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MODELLING OF SURFACE ROUGHNESS AND TOOL WEAR WHEN FINISH MILLING PROCESS OF THE CIRCULAR BEVEL GEAR

An experimental process to build the models of surface roughness and tool wear in the finish milling of the Gleason circular bevel gears was carried out in this study. The experiments were conducted according to a Box-Behnken matrix. Three cutting parameters were adjusted in each experiment including cutting speed, feed rate, and depth of cut. From the experimental results, the influences of cutting parameters on the surface roughness and tool wear were analysed in detail. Two models of surface roughness and tool wear were established with high accuracy. The optimal values of the cutting parameters were also determined to simultaneously ensure the minimum values of two output parameters. The further research directions were also suggested at the end of this study.

1. INTRODUCTION

Types of gears in general and circular bevel gears in particular are parts that are used very commonly in machine structures. Circular bevel gears are used to transmit the motion between two intersecting/non-intersecting axes in the space. This gear type is widely used in automobiles, tractors, ships, and aviation [1, 2]. Because the size of the tooth profile changes with the length of the tooth, the shaping of the surface of the curved bevel tooth is very complicated. The machining principle of the circular bevel gears is different when using different equipment types from different manufacturers. Therefore, curved bevel gears are also divided into many types according to the names of equipment manufacturers (machines) to process them such as Gleason system circular bevel gears [3], Klingelnberg system circular bevel gears [4, 5], Oerlicon system circular bevel gears [6]. etc. Among them, the Gleason system circular bevel gear is the most commonly used [1].

In addition to depending on the type of used equipment, the efficiency of the circular bevel gear machining process also depends on many factors such as machining methods, technological parameters, etc. [7, 8]. There are many machining methods for circular bevel

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gears such as the one-sided cutting method, the two-sided cutting method, the fixed mounting method, and the double-side cutting method [7, 8]. In particular, the two-sided cutting method is most commonly used because this method limits the use of many tool heads, the machining accuracy is high, the contact area of the gear pair is well matched, and the productivity is high, etc [7]. In summary, from the above analysis, it is shown that the Gleason system circular bevel gear that is machined by the two-sided cutting method is the most commonly used type.

Similar to other circular bevel gears, Gleason system circular bevel gears have outstanding advantages such as large load capacity, quiet operation, low impact, and large transmission ratio. These characteristics of circular bevel gears are increasingly demanded when they are used in mechanisms with high precision requirements [1]. In addition to those requirements, the surface roughness of the tooth flank and tool wear when machining circular bevel gears are also the issues of great concern. Because the surface roughness of the tooth flank directly influences on the wear phenomenon and the tool life [9–11], meanwhile, the wear phenomenon not only directly affects on the tool cost but also directly affects on the machining accuracy. Therefore, reducing surface roughness and reducing tool wear are also the topic that many scholars are trying to solve [12]. It can be said that the setting requirements when machining the circular bevel gears are general requirements about the quality of the machined surface, the transmission accuracy in the working process as well as the tool cost problem, etc. To meet the above requirements, many studies have been carried out to improve the productivity and accuracy when machining the circular bevel gear transmissions. The solutions for these requirements have been implemented from the design to the machining process.

Several studies related to gear design to improve the efficiency of the machining process have been found such as simulating the tooth surface shaping process [13, 14], or analyse the tooth contact error and transmission error of bevel gear transmission in CAD environment [15]. However, these studies only performing by the software without any actual implemented activities in the manufacturing of the gears. Therefore, the accuracy of the given solution has not been evaluated. A study was carried out to apply the reverse engineering method to set up the bevel gear pair drawings and the gear pairs in the CNC milling machines [16]. However, this research only performed the fabrication of several gears without testing the product specifications. Therefore, the machining accuracy also has not been evaluated. Another study was also carried out in a virtual environment that performed simulations to optimize the design of a bevel gear pair [17]. However, the fabrication of gears according to the optimal parameters that were indicated by the simulation results has not been performed. One solution that has been proposed to improve bevel gear machining productivity is to combine the technological steps including wire cutting, laser machining, and milling [18]. This study has demonstrated the advantages of the proposed solution in improving machining productivity. However, machining accuracy and tool life have not been considered by the authors of this study. One solution that has been proposed to improve the durability of the gears and to reduce the working noise is analysis of the gear pairing [19]. This solution can be used to increase the life of the gears during the using process. It was applied for gears that were fabricated before. However, the improvement of the accuracy and life of the product has not been considered from the stage of its manufacture.

Some other studies have also been carried out to improve the accuracy of gear machining such as: designing – manufacturing the large bevel gears [20]; applying the error compensation method when grinding teeth on 6-axis CNC machines [21]; building the surface of the bevel gear based on the theory of the involute sphere, thereby forming the surface from a set of points in space [22]; applying the involute spherical theory to build the bevel tooth surface for gear processing by pressure machining [23]; applying the Litvin's spatial fit theory to describe bevel gear surfaces [24]; studying on reducing the design errors during the construction of the involute line [25]; building a mathematical model of the bevel gear mesh [26]. However, all these studies have only performed the calculations or simulations but have not performed the gear manufacturing process or checked the product specifications. Therefore, the solutions that were used in these studies also have not been verified for the accuracy in the gear fabrication.

