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Effect of Cutting Parameters on Surface Roughness of Tooth Side in Gleason Spiral Bevel Gear Processing by Kyocera Solid Alloy End Mills

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Abstract.

The drive of spiral bevel gears has many advantages: smooth operation, high efficiency, great load bearing capacity, etc. The drive of spiral bevel gears can be processed by a number of methods such asusing 5-axis CNC machine, processing on specialized equipment, etc. However, using generating method to process gears offers a number of advantages, ensures precision, reduces cumulative errors, etc. To assure quality of the drive of gears during its movement, it is required to enhance the quality of post-processed gears. The paper presents findings about effect of cutting parameters on surface roughness of tooth side in Gleason spiral bevel gear processing by Kyocera solid alloy end mills. The findings are basis for technologists to select appropriate cutting parameters to improve the quality of tooth side in Gleason spiral bevel gear processing on 525 semi-automatic spiral bevel gear milling machine with generating method.

Keywords: Cutting parameters, surface roughness, spiral bevel gear.

1. INTRODUCTION

In Mechanics, the drive of spiral bevel gears has been widely used on planes, ships, machine tools, construction machines, etc. due to its various advantages such as high efficiency, great load bearing capacity, etc. The processing of different types of gears has been studied and applied by mechanical factories with various manufacturing methods such as metal cutting on machine tools or moulding using templates. To guarantee precision, metal cutting on specialized equipment with generating method is often used. Quality of the drive of gears during its operation depends on the quality of each post-manufactured gear, particularly the surface roughness of tooth side of the gear, one of the important factors enabling the drive of gears to work smoothly, reducing tooth side abrasion and increasing its durability and life span.

The relationship between surface roughness (R_a) and cutting parameters (V, S, t) isthe power function [1]:

$$R_a = C_p \,.\, V^a .\, S^b \,.\, t^c \qquad (1)$$

Of which: $C_p$is a constant; a, b, c are exponents. Experimental methods are used to identify constant C_p and exponents a, b, c.

2. EXPERIMENTS

2.1.Experimental equipment and processing materials

2.1.1.Processing equipment and cutting tools

- Specialized semi-automatic gear processing machine with marking 525 (made in Soviet Union) and generating method are used for processing (figure 1).

- Cutting tools: Kyocera end mill of Gleason spiral bevel gear with a piece of alloy, marking TKY03130-PV60 (made in Japan), number of teeth Z = 16, diameter nominal of the end mill d_n=228,6mm (figure2)

Figure1. 525 specialized semi-automatic gear processing machine

Figure 2. Kyocera end mill of Gleason spiral bevel gear with a piece of alloy

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2.1.2.Processing materials and coolant solution

- Processing materials are 20XMsteel under standard ГОСТ 4543-71. Steel grade is identified by spectral analysis, chemical components of the steel are presented in table 1. Figure 3 is the drawing of a processed gear, and figure 4 is the drawing of workpiece for experiments,

- Coolant solution: Industrial oil No. 32, capacity: 15 liters/minute,directly pouring.

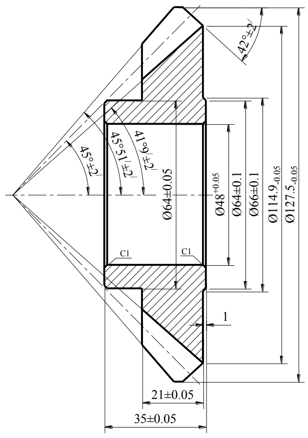

Figure 3. Drawing of gear manufacturing

Figure 4. Workpiece for experiments

Table 1. Chemical components of gear processing materials

Steel grade	Chemical components %								
	C	Si	Mn	Cr	Ni	Mo	Cu	S	P
20XM	0.2348	0.1930	0.682	0.9256	0.1826	0.2367	0.1546	0.0287	0.0265

2.1.3.Surface roughness measuring instrument

- Surface roughness measuring instrument: Surfcom 1800D, made in Japan, measuring head No. 0102521 (figure 5).

-Measuring parameters: Surface roughness value R_a under ISO standard.

