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Research on Effect of Process Parameters (V, S) on Tooth Side Roughness in Gleason Spiral Bevel Gear Machining By Solid Alloy End Mills

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Abstract - Digital control machine tools have been more widely used day by day, many of which can machine gears. However, spiral bevel gear machining ability is still a challenge to technologists. Therefore, using generating method to machine spiral bevel gears has been still popularly used with a number of advantages which ensure precision and limit cumulative errors, etc. To assure the quality of the drive of gears during its movement, it is required to enhance the quality of post-machined gears. The paper presents findings about effect of cutting velocity (V) and feed (S) on the roughness of tooth side in spiral bevel gear machining by solid alloy end mills. The findings are the basis for technologists to select appropriate process parameters to improve the quality of tooth side in Gleason spiral bevel gear machining on 525 semi-automatic spiral bevel gear milling machine with generating method.

1. INTRODUCTION

Gear machining technology plays an important role in mechanical manufacturing chain. A number of researches on gear machining on digital control machines have been carried out.

Figure 1. 525 specialized semi-automatic gear machine

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

However, spiral bevel gear machining with generating methods still brings various outstanding advantages and has been widely used. At present, materials for machining spiral bevel gears are mainly high-speed steel with low process parameters, quickly abraded end mills, etc., which affects output and post-machined gear quality.

The use of solid alloy end mills will limit abrasion, offer large process parameters, lengthen end mills' life span, and increase machining capacity. Quality of the drive of the gear during its operation depends on the quality of each post-manufactured gear, particularly the roughness of the gear, one of the important factors enabling the drive of gear to work smoothly, reducing tooth side abrasion and increasing its durability and life span. Therefore, process parameter survey during the use of solid alloy end mills is the basis for technologists to select appropriate process parameters to increase the quality of tooth side surface.

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

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

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 machining materials

2.1.1. Machining equipment and cutting tools

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

- Cutting tools: Kyocera end mill of Gleason spiral bevel gear with an alloy, marking TKY03130-PV60 (made in Japan), number of teeth Z = 16, diameter nominal of the end mill d_n = 228,6 mm (figure 2)

2.1.2. Machining materials and coolant solution

- Machining materials are 20XM steel 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 machined gear, and figure 4 is the drawing of workpiece for experiments

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

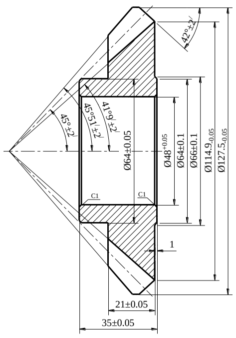

Figure 3. Drawing of gear manufacturing

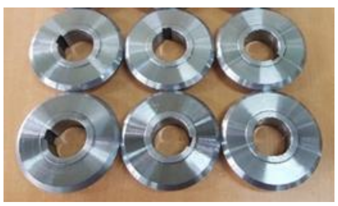

Figure 4. Workpiece for experiment

Table 1. Chemical components of gear machining 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. Roughness measuring instrument

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

- Measuring parameters: Roughness value R_a under ISO standard.

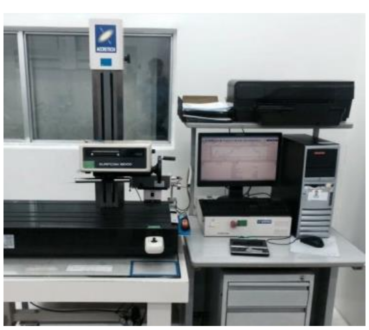

Figure 5. Surfcom 1800D roughness measuring instrument

2.2. Experimental methods

The research was implemented with 5 tests. Machining 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 are implemented. Test workpieces with sides machined ensure size and precision as required. Then, workpiece machining on 525 specialized semi-automatic gear machining machine with generating method was implemented. After milling process, the workpieces were cleaned, measured, tested so that the roughness could be evaluated. Matlab and Excel were used to calculate, draw graphs, and create formulas to identify the relationship between process parameters (V, S) and tooth side surface roughness of workpieces after machining (R_a).