The studies related to the machining problems in order to select the appropriate technological parameters to simultaneously ensure the criteria about surface roughness and tool wear has also attracted the attention of a number of scientists such as determining the influence of cutting parameters on tooth surface roughness [27-29]; predicting the surface roughness when machining circular bevel gears by end mills on CNC milling machines [30]; modelling the surface roughness [31], Pulsed-electrochemical honing (PECH) the tooth surface after milling process [32]; determining the influence of cutting parameters on tool wear [33, 34], predicting the tool wear (tool life) [35], etc.

Although finding the solutions to reduce surface roughness and tool wear when machining circular bevel gears have been carried out by many researchers with both experimental and theoretical methods. Among them, the experimental method is considered to be simpler and can be applied directly to production processes. However, a number of discoveries were found such as: Firstly: no experimental studies have been found to build models for both surface roughness and tool wear parameters; Secondly: the determination of the optimal value of the cutting parameters to simultaneously ensure the minimum values of surface roughness and tool wear has not been found in any published studies. This gap will be filled by this study. The next sections of this study are structured as follows: Section 2 presents the experimental process. An experimental process was carried out when changing the value of the cutting parameters while the surface roughness and tool wear were also determined in each experiment. Section 3 is the content of analysing the influence of cutting parameters on the surface roughness and tool wear, as well as building the models of these two parameters. The content of multi-objective optimization to determine the value of the cutting parameters to ensure the surface roughness and tool wear simultaneously having the minimum value will be presented in section 4. The conclusions are drawn and the works to be done in the future are the contents that closes this study.

2. EXPERIMENTAL PROCESS

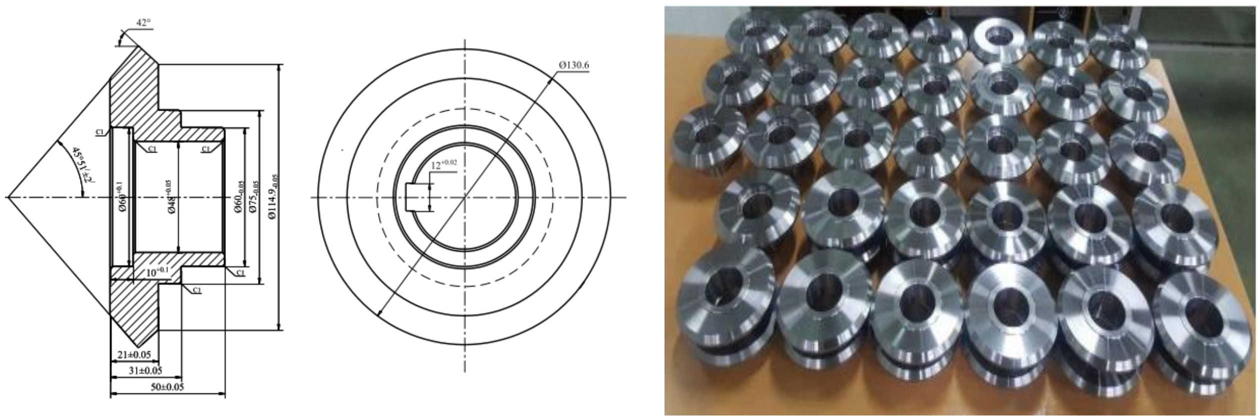
The workpiece to manufacture the gear are made from 20XM steel, which is a common material and is commonly used to manufacture the gears in general and the bevel gears in particular. After performing the analysis, the chemical compositions according to ASTM 415-

99A-2005 standard, the chemical compositions were determined by the weight of the chemiical elements of the workpiece as presented in Table 1. The hardness of the workpiece was tested on the ISH-MRD200 machine, and these workpieces reached hardness 40–42 HRC.

Table. 1. Chemical composition of the main elements of the workpiece

C	Si	Mn	Cr	Ni	Mo	Cu	S	P
0.2348	0.1930	0.6820	0.9256	0.1826	0.2367	0.1546	0.0287	0.0265

The workpieces were shaped to meet the technical requirements as shown by the drawing in Figure 1a. Figure 1b shows the images of some gear workpieces. These workpieces are used for milling the circular bevel gears with the basic parameters including the modulus at end face section of 4.5 mm, the helix angle at average cross section of 350; right twist direction; number of teeth of 27; the tooth height at the face cross section of 8,496 mm, and the gear accuracy level of 7-8-8-X (according to GOST standards - Russian Federation).



a) b)