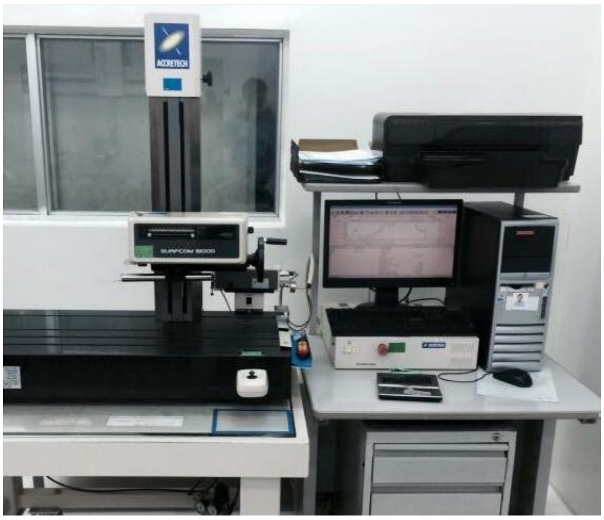

Figure 5. Surfcom 1800D surface roughness measuring instrument

2.2.Experimental methods

The research was implemented with 9 tests, each of which was carried out on 3 samples with 27 samples in total. Processing materials were 20XM steel whose chemical components were identified by spectral analysis. Experimental least squares method was used, regression equation was chosen, test parameters were identified then experiments were implemented.Processed test workpieces ensure size and precision as required. Then, workpiece processing on 525 specialized semi-automatic gear processing machine with generating method was implemented. After milling process, the workpieces were cleaned, measured, tested so that the surface roughness could be evaluated. Each sample had 10 random teeth measured, each teeth had 3 positions measured, the result was the average value of measurements at those 3 positions. Matlab and Excel were used to calculate, draw graphs, and create formulas to identify the relationship between cutting parameters (V, S, t) and tooth side surface roughness of the gears after processing (R_a).

2.3.Basis for evaluating experimental figures

2.3.1.Identifying the regression equation

To study the relationship between cutting parameters and surface roughness of the tooth side when cutting Gleason spiral bevel gears with Kyocera solid alloy end mill, the author team used least squares method with variable k and a regression function:

$$y = a_0 + a_1 x_1 + a_2 x_2 + \ldots,, + a_k x_k \quad (2)$$

2.3.2.Number of tests and test parameters

**Number of tests:*

- The relationship between input parameters and output parameters is described in the diagram (figure 6):

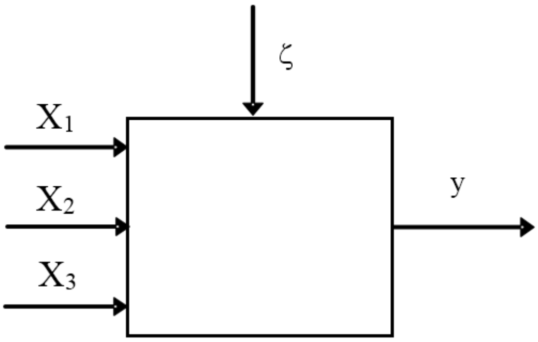

Figure 6. Relationship diagram between input parameters and output parameters

+ Input controllable variables X_i:

X_1: Cutting velocity V (m/min)

X_2: Feed S (sec/tooth)

X_3: Depth of cut t (mm)

+ Output controlled variable:

y: Surface roughness R_a (μm)

+ Uncontrolled variable:

ζ: Random variable

- The number of tests is determined [2] by the following formula:$N = 2^k = 8$

With input variable k = 3,we have main number of tests $N = 2^3 = 8$. To increase the precision, the author team implemented one more test in the centre. Total number of tests N = 8 + 1 = 9.

**Test parameters:*

On the basis of machine's specifications, processing materials, allowable scope of use of the cutting tools, cutting parameters for the research were selected in the following range:

+Cutting velocity V: 75–116m/ph.

+Feed S: 40–50 sec/tooth.

+Depth of cut t: 1.75– 2.25mm.

The experimental cutting parameters are presented in table 2.