2.3. Basis for evaluating experimental figures

2.3.1. Identifying regression equation

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

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

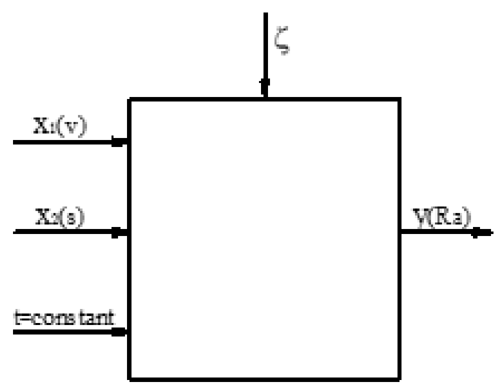

Figure 6. Relationship diagram between input parameters and output parameters

+ Input controllable variables x_i:
  x_1: Cutting velocity V (m/ph)
  x_2: Feed S (sec/tooth)
+ Output controlled variable:
  y: Surface roughness R_a (µm)
+ Uncontrolled variable:
  ζ: Random variable

- The number of tests is determined [3] by the following formula: $N = 2^k$

With input variable k = 2, we have main number of tests $N = 2^2 = 4$. To increase the precision, the author team implemented one more test in the center. Total number of tests N = 4 + 1 = 5.

** Test parameters:*

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

+ Cutting velocity V: 75 - 116 m/ph.

+ Feed S: 40 - 50 sec/tooth.

+ Depth of cut t: 1.75 mm.

The experimental process parameters are presented in table 2.

Table 2. Experimental process parameters

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

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

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

With t = constan, the relationship is presented by the following formula:

$R_a = C_p.V^a.S^b$ (3)

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

$\ln(R_a) = \ln(C_p) + a.\ln(V) + b.\ln(S)$ (4)

Setting $y = \ln(R_a)$; $a_0 = \ln(C_p)$; $a_1 = a$; $a_2 = b$; $x_1 = \ln(V)$; $x_2 = \ln(S)$

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

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

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**
Upper level	4.75359	3.91202
Lower level	4.31749	3.68888
Base level	4.53260	3.80666

2.4. Experimental results

After chemical components of the machining materials were analyzed, specific work pieces were created, and the experiments were implemented. Images of post-machined work pieces are in figure 7.

Figure 7. Post-machined gears

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

Table 4. Experimental results

Test	Encoded variables		**V**(*m/ph*)	**S**(*sec/tooth*)	**R_{atb}**(µm)
	x_1	**x_2**			
1	-1	-1	75	40	2.047
2	+1	-1	116	40	1.803
3	-1	+1	75	50	3.337
4	+1	+1	116	50	2.930
5	0	0	93	45	2.537

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:

$$S^2 = \sum_{i=1}^{i=k} [y_i - y'_i]^2 \quad (5)$$

Values $a_0, a_1, a_2, \ldots a_k$ are corresponding coefficients of matrix [A]: $[A] = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}$ With : [X] .[A] = [Y] (6)

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

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

Multiplying two sides of (6) 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:

$$[A] = [M]^{-1}.[X]^T.[Y] \qquad (7)$$

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

Table 5. Results after taking logarithm of test parameters

No.	**V** *(m/ph)*	**S** *(sec/tooth)*	**R_{atb}** *(µm)*	Ln(V) **x_1**	Ln(S) **x_2**	Ln(R_a) **y**
1	75	40	2.047	4.31749	3.68888	0.71638
2	116	40	1.803	4.75359	3.68888	0.58945
3	75	50	3.337	4.31749	3.91202	1.20507
4	116	50	2.930	4.75359	3.91202	1.07500
5	93	45	2.537	4.53260	3.80666	0.93098

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

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

$$\rightarrow [X] = \begin{bmatrix} 1 & 4.31749 & 3.68888 \\ 1 & 4.75359 & 3.91202 \\ 1 & 4.31749 & 3.68888 \\ 1 & 4.75359 & 3.91202 \\ 1 & 4.53260 & 3.80666 \end{bmatrix} [Y] = \begin{bmatrix} 0.71638 \\ 0.58945 \\ 1.20507 \\ 1.07500 \\ 0.93098 \end{bmatrix}$$

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

$$[A] = \begin{bmatrix} -6.06614 \\ -0.29490 \\ 2.18504 \end{bmatrix}$$

Then we have coefficients of the regression equation:

$a_0 = - 6.06614 \rightarrow C_p = e^{-6.06614} = 0.00232$

$a_1 = - 0.29490$; $a_2 = 2.18504$

So the regression equation is:

$$y = - 6.06614 - 0.29490x_1 + 2.18504x_2 \qquad (8)$$

Relation equation between roughness R_a and process parameters:

$$R_a = 0.00232. V^{-0.29490}. S^{2.18504} \qquad (9)$$

2.4.2. Evaluating the accuracy of the regression function

* Evaluating the accuracy

The accuracy is evaluated by [3] the formula:

$$r = \frac{\sigma_y^2 - \sigma'^2_y}{\sigma_y^2} \qquad (10)$$

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 roughness R_a, we have:

$y_i = \ln(R_{ai})$.

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

y_i' - logarithm of roughness R_a under the regression function.

N – number of tests.