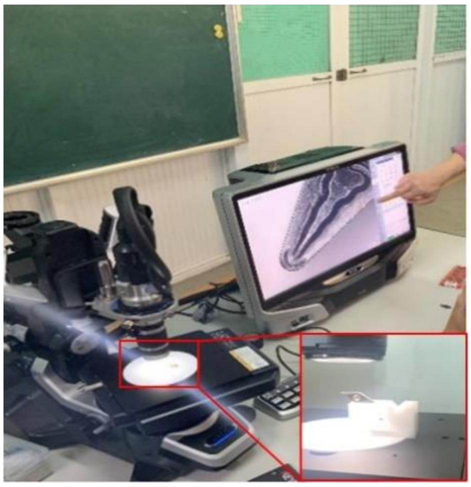
Fig. 1. Workpiece to manufacture the curved bevel gear: a) technical requirements of the workpiece, b) images of workpieces

Experiments were carried out on a gear milling machine 525 (USSR). Gleason cutting head were used during the experimental processes. The cutting inserts are coated with CVD hard alloy Ti(C,N)-Al2O3-TiN. This type of cutting insert has good thermal stability, high mechanical stability, high impact resistance, and suitable for finish cutting conditions. This material is used commonly to make cutting tools in machining in general and in gear machining in particular [36]. Each experiment used sixteen new cutting inserts to attach to cutting head. This work is done to eliminate the influence of tool wear on the evaluation of the criteria. Figure 2 shows the attachment of cutting inserts to the cutting head as well as the way they are used for gear machining.

Both surface roughness and tool wear were measured using a digital microscope VHX600 (KEYENCE - Japan) as shown in Fig. 3. This system is capable of magnifying the measured object up to 5000 times, and can measure the smallest value of 0.012 μm.

Fig. 2. The cutting Inserts in the Gleason cutting head (gear milling machine 525)

a)



b)

Fig. 3. Measurement of surface roughness and tool wear using a digital microscope (VHX600): a) measurement of surface roughness, b) measurement of tool wear

For each machined gear, the surface roughness was measured on at least three random teeth. For each tooth, measurement was performed on both convex and concave flanks. On each tooth flank, the surface roughness was also measured at least three times. it means that the surface roughness at each experiment is the average value of at least eighteen consecutive measurements to reduce random error in the measurement process. For both convex and concave flanks, the center position of the tooth flanks was chosen to measure surface roughness as shown in Fi. 4. This is the contact area of the tooth flank with the flank of the fit gear during operation. The contact time of the opposing tooth flanks at this position is the most compared to other positions, so the surface roughness at this position has a great influence on the working efficiency as well as the tooth life [1].

The new cutting tools were used in the experimental process. The tool wear was measured after the tool finished cutting all teeth of a gear. The position to measure the tool wear is the intersection area between the main cutting edge and the front cutting edge as shown in Fig. 5. In this area, the tool wear is mainly the flank wear. This parameter has a great influence on the dimensional accuracy and surface quality of the tooth flanks. This type of tool wear is also receiving the attention of many researchers [1].

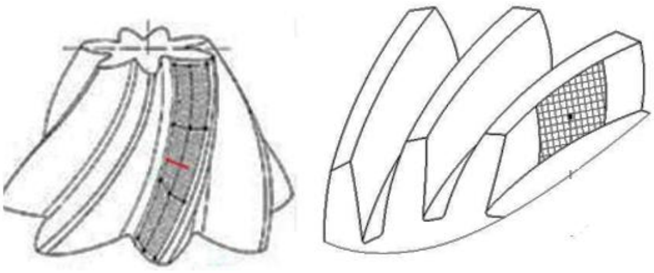


Fig. 4. Surface roughness measurement area (tooth flank)

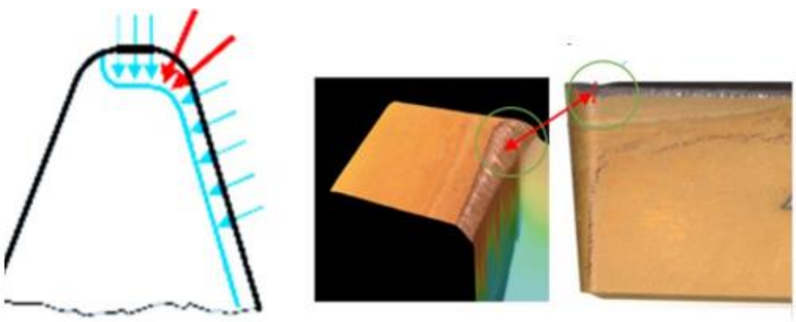


Fig. 5. Measurement position of tool wear

The experimental process is carried out according to the Box-Behnken matrix. This experimental matrix is commonly used in the optimization experimental process [37, 38]. Three input parameters were selected for adjustment in each experiment including cutting speed, feed rate, and depth of cut. Adjustment of these three parameters can be conducted quickly by the machine operator [37, 38]. Each parameter will be adjusted to three values corresponding to the coded levels –1, 0, and 1. The presentation of variables in coded form has the advantage that the experimental matrix will be clearly observed, and the regression models are also observed more clearly than the real numbers [39]. The values of these parameters were selected within their range according to several studies [1, 27, 28, 33], and were presented in Table 2.

