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An Investigation of the Optimization of Technological Parameters When Machining Straight Toothed Bevel Gears on 3-Axis CNC Milling Machine

Minh Quang Chau[a], Le Hung Duong[b], Minh Nhat Nguyen[c], Xuan Phuong Nguyen[b], Thi Minh Hao Dong[b,1]

[a] *Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam*

[b] *Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam*
E-mail: [1]minhhaodong@gmail.com

[c]*Ho Chi Minh city University of Technology (HUTECH), Ho Chi Minh City, Vietnam*
E-mail: nm.nhat@hutech.edu.vn

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Minh Quang Chau[a], Le Hung Duong[b], Minh Nhat Nguyen[c], Xuan Phuong Nguyen[b], Thi Minh Hao Dong[b,1]

[a] Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

[b] Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam
E-mail: [1]minhhaodong@gmail.com

[c]Ho Chi Minh city University of Technology (HUTECH), Ho Chi Minh City, Vietnam
E-mail: nm.nhat@hutech.edu.vn

***Abstract*— With the advantage of reducing the damage of bending stress up to 10 %, the straight-toothed bevel gears (STBG) with a shoulder-bearing are being used in many industries automobiles, trains, mining, space, machinery technology and aviation equipment. With the working characteristics of straight-tooth bevel gears, the manufacturing quality assessments are usually conducted through micro-dimensional values, surface gloss, and internal surfaces' contact ability in the transmission. Recently, research and application of gear machining methods on 3-axis CNC milling machines are gradually becoming more popular. Therefore, the study of the affection of technology parameters on the quality of shaping the STBG surface by evaluating the output factors (surface undulation, micro-geometry parameters and trace contact size) in the finishing step is very urgent. First of all, the paper goes into detail in building design solutions to create input data for the machining of STBG on CNC milling machines by profile attachment method. Moreover, the study also built the process of evaluating the machining quality of the STBG utilizing microgeometry and the contact size. The paper focuses on developing experimental equations that show the relationship between technological parameters (S, F, □Z) and roughness (Ra), deviation of tooth profile shape ($f_{f□}$), and trace contact size (bc, hc) of the Z11-16 m8 STBG transmission. From that, the optimal technology solution was identified to ensure the contact accuracy when processing the Z16-11 m8 STBG transmission on a 3-axis CNC milling machine.**

***Keywords*— straight bevel gear; 3-axis CNC milling machines; relationship equations; technological parameters; optimized model.**

I. INTRODUCTION

Straight toothed bevel gear (STBG) is widely used in many sectors of the economy, especially in the manufacturing industries of automobiles, trains, mining equipment, space, manufacturing machinery, and aviation equipment. In the field of automobile and machinery manufacturing, the demand for STBG production is very high. The attention in STBG is increasing because of the many outstanding advantages compared to other types of transmission.

In the past, because the surface forming theory of STBG was complicated and the machining technology of STBG was difficult to control in terms of quality, the STBG transmissions were usually designed with a simple structure to use in the transmission without high position accuracy needed. The use of simple structural transmissions has reduced the applicability and performance of the STBG transmissions.

However, in recent years with the high development of science and technology, the field of research and application of new technologies to the design and manufacture of high-quality STBGs has also been increasingly developed. The structure of STBGs has changed to improve efficiency and quality, which is more interested in researchers. The study of the manufacture of straight-toothed beveled gear is one of the main research directions with the advantage that the load capacity is significantly increased with the shoulder-block at the heel and toe of the tooth.

Recently, researches and applications of gear machining method on 3-axis CNC milling machine are gradually being more popular in the world. The researches related to the manufacturing of STBGs are mainly focused on the following areas: Eastwood et al. [1] have successfully established the methods of building the STBG surface based on the involute theory spherical to shape the surface from a set of points in space. Ding et al. [2] have used the theory of involute spherical to build the straight-tapered teeth surface to create CAD data on Catia V5 software for manufacturing molds in closed mold hot forging technology of gears. The study [3] applied Litvin's spatial gear theory to build the mathematical equations describing point coordinates in the Descartes coordinate system in order to describe STBG surface and helical bevel gear. Cihan and Yunus [4] investigated and evaluated the reduction of the effect of designing errors in the involute gear profile building by approximating the maximum errors based on the intersection between the bisector lines of two successive points with the theoretical involute gear profile. Thus, the above studies have applied the gear and shape characteristics of the involute profile to formulate the tooth surface equation in space and then change the input variable (tooth parameters) to digitize the surface. The studies above have modeled the surface of STBG for application in gear processing technology. However, those studies have not yet assessed the design deviations in surface digitization. These studies' surface digitization is being quantified in each free unit (usually the range of variation is 10) or there is an interest in error but has not been determined exactly. This problem leads to the difficulty to control tooth surfaces' accuracy when high precision is required [5].