By using Excel, we can calculate the accuracy:

$$\sigma_y^2 = \frac{1}{N-1}.\sum_1^n (y_i - y_{itb})^2 = \frac{1}{5-1} . 0.28848 = 0.07212$$

$$\sigma'^2_y = \frac{1}{N-1}.\sum_1^n (y_i - y'_i)^2 = \frac{1}{5-1} . 0.00032 = 0.00608$$

So the accuracy r is:

$$r = \frac{\sigma_y^2 - \sigma'^2_y}{\sigma_y^2} = \frac{0.07212 - 0.00608}{0.07212} = 0.916$$

Accuracy r = 91.6 %

* Testing coefficients a_i

- Identifying residual variance S_{du}: $$S_{du}^2 = \frac{S^2(A)}{N-k-1} \qquad (11)$$

Of which:

N – number of tests (N = 5).

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:

$$S^2(A) = 0.00033$$

Therefore: $S_{du}^2 = \dfrac{S^2(A)}{N-k-1} = \dfrac{0.00033}{5-2-1} = 0.000162 \Rightarrow S_{du} = 0.01274$

- Identifying the existence of coefficients a_i :

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

$$\left|t_{tính}^i\right| = \left|\frac{a_i}{S_{du}\sqrt{m_{ii}}}\right| \geq t_{bang}(N-k-1, r) \qquad (12)$$

Of which: m_{ii} is the term No. ii of matrix M^{-1} with:

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

$$[M]^{-1} = \begin{bmatrix} 398.4741 & -23.85017 & -76.31200 \\ -23.85017 & 5.25790 & 0.00154 \\ -76.31200 & 0.00154 & 20.07133 \end{bmatrix}$$

We have:

$$|t_{tinh}^0| = \left|\frac{a_0}{S_{du}\sqrt{m_{11}}}\right| = \left|\frac{-6.06614}{0.01274.\sqrt{398.4741}}\right| = |-23.8382| = 23.8382$$

$$|t_{tinh}^1| = \left|\frac{a_1}{S_{du}\sqrt{m_{22}}}\right| = \left|\frac{-0.29490}{0.01274.\sqrt{5.25790}}\right| = |-10.0885| = 10.0885$$

$$|t_{tinh}^2| = \left|\frac{a_2}{S_{du}\sqrt{m_{33}}}\right| = \left|\frac{2.18504}{0.01274.\sqrt{20.07133}}\right| = |38.2590| = 38.2590$$

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

With accuracy r = 91.6%; N-k-1 = 5-2-1 = 2

After the search we have $t_{bang}(2; 90) = 1.4759$ and $t_{bang}(2; 95) = 2.0150$

By using interpolation method, we have $t_{bang}(2; 91.6) = 1.6484$

Thus: $\left|t_{tính}^i\right| = \left|\dfrac{a_i}{S_{du}\sqrt{m_{ii}}}\right| \geq t_{bang}(N-k-1, r)$ with i = 0÷2

Therefore, coefficients a_i truly exist, the regression equation (8) exists so there exists a relationship between surface roughness and process parameters as follows:

$$R_a = 0.00232.\ V^{-0.29490}.\ S^{2.18504}$$

2.4.3. Relationship graph of roughness and process parameters

* Using Matlab to draw a graph describing the relationship between roughness R_a with cutting velocity (V) and feed (S) (figure 8)

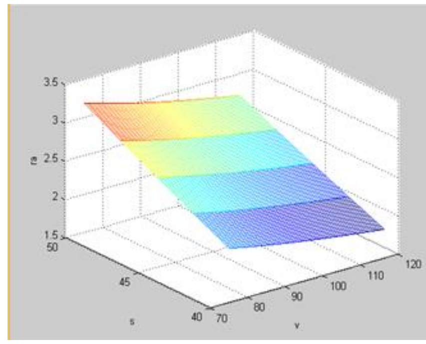

Figure 8. Relationship graph of R_a and V & S when t = 1.75 mm

Comment: After analyzing the graph in figure 8 and formula (9), we can see that cutting velocity V is inversely proportional with roughness value, feed (S) is proportional with roughness value; feed affects surface roughness R_a more than cutting velocity V.

3. CONCLUSION

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

$R_a = 0.00232.\ V^{-0.29490}.\ S^{2.18504}$

- The coefficients of the regression equation can be evaluated with accuracy r = 91.6%.

- According to research findings, when spiral bevel gears are machined on the 525 gear machining machine, the cutting velocity V is inversely proportional with roughness value, while feed (S) is proportional with roughness value; feed affects surface roughness R_a more than cutting velocity (V).

- Research findings help technical staffs select appropriate process parameters to increase productivity, surface quality, and precision of Gleason gears in machining on 525 machine with generating method.

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