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Taguchi-fuzzy multi-response optimization in fly cutting process and applying in the actual hobbing process

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Abstract

Background: Applying nanofluid made by adding alumina nanoparticles to industrial oil may reduce the cutting force, friction, and cutting temperature and, from that, improve the tool life in the hobbing process. However, it is difficult to set up the experiment for the actual gear hobbing process, because measuring the cutting force and temperature in the hobbing process is very complicated and expensive. Therefore, a fly hobbing test on the horizontal milling machine was performed to simulate the actual hobbing process.

Methods: In this research, the fuzzy theory was combined with the Taguchi method in order to optimize multi-responses of the fly hobbing process as the total cutting force, the force ratio F_z/F_y, the cutting temperature, and the surface roughness.

Results: The optimal condition—A1B1C3 (the cutting speed 38 mpm\, the nanoparticle size 20 nm, and concentration 0.5%)—was determined by analyzing the performance index (FRTS) of the fuzzy model. Furthermore, this condition was applied to the actual hobbing process in the FUTU1 Company and compared with the actual conditions of this company and other conditions using the nanolubricant with 0.3% Al_2O_3, 20 nm. The results show that it can reduce a maximum 39.3% of the flank wear and 59.4% of the crater wear on the hob when using the optimal conditions.

Conclusions: The study indicates that the optimal condition determined by using Taguchi-Fuzzy method can be applied in the FUTU1 company with the high efficiency.

Keywords: Gear hobbing, Optimization, Fuzzy, Fly cutting, Cutting fluid, Nanofluid

Background

The hobbing processes with complex kinematic motions cause the high friction coefficient, great cutting force, and high temperature. Those properties lead to hob wear, the main cause in reducing the quality of the hobbed gear, so using the suitable cutting fluid is very important. In recent years, nanolubricant, mixing the normal lubricant with nanoparticles, gradually became a new trend study for metal cutting enhancement. Especially, the Al_2O_3 nanoparticles have many properties such as heat resistance, spherical shape, and a high specific temperature, consistent with adding to the industrial oils, so it is suitable for the machining process (Sharma et al, 2015). Malkin and Sridharan (2009) indicated that the new cutting fluids mixing the Al_2O_3 powder with water were used to reduce the grinding forces and the cutting temperature and improve the surface roughness. Vasu and Reddy (2011) indicated that the using of the cutting fluids added Al_2O_3 nanoparticles which can decrease the tool wear, temperature, and surface roughness in machining 600 aluminum alloys. And the influences of nanofluids on surface roughness and tool wear in the hobbing process concluded that using nanofluids with Al_2O_3 nanoparticles resulted in decreasing surface roughness values (Ra, Rz) and tool wears in the manufactured spur gears, researched by Khalilpourazary and Meshkat (2014). But, the effect of Al_2O_3 nanoparticle size and concentration that added to the cutting

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fluids in gear hobbing on the fundamental parameters of the hobbing process has not been published yet.

Further, the experiments in the hobbing process are too expensive as the cost of the hob tools or a gear hobbing machine is very high, and it is very difficult to measure the cutting force and temperature during the machining process. A fly hobbing experiment was designed to simulate the actual hobbing process by many authors as Rech (2006), Umezaki et al. (2012), and Stein et al. (2012). The present paper experimentally investigates applying new nanofluids to reduce the hob wear by reducing the cutting force, friction, and cutting temperature in the fly hobbing process. A fuzzy model based on the Taguchi experiment design has been used to optimize the multi-responses of the fly hobbing process. Using Minitab 16, the signal-to-noise (S/N) ratios for different outputs of the fuzzy model (the total cutting force, the force ratio F_z/F_y, the cutting temperature, and the surface roughness) were calculated by the Taguchi method. Then, the S/N ratios are used to determine a resultant index (the FRTS index) for estimating the fly hobbing process by using fuzzy logic theory. These FRTS values were used for multi-response optimization and gave the optimum parameter level for the fly hobbing process. Furthermore, the optimum parameters were applied for the actual hobbing process and compared with the initial parameters.