The study [6] has implemented STBG machining technologies by hot forging method in terms of the specific studies of shoulder-bearing bevel gears. In our study, the authors have demonstrated that STBG can improve the damage resistance with a shoulder-bearing structure due to bending stresses caused by 8÷10% compared to gears with the same basic parameters. Kostrzewski et al. [7] presented the characteristics of STBG used in automobile differentials as well as the advantages and disadvantages of the STBG transmission. In this study, the authors conclude that the characteristic structure with shoulder-baring at both ends increases the load capacity and bending resistance of the transmission. Thus, the above studies have relied on the application of STBG types in the automotive industry to give their views on the working ability of STBG. Thereby clarifying the necessity for research and application of STBG in industry. The results show that by using industrial software, researchers have demonstrated the outstanding advantages of STBG with shoulder-baring to be more resistant to bending destruction than STBGs without shoulder-bearing with the same parameters. However, those studies still leave a lot of room for high-quality STBG machining methods [8].

Regarding the application of CNC machining in gear processing, the published studies focus on studying the application of the theoretical basis for forming gears on CNC milling machines. This is a research trend that needs more attention in gear processing technology. Pengbo et al. [9] presented the application of machining processes of molds and rotors on CNC machines to gear machining on CNC milling machines. The author has verified the process when processing Z16 m 4.5 cylindrical gears and concluded that gears' quality has reached level 4 precision according to DIN standards with micro geometry parameters. Peng et al. [10] have researched the application of CNC milling technology to processing V-shaped gears with limited structure when processed by traditional methods. Kawasak et al. [11] gave an overview of the STBG machining methods and the proposed STBG machining method on CNC milling machines and the product quality control plan on the 3-dimensional measuring machine. Gosselin et al. [12] studied the STBG machining method on a 3-axis CNC machine by building the surface forming method from the involute equation based on the gear layer's height. Through the research, the authors have come up with a method to build the toolpath data and confirm the correctness by successfully processing STBG with a surface roughness of 1.5 μm [13]. Thus, the above studies have confirmed 3-axis CNC milling machines' capabilities in gear surface machining technology. Demonstrating the processing on a CNC milling machine will thoroughly solve many traditional machining problems such as heel phenomena, structural changes, surface refinement, improve surface quality, and the limitations of specialized tooth cutters [14]. However, most researchers have not gone into evaluating the effect of the factors on the accuracy of gear machining on 3-axis CNC milling machines. There has been no research on methods of improving tooth productivity by a 3-axis CNC milling machine [15].

Regarding the characteristics of contact traces in gear processing, several studies based on gear ratios of gear pairs exist errors compared to transmission theory for many reasons. Thereby, the authors make a prediction plan to simulate the contact traces when transmission errors occur to describe the contact traces during the gearing or adjust the surface forming process to change the contact properties. Zhou et al. [16] have focused on the spatial gear theory and proposed a plan to improve the hypoid bevel gear transmission's contact ability by adjusting the transmission chain of the processing machine, indirectly changing tooth surface shape. Zschippang et al. [17] studied the simulation program to simulate cylindrical gear drive contact when considering transmission errors. Acinapura et al. [18] studied the gear theory's application to simulate gear contact in STBG when considered transmission errors. Thus, studies based on the gear ratio of gear pairs always exist as errors compared to the transmission theory for many objective reasons [19]. Thereby, the authors offer a prediction plan to simulate the contact traces when there is a transmission error on the transmission theory, lead to building the description of the contact traces in gear when there is a transmission error, or adjust the surface forming process to change the contact properties. However, these studies have not developed an explicit equation to control the contact traces or find a reliable quality control solution.

In summary, the researches on the STBG machining field on a 3-axis CNC milling machines mainly focus on applying the ability of CNC technology to process and manufacture bevel gear on 3-axis CNC milling machine, but there is no in-depth study about the effect of technological factors on the processing as well as the stability, productivity, and quality of products when machining on 3-axis CNC milling machines. Therefore, in this study, the authors focused on ensuring the design and technology to meet the design contact accuracy requirement while improving surface quality and machining productivity with the theoretical research combined with an experimental method in machining. The objective of this study is to develop experimental equations that show the relationship between technological parameters (S, F, ΔZ) and roughness (Ra), deviation of tooth profile shape ($f_{f\alpha}$) and contact trace size (bc, hc) of the Z11-16 m8 STBG transmission on a 3-axis CNC milling machine. Thereby building a basis for handling conflicts between machining time and contact quality with a multi-objective optimization problem.

II. Material and Method

A. Methodology

The process of optimizing the set of processing technology parameters is shown in Fig. 1. The process's important steps include experimental planning, conduct experimenting, data processing, relationships building, and solving the optimization problems. To support the data processing, regression modeling and optimal problem-solving in a highly reliable way, the authors used SIMULIA iSight software of Dassault Systèmes Simulia Inc. based on the theory presented above.