Table 2. Experimental cutting parameters

Parameters	Cutting velocity V (m/min)	Feed S (sec/tooth)	Depth of cut t (mm)
Minimum values	75	40	1.75
Maximum values	116	50	2.25

The relationship between surface roughness and cutting parameters is presented by formula (1):

$$R_a = C_p.V^a.S^b.t^c$$

Taking logarithm of radix e in equation (1), we have:

$$\ln(R_a) = \ln(C_p) + a.\ln(V) + b.\ln(S) + c.\ln(t) \quad (3)$$

Setting $y = \ln(R_a)$; $a_0 = \ln(C_p)$; $a_1 = a$; $a_2 = b$;

$a_3 = c$; $x_1 = \ln(V)$; $x_2 = \ln(S)$; $x_3 = \ln(t)$

We have: $y = a_0 + a_1x_1 + a_2x_2 + a_3x_3$

Upper level is $x_i^{(t)}$we have: $x_i^{(t)} = \ln x_{i\,max}$

Lower level is $x_i^{(d)}$: $x_i^{(d)} = \ln x_{i\,min}$

Base level is $x_i^{(0)}$: $x_i^{(0)} = \frac{1}{2}(\ln x_{i\max} + \ln x_{i\min})$

With range ρ_i,we have: $\rho_i = \frac{1}{2}(\ln x_{i\max} - \ln x_{i\min})$

After calculation, encoded values of test parameters are presented in table 3.

Table 3. Encoded values of test parameters

Factors	**x_1**	**x_2**	**x_3**
Upper level	4.75359	3.91202	0.81093022
Lower level	4.31749	3.68888	0.55961579
Base level	4.53260	3.80666	0.69314718

2.4. Experimental results

After chemical components of the processing materials were analysed, specific workpieces were created, and the experiments were implemented. Images of post-processed workpieces are in figure 7.

Figure 7. Post-processed gears

Post-processed workpieces were cleaned, measured, tested so that the surface roughness of the gear tooth side could be evaluated. Surface roughness measurements are presented in table 4.

Table 4. Experimental results

Test	Encoded variables			V	S	t	R_a (μm)
	X_1	X_2	X_3				
1	-1	-1	-1	75	40	1.75	2.047
2	+1	-1	-1	116	40	1.75	1.803
3	-1	+1	-1	75	50	1.75	3.337
4	+1	+1	-1	116	50	1.75	2.930
5	-1	-1	+1	75	40	2.25	3.417
6	+1	-1	+1	116	40	2.25	2.427
7	-1	+1	+1	75	50	2.25	3.770
8	+1	+1	+1	116	50	2.25	3.317
9	0	0	0	93	45	2.00	2.717

2.4.1.Experimental figure planning

According to least squares method, we have a general regression function:

$$y = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_k x_k$$

Identifying $a_0, a_1, a_2 \ldots a_k$ so that S has the smallest value:

$$S^2 = \sum_{i=1}^{i=k} \left[y_i - y'_i \right]^2 \quad (4)$$

Values $a_0, a_1, a_2, \ldots a_k$ are corresponding coefficients of matrix [A]:

$$[A] = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} \quad \text{With:} \quad [X].[A] = [Y] \quad (5)$$

-Input parameter matrix [X] is the logarithm of radix e of values V, S, t used in tests,

-Output parameter matrix [Y] has coefficients being logarithm of radix e of surface roughness values measured on test samples.

Multiplying two sides of (5) and transpose X^T of matrix X:

$$[X]^T.[X].[A] = [X]^T.[Y]$$

Setting $[M] = [X]^T.[X]$, we have:

$$[M].[A] = [X]^T.[Y]$$

Assuming $\det(M) \neq 0$, [M] is an invertible matrix, we have:

$$[A] = [M]^{-1}.[X]^T.[Y] \quad (6)$$

Taking logarithm of radix e of values V, S, t and R_a, we have the results as presented in table 5.

Table 5. Results after taking logarithm of test parameters

No.	V (m/min)	S (sec/tooth)	t (mm)	R_a (μm)	Ln(V) x_1	Ln(S) x_2	Ln(t) x_3	Ln(R_a) y
1	75	40	1.75	2.047	4.31749	3.68888	0.55961579	0.71621
2	116	40	1.75	1.803	4.75359	3.68888	0.55961579	0.58964
3	75	50	1.75	3.337	4.31749	3.91202	0.55961579	1.20497
4	116	50	1.75	2.930	4.75359	3.91202	0.55961579	1.07500
5	75	40	2.25	3.147	4.31749	3.68888	0.81093022	1.14634
6	116	40	2.25	2.427	4.75359	3.68888	0.81093022	0.88652
7	75	50	2.25	3.770	4.31749	3.91202	0.81093022	1.32708
8	116	50	2.25	3.317	4.75359	3.91202	0.81093022	1.19896
9	93	45	2.00	2.717	4.53260	3.80666	0.69314718	0.99941