Table 2. Values and levels of input parameters

Input parameters	Symbol	Unit	Coded	Values at the levels		
				-1	0	1
Cutting speed	v	m/min	x_1	93	117.5	142
Feed rate	f_t	s/tooth	x_2	40	50	60
Depth of cut	t	mm	x_3	0.25	0.5	0.75

The Box-Behnken experimental matrix was built using Minitab software with the number of experiments in the center of 3 (in the central experiment, all variables received the coded values of 0) [40]. The experimental matrix consists of fifteen experiments as presented in Table 3. During the experiment, the coolant that was used was produced by Vietnam (CN32 oil) with a viscosity of 32%, the irrigation flow into the cutting area of 20 litters/min.

Table 3. Experimental matrix and results

No.	Actual parameters			Coded parameters			*Ra* (μm)	*VBmax* (μm)
	v (m/min	f_t (s/tooth	t (mm)	x_1	x_2	x_3		
1	93	40	0.5	-1	-1	0	2.118	57.22
2	142	40	0.5	1	-1	0	1.528	37.42
3	93	60	0.5	-1	1	0	2.263	32.95
4	142	60	0.5	1	1	0	2.044	82.98
5	93	50	0.25	-1	0	-1	2.207	74.73
6	142	50	0.25	1	0	-1	1.499	69.42
7	93	50	0.75	-1	0	1	1.989	29.69
8	142	50	0.75	1	0	1	1.847	66.98
9	117.5	40	0.25	0	-1	-1	1.434	37.42
10	117.5	60	0.25	0	1	-1	1.923	51.25
11	117.5	40	0.75	0	-1	1	1.946	26.85
12	117.5	60	0.75	0	1	1	2.109	59.93
13	117.5	50	0.5	0	0	0	1.439	30.10
14	117.5	50	0.5	0	0	0	1.489	30.39
15	117.5	50	0.5	0	0	0	1.489	30.24

3. RESULTS AND DISCUSSION

The measured data about the surface roughness and tool wear at each experiment were stored in Table 3. Figs 6 and 7 show the influence of input parameters on the output parameters.

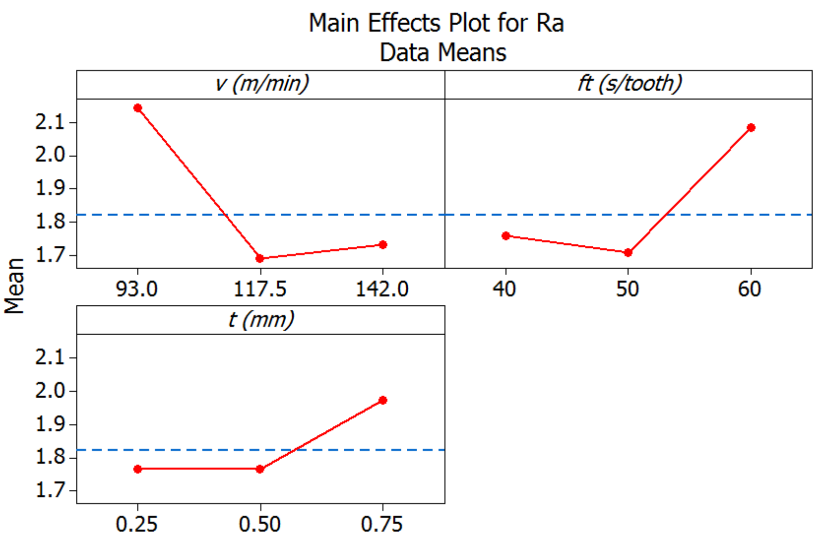


Fig. 6. Influence of cutting parameters on the surface roughness

The results from Fig. 6 show that:

– When the cutting speed increases from 93 m/min to 117.5 m/min, the surface roughness decreases rapidly, then, if the cutting speed continues to increase, the roughness increases slowly. This trend can be explained as following: When the cutting speed increases, the number of cuts of the cutting edge on the machined surface will increase, and then reducing the plastic deformation phenomenon on the machined surface. Because the metal layer that has just formed due to plastic deformation is removed by the cutting edge at high speed, thereby the surface roughness would be reduced. This is also the general trend of machining and cutting methods [41].

– However, if the cutting speed continues to increase, the above phenomena still occur, it also has the effect of reducing the surface roughness. But at this time, higher cutting heat generated will increase the plastic deformation of the surface metal layer. In addition, when increasing the cutting speed, the level of vibration of the cutting tool will also increase and it makes the surface roughness rapidly increased. These compensating effects cause the surface roughness to increase slowly.