Methods

Experimental setup

A fly hobbing test was performed on milling machining with a single tool coated with the TiN film and the same profile as a hob tooth used in a gear manufacture line at the Machinery Spare Parts No.1 Joint Stock (FUTU1) Company (see Fig. 1). The cutting conditions of the fly cutting process such as cutting depth and feed rate are set as becoming the same conditions with the hob tooth carrying the biggest load on the real hobbing process used in FUTU1, shown in Table 1.

Figure 2a shows the shape of chips produced by the tips of hob teeth while Fig. 2b shows the state of cutting in slot milling. The maximum chip thickness (s) and chip length (L) are calculated from the characteristics of the hobbing process by using equations by Hoffmeister 1970. The fly cutting process is performed with the cutting depth h and feed f' to give chips the same size as those produced by a hob tooth. The cutting depth h and feed f' can be calculated by the formals $h = r.(1 - \cos\theta)$; $f' = S/\sin\theta$, and $\theta = L/r$. So, the characteristics of the fly hobbing process are calculated and also showed in Table 2.

The workpiece made of chromium molybdenum steel (SCM420) was fixed on a KISTLER dynamometer. The KISTLER dynamometer mounted on the worktable of the milling machine allowed three dynamic forces to be measured. The total cutting force R is calculated from two measured forces F_y and F_z, as Fig. 3. Moreover, San Juan et al. (2010) found the formal calculation for the friction coefficient based on the thickness chip achieves its maximum value:

$$\mu = \frac{F}{N} = tan\left(\theta - \arctan\left(\frac{F_Z}{F_y}\right)\right) \tag{1}$$

where: μ is the friction coefficient value and θ is the angle calculated based on the thickness chip achieving its maximum value as Fig. 2b.

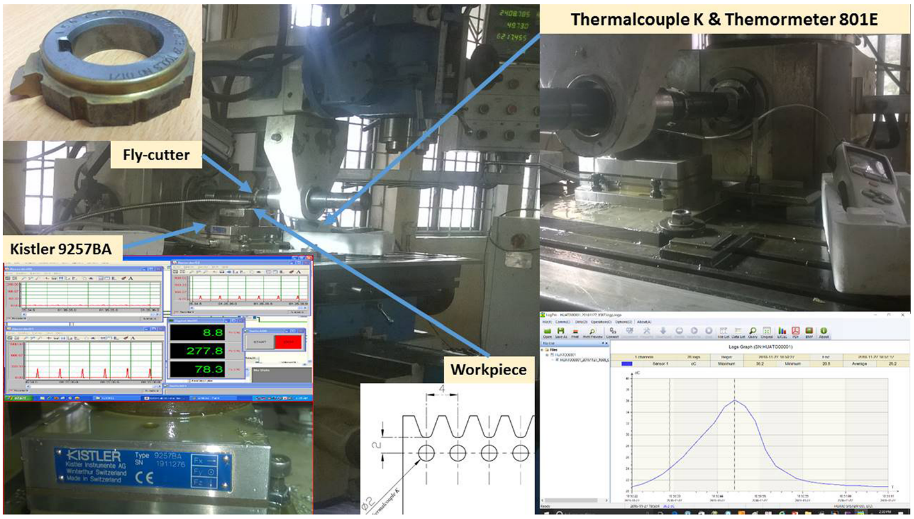

Fig. 1 Experimental setup

Table 1 The parameters of the hobbing process (from FUTU1)

Tool	Module (mm)	Outside diameter (mm)	Rake angle (°)	Depth of cut (mm)	Feed rate (mm)	Spindle speed (mpm)
DTR-DIN-AA-TIN	1.75	60	0	4375	1.27	200–300

According to Eq. (1), the friction coefficient can be represented by the ration force F_z/F_y; the friction coefficient value decreases when the ratio force F_Z/F_y increases. So, the ratio force F_Z/F_y was one of the output parameters of the analysis experiment.