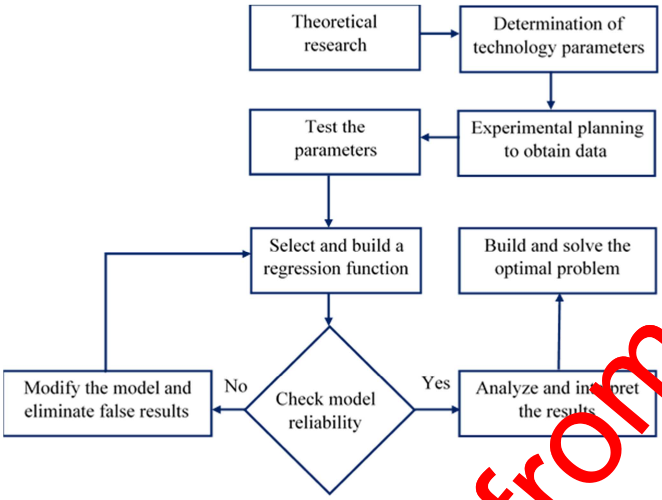

Fig. 1 Multi-goal optimization process

According to the study [20], surface roughness and dimensional accuracy in machining surfaces in space in general and tooth surfaces in particular, are directly affected by the machining parameters such as feed rate (F), spindle speed (S) and cutting depth along (ΔZ). In addition, derived from the actual gear machining experience and Matlab program, it is found that: the set of machining technology parameters (F, S, ΔZ) will affect surface accuracy and the surface deviation will change the contact point on the tooth surface thereby indirectly changing the size value of the contact trace. Therefore, the number of design variables, also called the number of input factors, was selected by the author using three factors as shown in Fig. 2.

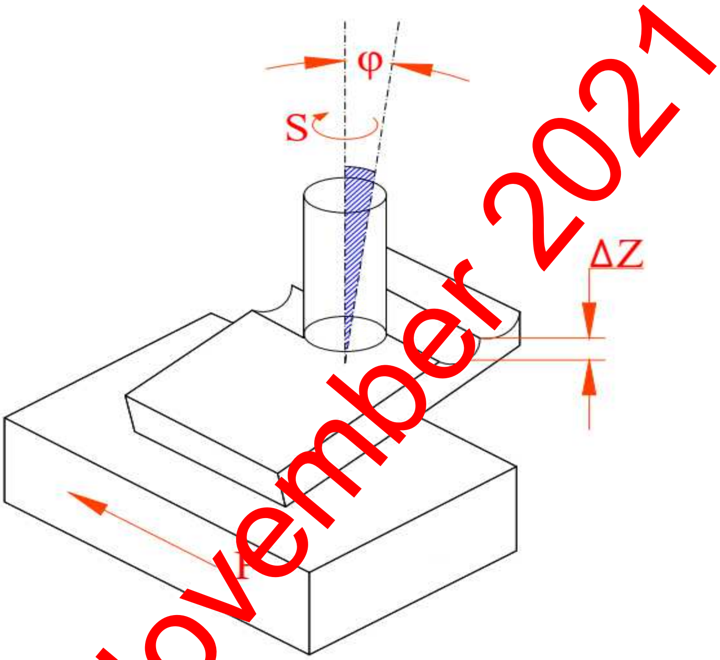

Fig. 2 Experimental input factors description

The upper bound value of the parameter set (S, F, ΔZ) is selected based on the cutting tool manufacturer's recommendation. In addition, for the upper bound of the parameter (F, S), CNC milling machines' machinability should be considered. The upper bound value of the parameter set (S, F, ΔZ) is selected based on the cutting tool manufacturer's recommendation. In addition, for the upper bound of the parameter (F, S), we need to pay attention to CNC milling machines' machinability. From the information of the machine and cutting tools, the experimental area of the parameters has determined as follows: Spindle speed: S = (6000 - 10000) rpm; Feed rate: F = (550 - 2200) mm/min; Cutting depth: ΔZ = (0.05 - 0.2) mm

The experiments are carried out with the assumptions: (i) Synthesis of interfering factors affecting machining quality is stable and constant throughout the machining process; (ii) Synthesis of interfering factors on assembly location that are stable and constant during the measuring of contact traces; (iii) The experiment only studies the effect in the finishing mode and the finishing allowance are equal at all positions with t = 0.2 (mm); (iv) Processed material is 20XM steel with chemical composition as shown in Table I. The mechanical properties of material were improved according to the study's heat treatment method by Nguyen et al. [21].

TABLE I
Composition of 20XM Steel

Chemical composition (%)							
C	Si	Mn	Cu	Ni	Cr	P	S
0.18÷0.24	0.17÷0.37	0.50÷0.80	≤ 0.03	≤ 0.03	0.70÷1.00	0.030 max	0.035 max
Mechanical and physical properties							
Tensile		Melting point		Relative elongation		Brinell hardness	
sb/Mpa		ss/MPa		%		HB	
≥835		≥540		≥10		≤179	

B. *Experimental set-up*

Experimental methods were used to collect input databases. The experimental sample to study is a Z16m8 STBG with shoulder-baring with the specifications as shown in Table II. The machining equipment is a SUPER TONADO HCMC-11000 3-axis CNC milling machine of Harfort company, with the brand with infinitely rotating speed of spindle from 0 to 10000 rpm, the maximum feed rate is 8000 mm/s. For the results to meet the reliable output, the gear machining process will be controlled for the sudden change of shear force through the force measurement module of the machine.