– It should be noted that the feed rate is calculated at the time which the gear rotates by an angle equal to the angle between the two teeth. That means when the feed rate is 40 s/tooth, the gear will rotate faster than when the feed is 50 s/tooth. In this case, when the gear rotation speed (ie. feed rate) is reduced from 40 s/tooth to 50 s/tooth, the surface roughness will decrease. This phenomenon is caused when the rotation speed of the gear decreases, it will increase the time that the cutter remove the metal layer on the workpiece surface. So, the plastic deformation on the surface metal layer is also reduced. This is the cause of the decreasing of surface roughness as the results from previous publication [42]. However, if the gear rotation speed continues to decrease (feed rate reduces from 50 s/tooth to 60 s/tooth), the heat transfer time from the cutting tool to the work surface will increase, this phenomenon again increases the plastic deformation of the metal surface layer, so the surface roughness increases as published reference [42].

– The surface roughness almost unchanged when the cutting depth increases from 0.25 mm to 0.5 mm. However, if the depth of cut continues to increase, the surface roughness increases rapidly. This phenomenon can be explained as follows. When the depth of cut is small, the factors such as cutting force, cutting temperature, etc. have negligible influence on the plastic deformation of the machined surface metal layer, so it has little effect on the surface roughness. When the depth of cut increases, all factors such as cutting heat, cutting force, etc. increase. Then, plastic deformation of the surface metal layer increases, and therefore, the surface roughness will increase. In addition, when the depth of cut increases, the vibration levels of the tool and workpiece also increase, these factors also contribute to the increase of the surface roughness as the results of reference [41].

The results from Figure 7 show that:

– When the cutting speed increases from 93 m/min to 117.5 m/min, the tool wear decreases. Conversely, if the cutting speed continues to increase, the tool wear increases rapidly. When the cutting speed is a small value, less cutting heat is generated, it means that less heat is transferred to the tool, thus, making the tool wear to be small. When the cutting speed increases, the generated heat during the cutting process increases, so the transferred heat to the cutting tool also increases, which is the cause of the rapid increase in the tool wear [42].

– The feed rate has a great influence on the tool wear. When the feed rate changes from 40 s/tooth to 60 s/tooth, which means that the gear rotation speed decreases gradually, then the time to complete the cutting of a gear will increase and will make the tool wear increases rapidly.

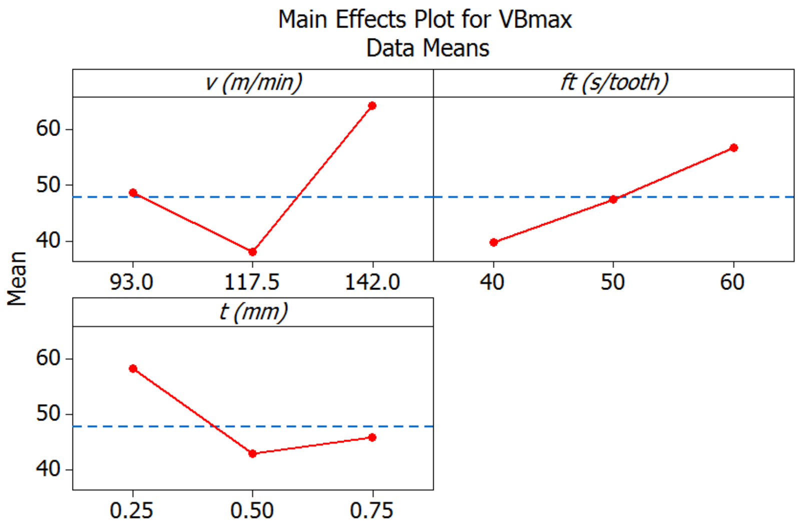


Fig. 7. Influence of cutting parameters on the tool wear

– When the cutting depth increases from 0.25 mm to 0.5 mm, tool wear tends to decrease. This phenomenon can be explained that when the depth of cut increases, the volume of the tool head submerged in the workpiece increases, the transferred heat to the work piece increases, then the heat on the cutting edge will reduce, thus, the tool wear reduces. If the cutting depth continues to increase, the cutting generated heat increases rapidly, although, the transferred heat to the workpiece also increases, the residual heat at the tool tip is still high, So, it leads the tool wear increasing rapidly [42].

From the analysed results, it seems that the influence of cutting parameters on the surface roughness and tool wear is relatively complex. It is very difficult to determine the values of the cutting parameters to ensure simultaneously the minimum values of surface roughness and the tool wear. The analysed results from Figs 6 and 7 show that: when the cutting speed was large (assuming the cutting speed is 142 m/min), the surface roughness was a small value, but also in this situation, the tool wear was also very large. In another case, when the cutting depth was small, the surface roughness was also small, but the tool wear was large, and so on. Thus, in order to ensure simultaneously the minimum values of surface roughness and tool wear, it is not possible to determine the value of the input parameters if only observing the results in Figures 7 and 8. In these situations, a commonly used method is to build the regression models showing the relationship between surface roughness, tool wear and input parameters. These are the surface roughness modelling and tool wear regression models. These models will be the basis to determine the values of the cutting parameters to ensure the setup requirements [39, 40]. To build these models, the analysis of variance (ANOVA) was performed using Minitab software, the analysed results are presented in Tables 4 and Table 5.