The thermocouple type k was inserted into the workpiece in order to determine the temperature of the workpiece by using the thermometer 801E HUATO, shown in Fig. 1. The ISO VG46 industrial oil was popularly used for the gear-cutting processes in the FUTU1 Company due to its economic characteristics. The Al_2O_3 nanoparticles made by the US Research Nanomaterials have a high sintering temperature, heat resistance, and coefficient of heat transfer and spherical structure. According to Khalilpourazary, nanopowders were mixed with the industrial oils following the weight ratio of 0.1% ÷ 0.5% in order to produce the nanolubricant. To compare and evaluate the cooling-lubrication effectiveness of the nanofluid, Al_2O_3 nanoparticles with the size of 20, 80, and 135 nm, and the concentration of 0.1, 0.3, and 0.5% were selected according to the economical requirement.

Design of Taguchi experiments

The Taguchi design was chosen to research the effects of some factors on the total cutting force, the force ratio F_z/F_y, the cutting temperature, and the surface roughness in the fly hobbing process. Table 3 shows the L18 orthogonal array chosen from Taguchi's standard-orthogonal-array table. The Taguchi method popularly uses the S/N ratio to consider the influence of the survey parameters on the output parameters. The greater the value of the S/N ratio, the less the impact of the noise parameters. The S/N ratio is determined as follows (Roy, 1990):

$$S/N = -10\mathrm{Log}_{10}[\mathrm{MSD}] \tag{2}$$

where MSD is the mean square deviation for output parameters. The MSD values can be determined by three types of the S/N ratio characteristics: nominal the better, smaller the better, and greater the better. According to Eq. (1), the friction coefficient value decreases when the ratio force F_Z/F_y increases. Thus, to reduce the friction coefficient, the greater the

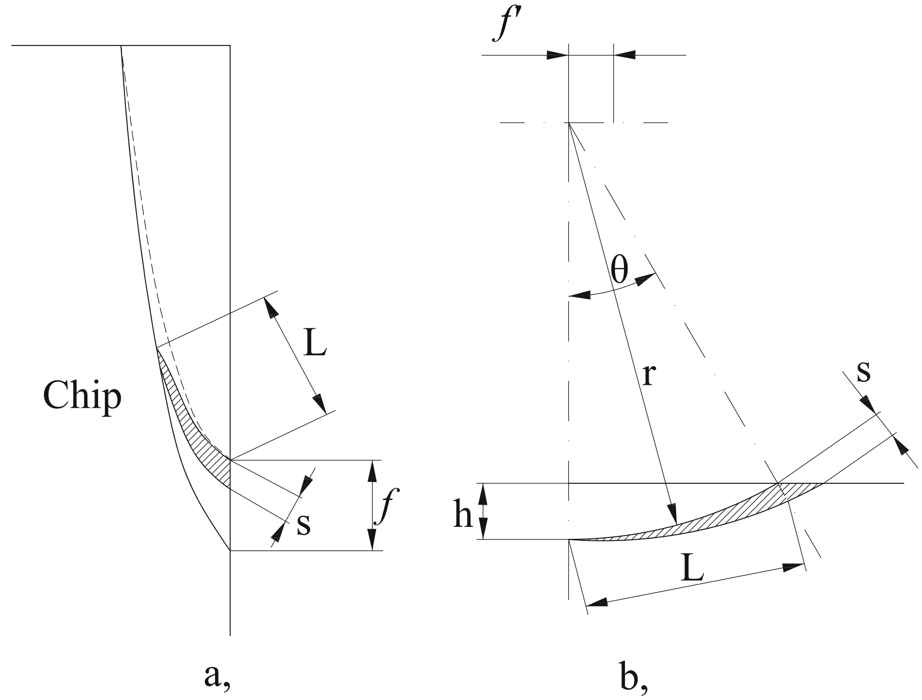

Fig. 2 The size of chip in gear hobbing process (**a**) and in fly hobbing test (**b**)

Table 2 The dimensions of maximum chips produced during hobbing and the cutting condition required to produce the same chips in fly hobbing on the milling machine

Hobbing process				Fly hobbing process on milling machine	
Number of threads of hob	Feed of hob (mm/rev)	Length of chips (mm)	Max thickness of chip (mm)	Depth of cut (mm)	Feed of table (mm/rev)
1	1.27	12.92	0.108	2.75	0.259

better quality characteristic for the ratio force F_Z/F_y must be taken. With the total force, temperature and surface roughness, the smaller the better quality parameters were chosen to calculate the S/N ratio.