The surface roughness measuring device is SurftestSJ-301 from the Mitutoyo company. The roughness measurement method is measured in a direction perpendicular to the machining direction (Fig. 3). As we know, the surface roughness index will have the biggest value in the perpendicular direction and minimum when measured coinciding with the machining direction. The value taken for experimental evaluation is the Ra index (the Ra value is verified on both left and right surfaces of the tooth and takes the average maximum value on each tooth surface after 3 measurements). The machine used to check the deviation of the gear profile shape is the ZE800. The contact trace will be collected through the 5A725 contact trace tester. Measurements of width and length of the contact traces are done with a mechanical clamp with a tolerance of 0.01 mm.

TABLE II
MAIN PARAMETERS OF Z11,16-M8 TRANSMISSION

Parameters	**Dimensional**	**Active gear**	**Passive gear**
Teeth No., Z	-	16	11
Modulus, m	-	8	8
Teeth width, B	mm	30	30
Axial angle, β	degree	90	90
Pressure angle, α	degree	20	20
Accuracy (DIN), Δ	-	4	4
Coefficient correction, ξ	-	0	0
Bevel angle divided, φ_c	degree	55.48	34.52
Teeth height, h	mm	17.5	17.5
Mounting mode	-	slippery hole	slippery hole
Material	-	20XM	20XM

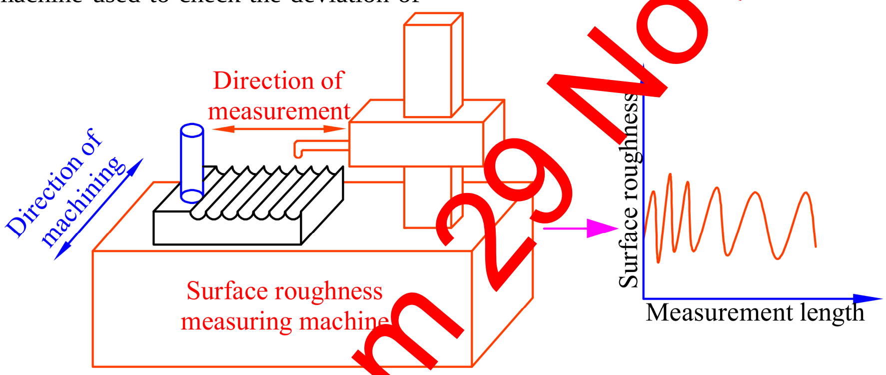

Fig. 3 The roughness measuring method

The tool used for finishing is the R2 ball milling cutter with two cutting edges GSBNH202003506 of NACHI, Japan. When programming the gear machining, the actual size of the tool is pre-determined and deviation checked during data collection (the products with variations in dimensions are eliminated and do not collect to output data). The recommended set of technological parameters for the selected tool is: S ≤ 10000 rpm, F ≤ 2200 mm/min, ΔZ ≤ 0.2 mm.

C. *The optimal Model Building*

The regression model is selected firstly to build the regression equation is the quadratic response model. The regression model's accuracy is assessed by the R-squared coefficients, mean error, and mean square error. If the SRM model is not suitable, the higher linearity models will be chosen such as the RBF model, ANN model or Kriging model with higher nonlinearity.

For the selected RSM model and the three factors number of input variables, to limit the number of the tests while ensuring the maximum level of feedback without losing the overview of the results, the orthogonal matrix planning method is used to experiments with the inputs are: (F, ΔZ) are divided into four levels and (S) is divided into three levels. According to formula (1), in order to collect input data, we need to determine the rank of the experimental matrix through the minimum number of experiments. With n> 10, the L32 experiment matrix is chosen with three inputs. The L32 matrix will have 32 test sets processed by iSight software from the Full Factor method's database giving the results shown in Table III. For each test point, the author will conduct three tests on the teeth No. 01 - 06 and 11 of the gear Z16 m8, then the average value per measurement is taken (through the actual testing, the output quality of Z11 and Z16 gear are like the test parameters, so the author chose Z16 gear to collect data).