A parameter is determined to have a significant influence on the output parameter when the probability *P* value of that parameter is less than the significance level (usually, the significance level is chosen to be 0.05 [38–40]). The smaller the probability value of a certain parameter, that parameter has more influence on the output parameter. Then, the magnitude of the coefficients (the absolute values of the coefficients) of that parameter in the regression model is larger [38–40].

Table 4. ANOVA for Ra

Source	Coefficients	Sum of quare	Degree of freedom	F-value	P-value	
Regression		1.28362	9	16.89	0.003	Significant
Linear	1.4723	0.64523	3	25.47	0.002	Significant
x_1	–0.2073	0.34404	1	40.75	0.001	Significant
x_2	0.1641	0.21550	1	25.52	0.004	Significant
x_3	0.1035	0.08570	1	10.15	0.024	Significant
Square		0.49733	3	19.63	0.003	Significant
x_1^2	0.2742	0.22780	1	32.88	0.002	Significant
x_2^2	0.2417	0.19823	1	25.55	0.004	Significant
x_3^2	0.1389	0.07130	1	8.44	0.034	Significant
Interaction		0.1410	3	5.57	0.047	Significant
$x_1 \times x_2$	0.0927	0.03441	1	4.08	0.100	Not significant
$x_1 \times x_3$	0.1415	0.08009	1	9.49	0.027	Significant
$x_2 \times x_3$	–0.0815	0.02657	1	3.15	0.136	Not significant
Residual Error		0.04221	5			
Lack-of-Fit		0.04055	3	16.22		
Pure Error		0.00167	2			
Total		1.32584	14			
R^2	96.82%		Adjusted-R^2	91.08%		

The analysed results from the Table 4 show that:

– All three input parameters including cutting speed (x_1), feed rate (x_2), and depth of cut (x_3) have significant influence on the surface roughness, because the probability P values of all three parameters are all less than 0.05. The cutting speed that is the parameter has the greatest influence on the surface roughness, followed by the influence of the feed rate, and the third parameter that has the influence on the surface roughness is the depth of cut.

– The influence of the squares of the input parameters on the surface roughness also decreases in the order of x_1^2, x_2^2, x_3^2.

– The interaction between cutting speed and depth of cut (x_1 and x_3) has a significant effect on the surface roughness. The interaction between the cutting speed and the feed rate (x_1 and x_2), and the interaction between the feed rate and the depth of cut (x_2 and x_3) have no significant influence on the surface roughness. However, we should not remove these two interactions from the regression model, because doing like that will reduce the accuracy of the model [38-40]. Therefore, all quantities are kept in the regression model, and we obtained the regression model of surface roughness as presented in model (1).

$$\begin{aligned} y_1 = R_a = 1.4723 - 0.2073x_1 + 0.1641x_2 + 0.1035x_3 \\ +0.2742x_1^2 + 0.2417x_2^2 + 0.1389x_3^2 \\ +0.0927x_1 \cdot x_2 + 0.1415x_1 \cdot x_3 - 0.0815x_2 \cdot x_3 \end{aligned} \tag{1}$$

Model (1) has a determination coefficient (R^2) of 96.82%, which is very close to 1. This proves that the obtained data are suitable for building a high-order regression model (order 2). However, it is noted that a large value of R^2 does not necessarily reflect the regression model with high accuracy. To evaluate the accuracy of the regression model, it is necessary to evaluate the adjusted-determination coefficient (Adjusted-R^2) [38-40]. Model (1) has an

Adjusted-R^2 of 91.08%, it means that 91.08% of the change of the surface roughness is due to the change of the input parameters. This confirms that the model (1) has a very high accuracy. Besides, the probability P value of this model is 0.003, which is also much smaller than the significance level. This result also reinforces the statement that the model (1) has a very high accuracy.

Both two coefficients R^2 and Adjusted-R^2 will decrease if we remove the parameters that have little influence on the surface roughness from the regression model. To verify this statement, we assume to remove the interaction between x_1 and x_2, and the interaction between x_2 and x_3. After removing these two interactions, the regression model must be rebuilt [39–40]. The new regression model was rebuilt as presented by (2).

$$y_1 = R_a = 1.4723 - 0.2074x_1 + 0.1641x_2 + 0.1035x_3 + 0.2742x_1^2 + 0.2417x_2^2 + 0.1390x_3^2 + 0.1415x_1 \cdot x_3 \tag{2}$$

The model (2) has R^2 and Adjusted-R^2 coefficients of 92.22% and 84.43%, respectively, which means that the change of surface roughness only depends on the change of input parameters with the percentage of 84.43%, the rest percentage is due to the influence of the confounding factors. Thus, it is clear that the model (1) has higher accuracy than model (2). Therefore, model (1) will be used to carry out the next contents of this study.

