according to the grinding wheel manufacturer's recommendation.

4. RESULTS AND DISCUSSION

The experiments were carried out in the order of the experiments as listed in Table 3, measuring the surface roughness of machining parts and calculating the MRR for each experiment measured and calculated results are presented in Table 4.

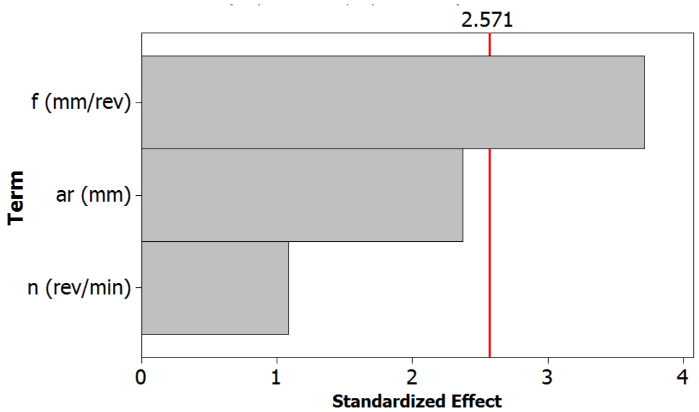
Table 4. Experimental results

No.	n (rev/min)	f (mm/rev)	a_r (mm)	Ra (µm)	Rz (µm)	MRR (mm^3/min)
1	400	0.05	0.01	0.51	2.06	82.439
2	400	0.075	0.015	0.73	4.52	105.976
3	400	0.09	0.02	0.59	4.24	169.533
4	600	0.05	0.015	0.38	1.77	70.650
5	600	0.075	0.02	0.42	3.53	141.277
6	600	0.09	0.01	0.76	2.12	84.795
7	800	0.05	0.02	0.39	2.35	94.185
8	800	0.075	0.01	0.59	1.97	70.662
9	800	0.09	0.015	0.64	3.18	127.171

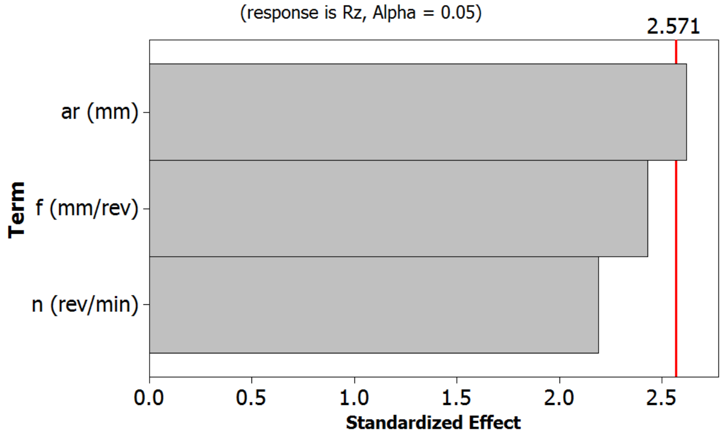
Figure 2 present the Pareto graphs about the influence of the input parameters on the output parameters with the chosen significance level by 0.05. Then the limit line of the Parate chart (red line) is equal to 2.571. The plot (horizontal gray line) of a parameter that exceeds this limit is considered to have a significant effect on the output. Accordingly, it is shown in Fig. 2a that the feed rate is a parameter that has a significant influence on *Ra*. This means that this parameter has a significant effect on *Ra*. The workpiece speed and cutting depth have a negligible effect on *Ra*. For *Rz*, only the depth of cut that is the parameter has a significant influence on *Rz*, as shown in Fig. 2b. This can be explained that when the feed rate changes, it will change the degree of the scratching of the grinding grains on the workpiece surface, thereby affecting on the surface roughness. This is an issue that was discussed in several published studies [33, 37]. When changing the depth of cut, it will change the amount of heat that was generated and transferred to the workpiece during the grinding process. The change in the amount of heat transferred to the workpiece will change the plastic deformation of the surface metal layer, which is the reason for the change in surface roughness [38, 39].