From Table 5 and the regression equation (2) we have:

$$[X] = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}$$

$$\rightarrow [X] = \begin{bmatrix} 1 & 4,31749 & 3,68888 & 0,55961579 \\ 1 & 4,75359 & 3,68888 & 0,55961579 \\ 1 & 4,31749 & 3,91202 & 0,55961579 \\ 1 & 4,75359 & 3,91202 & 0,55961579 \\ 1 & 4,31749 & 3,68888 & 0,81093022 \\ 1 & 4,75359 & 3,68888 & 0,81093022 \\ 1 & 4,31749 & 3,91202 & 0,81093022 \\ 1 & 4,75359 & 3,91202 & 0,81093022 \\ 1 & 4,5326 & 3,80666 & 0,69314718 \end{bmatrix}$$

$$[Y] = \begin{bmatrix} 0,71621 \\ 0,58964 \\ 1,20497 \\ 1,07500 \\ 1,14634 \\ 0,88652 \\ 1,32708 \\ 1,19896 \\ 0,99941 \end{bmatrix}$$

Using Excel to calculate, we have matrix [A]:

$$[A] = \begin{bmatrix} \text{-4,2132} \\ \text{-0,3692} \\ 1{,}6418 \\ 0{,}9659 \end{bmatrix}$$

Then we have coefficients of the regression equation:

a_0 = - 4.2132→ $C_p = e^{-4.2132}$=0.0148

a_1 = -0.3692; a_2 = 1.6418; a_3 = 0.9659

So the regression equation is:

$$y = -4.2132 - 0.3692x_1 + 1.6418x_2 + 0.9659x_3 \quad (7)$$

Relationship equation between R_a and cutting parameters:

$$\mathbf{R_a} = 0.0148.\ \mathbf{V}^{-0.3692}.\ \mathbf{S}^{1.6418}.\ \mathbf{t}^{0.9659} \quad (8)$$

2.4.2.Evaluating the accuracy of the regression function

**Evaluating the accuracy*

The accuracy is evaluated by [2] the formula:

$$r = \frac{\sigma_y^2 - \sigma'^2_y}{\sigma_y^2} \quad (9)$$

Of which:

$$\sigma_y^2 = \frac{1}{N-1}.\sum_1^n (y_i - y_{itb})^2$$

$$\sigma'^2_y = \frac{1}{N-1}.\sum_1^n (y_i - y'_i)^2$$

With: y_i- logarithm of radix e of R_a, we have: $y_i = \ln(R_{ai})$.

y_{itb}- average value of logarithm of radix e of R_a as measured in the experiments.

y_i' - logarithm of R_a under the regression function.

N- number of tests.

By using Excel, we can calculate the accuracy:

$$\sigma_y^2 = \frac{1}{N-1}.\sum_1^n (y_i - y_{itb})^2 = \frac{1}{9-1}\ .\ 0{,}4751\ = 0{,}0594$$

$$\sigma'^2_y = \frac{1}{N-1}.\sum_1^n (y_i - y'_i)^2 = \frac{1}{9-1}\ .\ 0{,}0367 = 0{,}0046$$

So the accuracy *r* is:

$$r = \frac{\sigma_y^2 - \sigma'^2_y}{\sigma_y^2} = \frac{0{,}0593 - 0{,}0046}{0{,}0594} = 0{,}923$$

Accuracy r = 92.3%

**Testing coefficients a_i*

-Identifying residual variance S_r:

$$S_r^2 = \frac{S^2(A)}{N-k-1} \quad (10)$$

Of which:

N–number of tests (N = 9)

k -number of parameters to be determined (except for a_0).

$$S^2(A) = ([Y]-[X].[A])^T.([Y]-[X].[A])$$

Using Excel to solve matrix problems, we have:

$$S^2(A) = 0.0367$$

Therefore:

$$S_r^2 = \frac{S^2(A)}{N-k-1} = \frac{0{,}0367}{9-3-1} = 0{,}0073 \Rightarrow S_r = 0.0856$$

-Identifying the existence of coefficients a_i:

Existing coefficients a_i [3] are identified in the formula:

$$\left|t_{cal}^i\right| = \left|\frac{a_i}{S_r\sqrt{m_{ii}}}\right| \geq t_{table}(N-k-1, r) \quad (11)$$