Table 5. ANOVA for *VB*max

Source	Coefficients	Sum of quare	Degree of freedom	F-value	P-value		
Regression		4831.27	9	7.84	0.018		Significant
Linear	30.243	1369.84	3	6.67	0.034		Significant
x_1	7.776	483.76	1	7.07	0.045		Significant
x_2	8.525	581.41	1	8.49	0.033		Significant
x_3	-6.171	304.67	1	4.45	0.089		Not Significant
Square		1696.04	3	8.26	0.022		Significant
x_1^2	19.371	1263.69	1	20.24	0.006		Significant
x_2^2	3.028	18.20	1	0.49	0.513		Not Significant
x_3^2	10.591	414.15	1	6.05	0.057		Not Significant
Interaction		1765.39	3	8.60	0.020		Significant
$x_1 \times x_2$	17.457	1219.06	1	17.81	0.008		Significant
$x_1 \times x_3$	10.650	453.69	1	6.63	0.050		Significant
$x_2 \times x_3$	4.813	92.64	1	1.35	0.297		Not Significant
Residual Error		342.28	5				
Lack-of-Fit		342.24	3	5423.72			
Pure Error		0.04	2				
Total		5173.55	14				
R^2	93.38%		Adjusted-R^2				81.48%

The data in Table 5 shows that:

– The feed rate (x_2) that is the parameter has the greatest influence on the tool wear, followed by the degree of influence of the cutting speed (x_1), while the depth of cut (x_3) has a negligible influence on the tool wear.
– The squared quantity of the cutting speed (x_1^2) also has a significant effect on the tool wear. The squared quantities of the other two parameters (x_2^2 and x_3^2) have a negligible influence on the tool wear.
– The interaction between cutting speed and feed rate (x_1 and x_2), and the interaction between cutting speed and depth of cut (x_1 and x_3) also significantly influence on the tool wear. The remaining interaction (x_2 and x_3) has no significant effect on the tool wear.

Although there are some parameters that have little effect on the tool wear, we should not exclude them from the regression model, because if removing them from the regression model, the accuracy of the model will reduce [38-40].

Model (3) shows the relationship between tool wear and input parameters. Both parameters including R^2 and Adjusted-R^2 of model (3) are also close to 1. It means that the model (3) also has the high accuracy. The probability P value of (3) is equal to 0.018, much smaller than the significance level, which also proves this statement.

$$\begin{gathered} y_2 = VB_{max} = 30.243 + 7.776x_1 + 8.525x_2 - 6.171x_3 \\ +19.317x_1^2 + 3.028x_2^2 + 10.591x_3^2 \\ +17.4575x_1 \cdot x_2 + 10.650x_1 \cdot x_3 + 4.813x_2 \cdot x_3 \end{gathered} \tag{3}$$

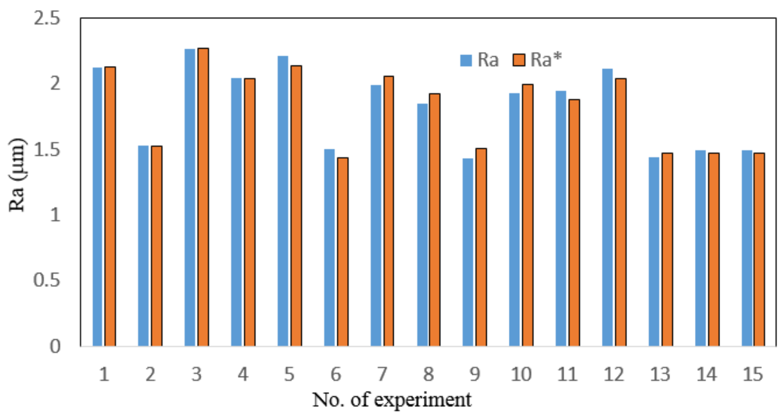


Fig. 8. Measured surface roughness (Ra) and predicted surface roughness (Ra*)

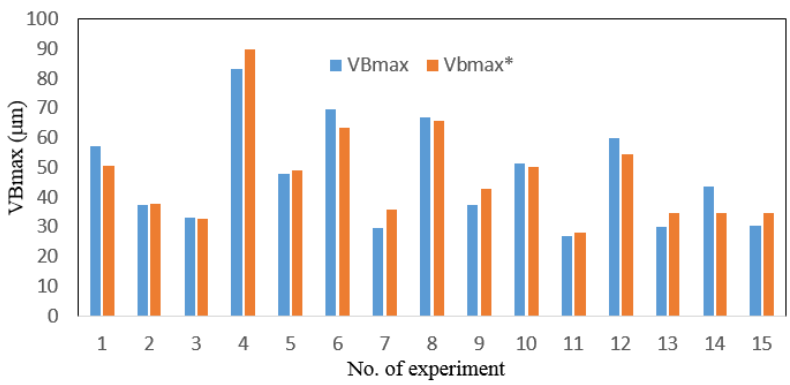


Fig. 9. Measured tool wear (*VB*max) and predicted tool wear (*VB*max*)

Using two models (1) and (3) to calculate the surface roughness (Ra*) and tool wear (*VB*max*) with the same values of cutting parameters as used in the experimental process. Figures 8 and 9 present the compared results of surface roughness and tool wear when measuring in the experimental and predicting by regression models. The results show that in all experiments, the predicted values by the regression model are very close to those ones from experimental process. The mean deviation between the experimental results and the calculated results by the regression models are only 0.043 (μm) for surface roughness and 3.94 (μm) for tool wear. Therefore, the construction of these two regression models was determined to be successful.