The two parameters, including cutting depth and the feed rate, are directly related to the volume of the material removed from the workpiece surface in a unit of time. In this case, if vibration and elastic deformation (of the grinding wheel and workpiece) arising from the grinding process are ignored, the depth of cut is the thickness of the removed material. At the same time, the feed rate has a direct influence on the time to complete the entire length of the workpiece. Therefore, the depth of cut and the feed rate has a significant influence on the MRR. This result is completely consistent when observing Fig. 2c. The results in this figure also showed that the workpiece velocity has a negligible effect on the MRR.

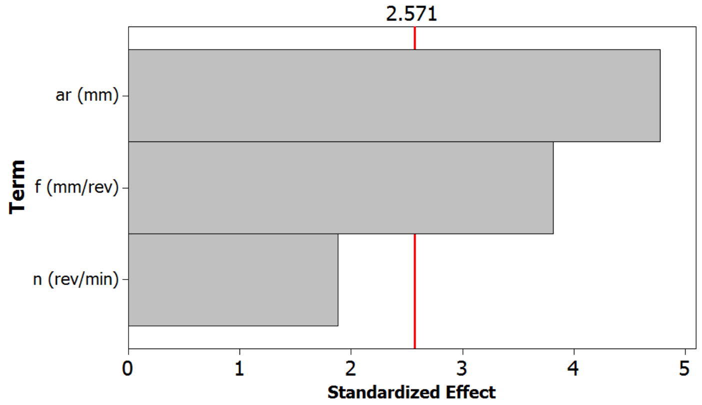
As such, it is clear that the influence degrees of the input parameters on the output parameters are not the same. Therefore, it is very difficult to select the values of the input parameters to ensure the objectives of the output parameters (minimum *Ra* and *Rz*, largest *MRR*). On the other hand, observing data in Table 4 shows that: MRR has the largest value in experiment # 3, while *Ra* has the smallest value in experiment # 4, while *Rz* has the smallest value in experiment # 4. Therefore, it is necessary to perform multi-objective Optimization to find the experiment where MRR is considered to be "maximum", *Ra* and *Rz* are considered to be "minimum".



a. Influence of input parameters on *Ra*



b. Influence of input parameters on *Rz*



c. Influence of input parameters on MRR

Fig. 2. Pareto diagram about Influence of the input parameters on the output parameters

5. MULTI-OBJECTIVE OPTIMIZATION USING PSI METHOD

The performing steps according to the PSI method were presented in detail in Chapter 2. The application of the PSI method in this study was performed as follows.

Step 1**:** Determine the objectives. The objectives of this study are the determination of the best solution in the solutions as listed in Table 4. At that solution (experiment), *Ra* and *Rz* are considered "minimum", and MRR is considered "largest".

Step 2: Create a decision matrix based on the available information. From the data in Table 4, the last three columns form a 9-row 3-column matrix, which is the matrix where we need to identify the row considered "best" in 9 rows.

Step 3: The standardization values of the attributes were calculated by Eq. (1) and Eq. (2). These values were calculated and listed in Table 5.

Step 4: The average values of normalized data were calculated by Eq. (3). These values were also listed in Table 5.

Step 5: Determine the preferred values from the average values by Eq. (4): $\varphi_{Ra} = 0.2933$; $\varphi_{Rz} = 0.4099$; $\varphi_{MRR} = 0.3259$.

Step 6: Determine the deviation in the preferred value by Eq. (5): $\varnothing_{Ra} = 0.7067$; $\varnothing_{Rz} = 0.5901$; $\varnothing_{MRR} = 0.6741$.

Step 7: Determine the overall preferred value for the criteria by Eq. (6): $w_{Ra} = 0.3586$; $w_{Rz} = 0.2994$; $w_{MRR} = 0.3420$.

Step 8: Calculate the Preference Selection Index θ (PSI) of each solution by Eq. (7). These calculated results were presents in Table 6.