Of which: m_{ii} is the term No. ii of matrix M^{-1} with: $[M] = [X]^T.[X]$

$$[M]^{-1} = \begin{bmatrix} 202{,}9514 & -11{,}9250 & -38{,}1571 & -5{,}4184 \\ -11{,}9250 & 2{,}6290 & 0{,}0004 & 0{,}0004 \\ -38{,}1571 & 0{,}0004 & 10{,}0384 & -0{,}0035 \\ -5{,}4184 & 0{,}0004 & -0{,}0035 & 7{,}9131 \end{bmatrix}$$

We have:

$$\left|t_{cal}^0\right| = \left|\frac{a_0}{S_r\sqrt{m_{11}}}\right| = \left|\frac{-4{,}2132}{0{,}0856.\ \sqrt{202{,}9514}}\right| = \left|-3{,}4535\right| = 3{,}4535$$

$$\left|t_{cal}^1\right| = \left|\frac{a_1}{S_r\sqrt{m_{22}}}\right| = \left|\frac{-0{,}3692}{0{,}0856.\sqrt{2{,}6290}}\right| = \left|-2{,}6589\right| = 2{,}6589$$

$$\left|t_{cal}^2\right| = \left|\frac{a_2}{S_r\sqrt{m_{33}}}\right| = \left|\frac{1{,}6418}{0{,}0856.\sqrt{10{,}0384}}\right| = \left|6{,}0512\right| = 6{,}0512$$

$$\left|t_{cal}^3\right| = \left|\frac{a_3}{S_r\sqrt{m_{44}}}\right| = \left|\frac{0{,}9659}{0{,}0856.\sqrt{7{,}9131}}\right| = \left|4{,}0096\right| = 4{,}0096$$

- Searching in Student's t-distribution with t_{table} (N-k-1; r)

With accuracy r = 92.3%; N-k-1 = 9-3-1 = 5

After the search we have $t_{table}(5\ ;\ 90) = 1.4759$ and $t_{table}(5\ ;\ 95) = 2.015$

By using interpolation method, we have $t_{table}(5\ ;\ 92{,}3) = 1.7239$

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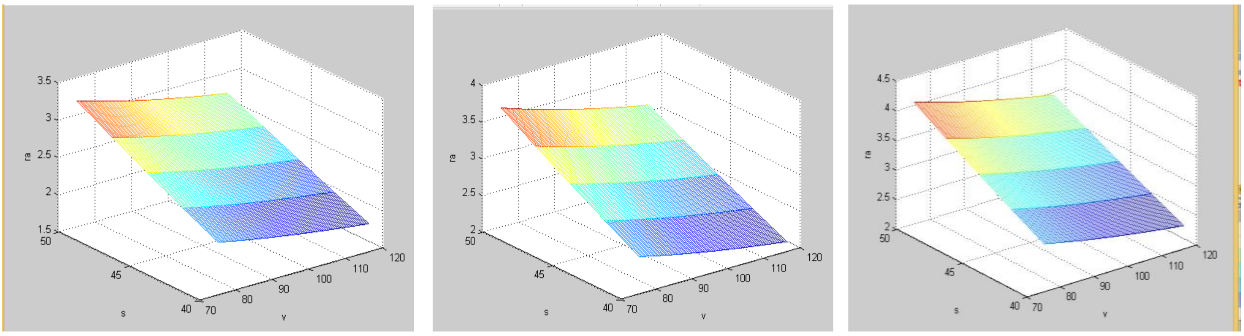
Thus: $\left|t_{cal}^{i}\right| = \left|\dfrac{a_i}{S_r\sqrt{m_{ii}}}\right| \geq t_{table}(N-k-1,r)$ with i = 0÷3

Therefore, coefficients a_i truly exist, andthe regression equation (7) exists so there exists a relationship between surface roughness and cutting parameters as follows:

$\mathbf{R_a}=0.0148 \,.\, \mathbf{V}^{-0.3692} .\, \mathbf{S}^{1.6418} .\, \mathbf{t}^{0.9659}$