4. MULTI-OBJECTIVE OPTIMIZATION

In this study, the purpose of solving the multi-objective optimization problem is to determine the values of the cutting parameters to simultaneously ensure the minimum values of surface roughness and tool wear. Therefore, the problem can be written in the form of mathematical relationship as model (4).

$$\begin{cases} y_1 = f(x_1, x_2, x_3) \longrightarrow min \\ y_2 = f(x_1, x_2, x_3) \longrightarrow min \\ y_1, y_2 > 0 \\ -1 \le x_1, x_2, x_3 \le 1 \end{cases} \tag{4}$$

With w_1 and w_2 are the weights of surface roughness and tool wear, respectively, then the model (4) can be rewritten by model (5).

$$\begin{cases} y = w_1 \cdot y_1 + w_2 \cdot y_2 \longrightarrow min \\ y_1, y_2 > 0 \\ -1 \le x_1, x_2, x_3 \le 1 \end{cases} \tag{5}$$

The values of w_1 and w_2 were calculated according to the *MEREC* (Method Based on the Removal Effects of Criteria) method. This is a highly accurate method, and it has also been recommended for use [43]. The detailed description of the weighting steps by this method can be found in several published references [43, 44]. According to this method, the values of w_1 and w_2 were determined to be 0.3158 and 0.6842, respectively.

The tool to solve the optimization problem is the Generalized Reduced Gradien (GRG) algorithm. The details of this algorithm can be found in several references [45, 46]. The GRG algorithm was used to solve the model (4). The solved results are presented in Table 6.

Table 6. Optimal values

x_1	0.2196
x_2	-1.000
x_3	0.4463
y_1	1.6340 (μm)
y_2	21.6391 (μm)
y_3	15.3215 (μm)

From the coded optimal value, the actual optimal values of cutting speed, feed rate, and depth of cut were 120.67 (m/min), 40 (s/tooth), and 0.61 (mm), respectively.

Several experiments were conducted with the optimal values of cutting parameters, the measured values of surface roughness and tool wear in these experiments were stored in Table 7.

Table 7. Testing with the optimal cutting parameters

No.	*v* (m/min)	*ft* (mm/tooth)	*t* (mm)	Ra (μm)	*VB*max (μm)
1	120.67	40	0.61	1.77	24.86
2				1.77	24.12
3				1.82	24.07
4				1.86	23.44
5				1.79	23.97

From the data in Table 7, it is shown that the average value of surface roughness and tool wear when tested are 1.80 μm and 24.08 μm, respectively. These values are very close to the values that are determined when solving the optimization problem. The average deviation between the calculated and the experimental values is only 9.5% for surface roughness and 10.21% for tool wear. It proves that the optimization problem was solved with high accuracy, and once again we can confirm the optimal values of cutting parameters were cutting speed of 120.67 m/min, the feed rate of 40 s/tooth, and the depth of cut of 0.61 mm.

CONCLUSION

In this study, the experimental milling of Gleason gears with 20XM materials was conducted using CVD Ti(C,N)-Al2O3-TiN coated cutting inserts. Some conclusions are drawn as follows:

1. All three cutting parameters including cutting speed, feed rate, and depth of cut have significantly influence on the surface roughness. In which, cutting speed is the parameter that has the greatest influence on the surface roughness, followed by the influence of the feed rate, and finally, the influence of the cutting depth.
2. Feed rate is the parameter that has most effect on the tool wear, followed by the degree of influence of cutting speed, while depth of cut has a negligible influence on the tool wear.
3. Using the surface roughness model to predict the surface roughness, then comparing with the experimental results, it shows that the mean deviation between the predicted results and the experimental results is only 0.17 μm. For tool wear, the mean deviation between the predicted and experimental results is only 2.46 μm.
4. In order to simultaneously ensure the minimum values of the surface roughness and tool wear, the optimal values of cutting speed, feed rate, and depth of cut were 120.67 m/min, 40 s/tooth, and 0.61 mm, respectively.
5. In addition to the cutting parameters, determination of the optimal values of other parameters such as lubricating and cooling parameters, the structure parameters of the

cutting inserts, etc. to ensure the multiple objectives (cutting temperature, cutting force, surface roughness, tool wear, etc.) are the works that the authors of this study will perform in the near future.

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