Step 9: Rank the solutions as presented in Table 6.

Table 5. Standardization value of the attributes

No.	*Ra* (µm)	*Rz* (µm)	MRR (mm^3/min)	N_{Ra}	N_{Rz}	N_{MRR}
1	0.51	2.06	82.439	0.7451	0.8592	0.4863
2	0.73	4.52	105.976	0.5205	0.3916	0.6251
3	0.95	4.24	169.533	0.6441	0.4175	1.0000
4	0.38	1.77	70.650	1.0000	1.0000	0.4167
5	0.59	3.53	141.277	0.9048	0.5014	0.8333
6	0.76	2.12	84.795	0.5000	0.8349	0.5002
7	0.39	2.35	94.185	0.9744	0.7532	0.5556
8	0.59	1.97	70.662	0.6441	0.8985	0.4168
9	0.64	3.18	127.171	0.5938	0.5566	0.7501
Mean				0.6691	0.6903	0.6205

Table 6. Values of θ in PSI and ranking

No.	*Ra* (µm)	*Rz* (µm)	*MRR* (mm^3/min)	θ	Ranking
1	0.51	2.06	82.439	28.9938	7
2	0.73	4.52	105.976	37.8589	4
3	0.59	4.24	169.533	59.4613	1
4	0.38	1.77	70.650	24.8285	9

5	0.42	3.53	141.277	49.5242	2
6	0.76	2.12	84.795	29.9072	6
7	0.39	2.35	94.185	33.0547	5
8	0.59	1.97	70.662	24.9678	8
9	0.64	3.18	127.171	44.6741	3

From the ranked results in Table 6, it shows that experiment # 3 is the best experiment of 9 experiments, besides that experiment # 4 is the worst experiment. In experiment # 3, it is clear that *MRR* has the largest value in 9 experiments (*MRR = 169,533* mm^3/min), *Ra* is 0.59 µm, smaller than the value of *Ra* in experiment # 2, # 6 and # 9, *Rz* is 4.24 µm, this value is quite large, it is only smaller than the value of *Rz* in experiment # 2. Although *Ra* and *Rz* in experiment # 3 are not the minimum values in 9 experiments, for the purpose of multi-objective Optimization, it can be confirmed that experiment # 3 is the "best" solution.

6. CONCLUSION

In this study, the cylindrical grinding experiments were performed to machine the SCM440. Three parameters that were chosen as the input parameters were workpiece speed, feed rate, and depth of cut. *Ra*, *Rz*, and MRR were selected as the output parameters of the experimental process. The analysing process of experimental data has determined the influence degree of input parameters on the output parameters. PSI method was applied to solve the multi-objective optimization problem. Several conclusions are drawn from this study as follows:

1. The workpiece speed has a negligible influence on all three parameters, including *Ra*, *Rz*, and MRR. The feed rate has a large effect on *Ra* and MRR but has a negligible effect on *Rz*. The depth of cut has a great influence on *Rz* and MRR but has a negligible effect on *Ra*.
2. The cutting parameters that were applied to simultaneously obtain the minimum value of *Ra*, the minimum value of *Rz*, and the maximum of MRR were workpiece of 400 rev/min, feed rate of 0.09 mm/rev, and cutting depth of 0.02 mm.
3. PSI is a quite simple multi-objective optimization method. When applying this method, only need to perform through nine simple mathematical equations sequentially. Therefore, this method has been applied in several studies. This is the first time that the PSI method was successfully applied to solve the multi-objective Optimization in the cylindrical grinding process. This is a method that promises to be successful when applied to solve the multi-objective problem in different machining methods.
4. This study only shows the best value among the surveyed value levels of the input parameters. In fact, the value at a level that is considered best may not be the best value for that parameter. In addition, many parameters affecting the efficiency of the grinding process have not been considered, such as grinding wheel dressing parameters, cooling and lubrication parameters, etc. These are necessary issues to be performed in the next research to complete the evaluation of the grinding process of the SCM440 steel.

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