$$n > \frac{(k+1)(k+2)}{2} \qquad (1)$$

TABLE III
EXPERIMENTAL MATRIX AND TEST DATA OF EXPERIMENTAL POINTS

Counter	Input			Output			
	Δz (mm)	F (mm/min)	S (rpm)	Ra (μm)	f_{fa} (μm)	bc (mm)	hc (mm)
L1.1	0.05	550	6000	0.4	3.9	21.6	8
L1.2	0.1	1100	6000	0.83	4.8	16.6	5.8
L1.3	0.15	1650	6000	1.66	5.3	14.6	4.8
L1.4	0.2	2200	6000	2.71	5.7	13.2	4.5
L1.5	0.05	550	6000	0.29	3.7	21.4	7.8
L1.6	0.1	1100	6000	0.85	4.7	17	6
L1.7	0.15	1650	6000	1.91	5.5	15	5.3
L1.8	0.2	2200	6000	2.9	5.9	13	4
L1.9	0.05	1100	8000	0.39	3.9	21	6.6
L1.10	0.1	550	8000	0.46	4.2	19.1	7.7
L1.11	0.15	2200	8000	1.89	4.7	14.8	4.6
L1.12	0.2	1650	8000	2.01	4.8	14.4	4.7
L1.13	0.05	1100	8000	0.3	3.7	20.8	6.5
L1.14	0.1	550	8000	0.4	3.9	21	8
L1.15	0.15	2200	8000	2	4.3	15	4.4
L1.16	0.2	1650	8000	2.01	3.5	14.2	5
L1.17	0.05	2200	10000	0.5	2.7	20	4.8
L1.18	0.1	1650	10000	0.97	4.1	17.5	5.3
L1.19	0.15	1100	10000	0.9	4.5	16.6	5.8
L1.20	0.2	550	10000	0.83	4.5	16.7	7
L1.21	0.05	2200	10000	0.55	3	21	5.2
L1.22	0.1	1650	10000	1	4	17	5
L1.23	0.15	1100	10000	0.85	4.4	16.4	6
L1.24	0.2	550	10000	0.9	4.6	16	7.5
L1.25	0.05	1650	6000	1.1	3.8	19.1	5.9
L1.26	0.1	2200	6000	1.44	5.1	16.2	4.2
L1.27	0.15	550	6000	0.74	5	16.4	7.1
L1.28	0.2	1100	6000	1.62	5.3	14.3	5.3
L1.29	0.05	1650	6000	0.5	4.1	19.4	5.5
L1.30	0.1	2200	6000	1.39	4.9	15.6	4.5
L1.31	0.15	550	6000	0.73	4.9	16.5	6.7
L1.32	0.2	1100	6000	1.55	5.5	14	5.6

After obtaining the database of output parameters (P, f_{fa}, hc, bc) corresponding to 32 experimental points as shown in Table III, iSight software is used to process data and check the models' suitability. The R2 specific data of the parameters is R2 of surface roughness reaching 95.35%; R2 of profile error is 90.18%; R2 of the contact track length is 94.98%; R2 of the contact width is 92.94%. Table IV presents the full evaluation coefficients in the approximate modeling of the factors.

TABLE IV
MODEL RELIABILITY EVALUATION

Coefficient	Ra	f_{fa}	bc	hc
Average absolute error (≤ 0.2)	0.0406	0.0558	0.0491	0.0653
Maximum error (≤ [illegible])	0.1957	0.2037	0.2199	0.1524
RSME error (≤ 0.2)	0.0572	0.0731	0.067	0.077
Determination coefficient R^2 (≥ 0.9)	0.9535	0.9018	0.9498	0.9294

III. RESULTS AND DISCUSSION

According to empirical regression theory, when the coefficient of determination > 90%, the models will meet the suitability level and do not need to convert to a higher model with higher linearity. After checking the suitability of the model, we can describe the relationships between responses to input variables according to the mathematical equations. The relationship equation of surface roughness Ra and parameter set (ΔZ, S, F) is:

$$\begin{aligned} Ra = 1.0162 - 0.5753a + 0.00032b \\ - 0.00022c + 6.72a^2 \\ - 3.1056.10^{-8}b^2 \\ + 1.0765.10^{-8}c^2 \\ + 0.0051ab \\ + 5.6855.10^{-5}ac \\ - 2.4112.10^{-8}bc \end{aligned} \quad (2)$$

The equation describes the relationship of tooth profile deviation f_{fa} with parameters (ΔZ, S, F)

$$f_{fa} = 1.0065 - 0.5733a \quad (3)$$

Equation of the contact trace length bc with parameter set (ΔZ, S, F)

$$bc = 1.0065 - 0.5733a \quad (4)$$

Equation of the contact trace width hc with parameter set (ΔZ, S, F)

$$hc = 1.0065 - 0.5733a \quad (5)$$

In which: a - Depth of cut; b - Feed rate; c - The spindle speed.

The regression equations obtained in equations (2), (3), (4), and (5) will be the data that helps the technology designer to determine the machining result parameters when the input technology parameters in the research domain are given. In addition, these are also the target functions for the optimization of technological parameters.

Besides the mathematical equations representing relationships between parameters, we also obtain diagrams showing multidimensional relationships from experimental databases to evaluate the trends and influence levels on machining quality factors.