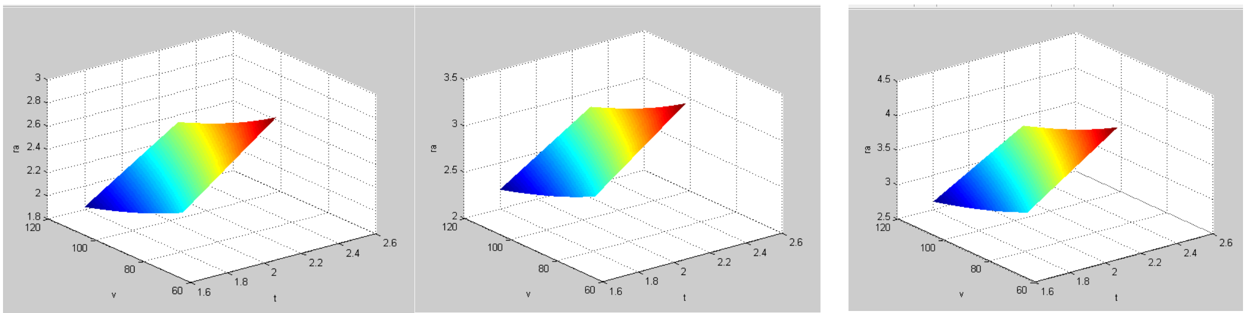
2.4.3. Relationship graph of surface roughness and cutting parameters

*Using Matlab to draw graphs describing the relationship between R_a and 2 values of cutting parameters. Relationship graph of R_a and V & S (figure 8), relationship graph of R_a and V & t (figure 9); relationship graph of R_a and S & t (figure 10).



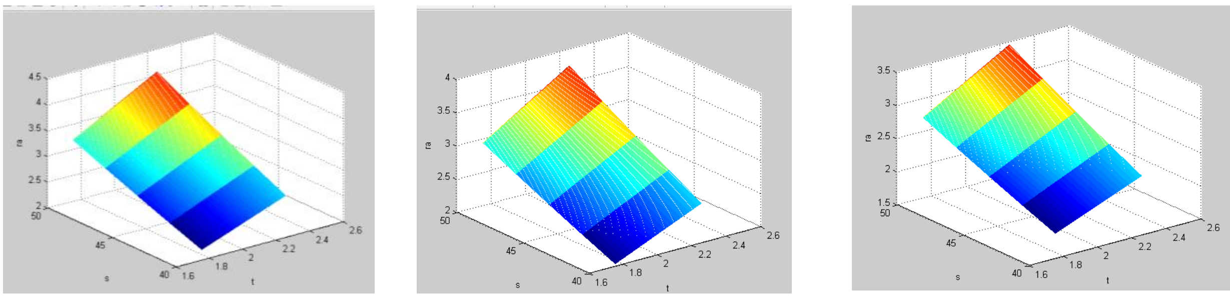
a) With t =1.75 mm *b) With t =2mm* *c) With t =2.25mm*

Figure 8. Relationship graph of R_a and V & S



a) With S = 40 mm/min *b) With S = 45 mm/min* *b) With S = 50 mm/min*

Figure 9. Relationship graph of R_a and V&t



a) With V = 75 m/min *b) With V = 93m/min* *c) With V = 116m/min*

Figure 10. Relationship graph of R_a and S&t

Comment: After analyzing graphs in figures 8, 9, 10 and formula (8), we can see that cutting velocity V is inversely proportional with surface roughness value, feed (S) and depth of cut (t) are proportional with surface roughness value; feed affects surface roughnessR_a the most, followed by depth of cut (t). Cutting velocity V has the smallest effect.

3. CONCLUSION

- The mathematical relationship between cutting parameters (V, S, t) and surface roughness of the tooth side of Gleason spiral bevel gears after processing has been determined and presented in the following formula:

$$\mathbf{R_a}=0.0148\ \mathbf{.}\ \mathbf{V}^{-0.3692}\ \mathbf{.}\ \mathbf{S}^{1.6418}\ \mathbf{.}\ \mathbf{t}^{0.9659}$$

- The coefficients of the regression equation can be evaluated with accuracy r = 92.3%.
- According to research findings, when spiral bevel gears are processed on the 525 gear processing machine, the cutting velocity is inversely proportional with tooth side surface roughness, while feed and depth of cut are proportional with tooth side surface roughness. Of which, feed (S) affects tooth side surface roughness after processing the most, followed by depth of cut (t) and cutting velocity (V), respectively.
- Research findings help technologists select appropriate cutting parameters to increase productivity, surface quality, and precision of Gleason gears in processing on 525 machinewith generating method.

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