A. Evaluate the Effect of the Parameter Set on the Shape Error f_{fa}

Analysis of f_{fa} coefficient data with constant S values (6000 rpm - S the effect of S to f_{fa} value is rather small) at four values ΔZ = {0.05, 0.075, 0.1 and 0.2}. Fig. 4 shows the relationship diagram constructed linearly on the intermediate point data giving us an overview of the relationships. Through the diagram in Fig. 4 we can see that with small ΔZ, profile shape deviation tends to be uniform, while when ΔZ is large, the deviation has a large difference and is harder to control. With the data from the graph of relation f_{fa}, we see that the graph of the effect of the longitudinal shear depth has the largest slope. This means that in the research domain, the ΔZ value has a great influence on the variation in profile shape error.

In addition, the approximate model results also give us the relational results in contour or 3D format as shown in Fig. 5 to evaluate in specific cases.

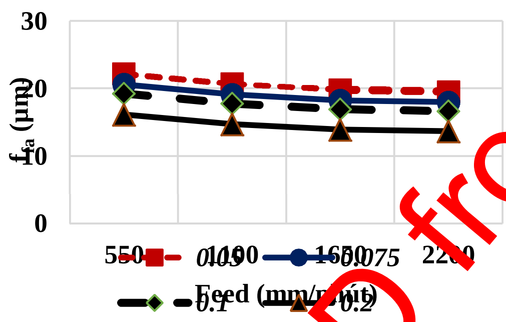

Fig. 4 f_{fa} values with S = 6000 rpm

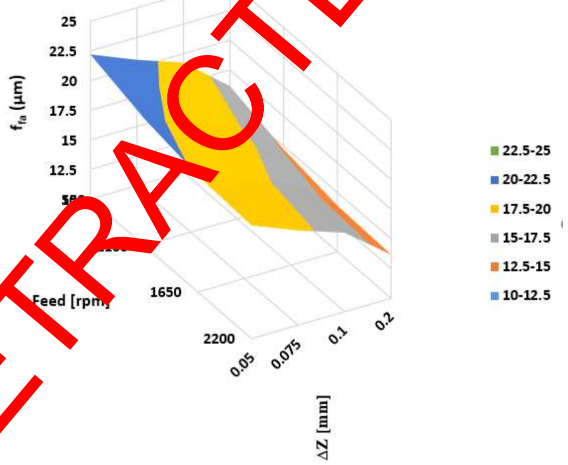

Fig. 5 Relationship between ffa with ΔZ and F in S = 6000 rpm mode

B. Evaluate the effect of the parameter set on the contact trace length bc

Analyze bc data with constant S values (6000 rpm) at four values of ΔZ = {0.05, 0.075, 0.1 and 0.2}. Through the diagram in Fig. 6, we see that the index bc varies equally with the values of ΔZ.

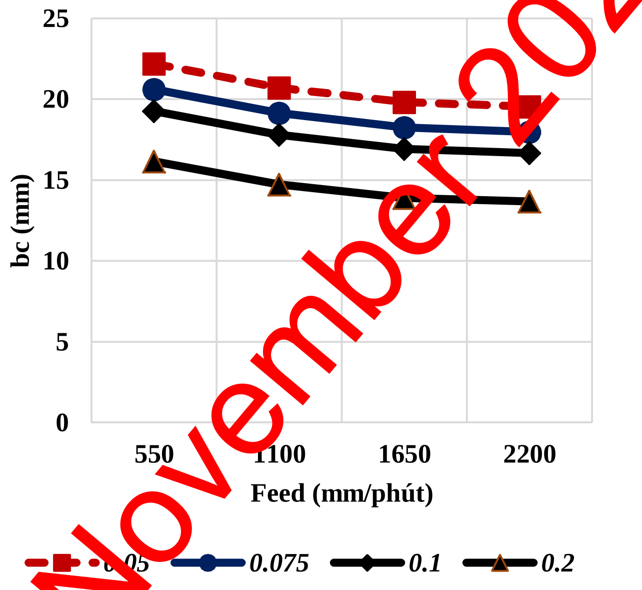

Fig. 6 bc values with S = 6000 rpm

The diagram of Fig. 7 shows the relationship between experimental parameters and the value of the contact trace length bc.

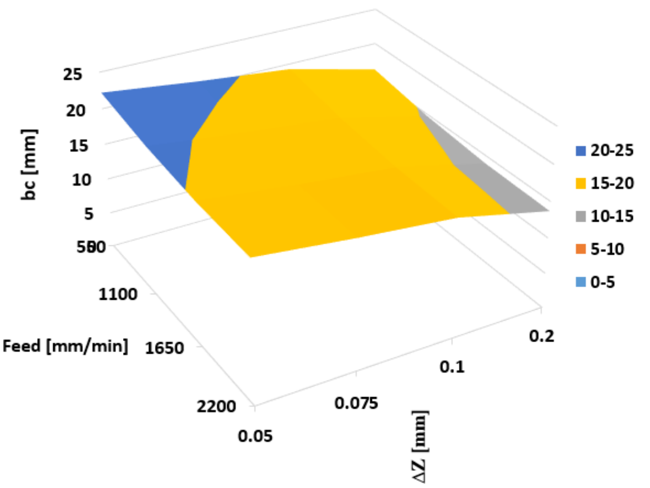

Fig. 7 Relationship diagram between bc with ΔZ and F in S = 6000 rpm mode

C. Evaluate the effect of the parameter set on the contact trace height hc

Also with the parameter S = 6000 rpm and ΔZ = {0.05, 0.075, 0.1 and 0.2} mm we get the diagram of hc as shown in Fig. 8, we see that the hc index of linear variation has degree steeper than bc and the values tend to converge when advancing is large. The diagram of Fig. 9 shows the relationship between experimental parameters and the value of the contact trace length hc.

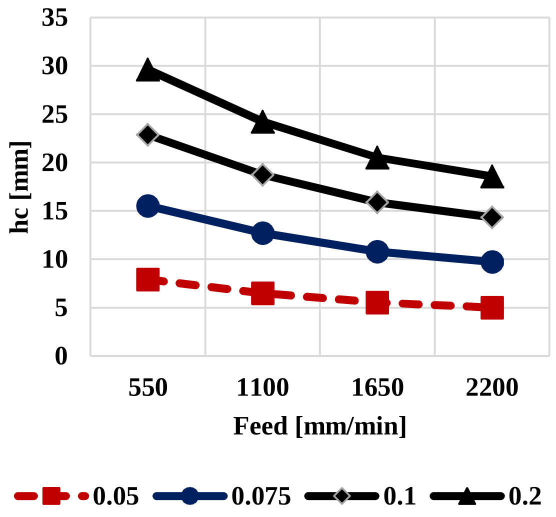

Fig. 8 hc values with S = 6000 rpm

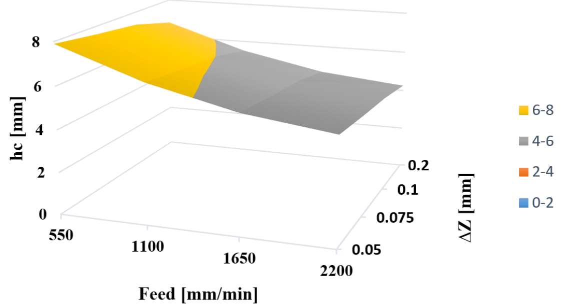

Fig. 9 The relationship diagram between hc with ΔZ and F in S = 6000 rpm mode

D. Evaluate the effect of the parameter set on micro undulating Ra

Also with the parameter S = 6000 rpm and ΔZ = {0.05, 0.075, 0.1 and 0.2} mm we obtain the diagram of Ra as shown in Fig. 10, we see that when F increases, Ra value increases, however, with the bigger residue, the growth rate of Ra tends to be faster. The diagram in Fig. 11 shows the relationship between experimental parameters and the micro undulating Ra's value.

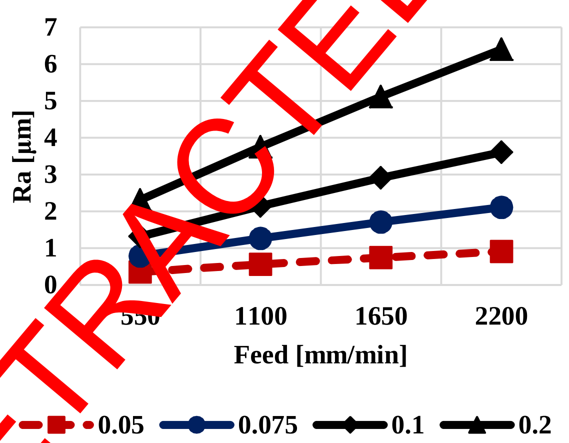

Fig. 10 Ra value with S = 6000 rpm

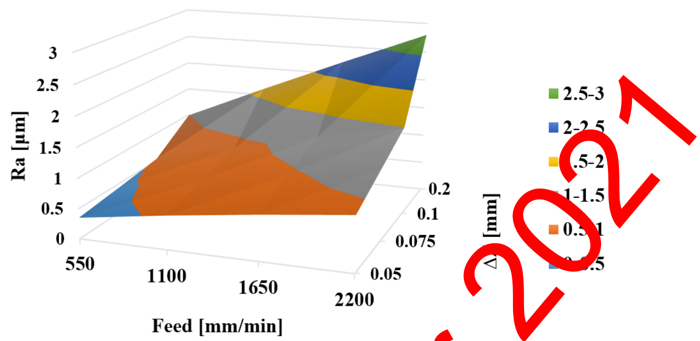

Fig. 11 Relationship diagram between Ra with ΔZ and F in S = 6000 rpm mode

E. Optimizing the problem

The researched results above showed that the longitudinal cutting depth must be small when we want to achieve good contact trace size. However, the small depth of longitudinal cutting will increase the machining distance, which means the machining time will be increased. This causes a conflict of interest between machining productivity and product quality. To solve this problem in the most reasonable way, the problem of multi-objective optimization with separate tasks must be used in which, the most reasonable problem is finding the maximum set of values (bc, hc, F, ΔZ), with the condition that Ra and $f_{f\alpha}$ must satisfy the requirements of gloss and machining accuracy. The problem will be described in the form of finding Ω = [ΔZ, S, F] to minimize the machining time (maximize ΔZ and maximize F); Maximum contact trace (maximize lc and maximize hc). At the same time, the following conditions must be satisfied:

$$\begin{cases} f_{f\alpha} \le [f_{f\alpha}] \\ R_a \le [R_a] \\ 6000 \le S \le 10000 \\ 550 \le F \le 2200 \\ 0.05 \le \Delta Z \le 0.2 \end{cases}$$

Use the NSGA-II algorithm to find the optimal result, after running the algorithm with the parameter set (20-20-0.9-10-20) when there is no constraint, the result is the optimization machining parameter set as shown in Fig. 12. Depending on the specific case, the designer can choose a suitable parameter set according to technical requirements.

In case the transmission needs to be machined with surface roughness Ra ≤ 0.63µm and level 4 profile shape accuracy (f_{fa} ≤ 6µm), we remove the non-feasible points and the program proposes the solution in the run of 2352 with (ΔZ = 0.058 mm, F = 1818 mm/min, S = 9102 rpm) and gives us the prediction results (bc = 19.90 mm, hc = 5.35 mm, f_{fa} = 3.44 µm, Ra = 0.542 µm). Test the parameters set, we get that the deviation between the real results and the calculated parameters is: bc 7%, hc 6%, $f_{f\alpha}$ 3% and Ra 6%, respectively. This deviation is acceptable in mechanical machining.

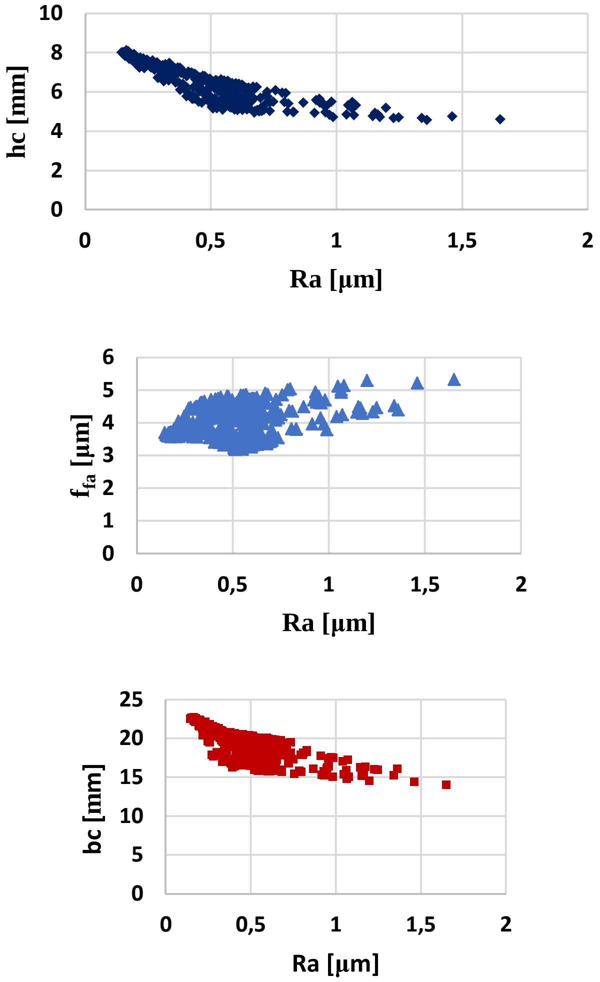

Fig. 12 Pareto optimization diagram in case of no constrain

IV. CONCLUSION

By the scientific experimental method to systematically affect the machining technology factors, the author has collected the research object information to draw useful conclusions for the selection of machining parameters suitable for each specific case in the surface adhesion method on 3-axis CNC milling machine. Moreover, measuring and calculating according to measurement theory and experimental planning and tools for optimizing technological parameters. Experimental regression functions have been established between technological parameters (F, S, ΔZ) with surface roughness (Ra), shape error (f_{fa}), contact trace size (bc, hc)) when machining the Z16-11 m8 STBG transmission on a 3-axis CNC milling machine, this is the basis for machining the STBG on a 3-axis CNC milling machine and is the premise for the study of other gears. A solution has been developed to ensure the required contact trace size when machining the STBG Z11-16m8 on a CNC milling machine. A solution has been found to resolve the conflict of interests between machining productivity and machining quality when machining STBG on.

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