The MSD for the greater the better quality characteristic can be calculated by (Montgomery, 2004):

$$\mathrm{MSD} = \frac{1}{n}\sum\nolimits_{i=1}^{n}\frac{1}{x_i^2} \tag{3}$$

The MSD for the smaller the better quality characteristic can be calculated by (Montgomery, 2004):

$$\mathrm{MSD} = \frac{1}{n}\sum\nolimits_{i=1}^{n}x_i^2 \tag{4}$$

where x_i is the total cutting force and n is the number of experiments.

The fuzzy logic optimization based on the Taguchi methodology

The theory of fuzzy logic is the mathematical model, suitable to solve uncertain and vague information. So, the fuzzy model can be used to optimize multi-objects by converting the S/N ratios of the Taguchi experiment into a single index. However, the S/N ratio values are calculated for the quality properties with different units by using the Taguchi model and converted to the non-unit values. And, “the greater the better” and “the smaller the better” categories are chosen to transform the S/N ratio values into a range between 0 and 1, while 0 means the worst performance and 1 the best. The normalized value for the smaller the better category can be determined by:

$$x_i^*(k) = \frac{\max(x_i(k)) - x_i(k)}{\max(x_i(k)) - \min(x_i(k))} \tag{5}$$

The normalized value for the greater the better category can be calculated by:

$$x_i^*(k) = \frac{x_i(k) - \min(x_i(k))}{\max(x_i(k)) - \min(x_i(k))} \tag{6}$$

where $x_i^*(k)$ is the value after normalization for the kth response under ith experiment.

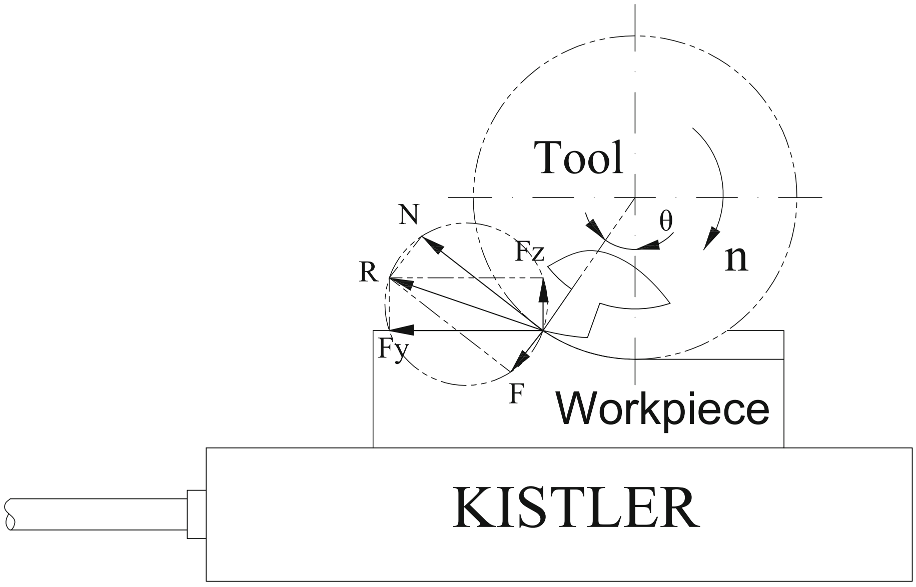

Fig. 3 The cutting force of the fly hobbing process

Table 3 Experimental design based on L18 orthogonal array

Exp. no.	Cutting speed *A* (mpm)	Nano. size *B* (nm)	Nano. con. *C* (%)
1	38	20	0.1
2	38	20	0.3
3	38	20	0.5
4	38	80	0.1
5	38	80	0.3
6	38	80	0.5
7	38	135	0.1
8	38	135	0.3
9	38	135	0.5
10	50	20	0.1
11	50	20	0.3
12	50	20	0.5
13	50	80	0.1
14	50	80	0.3
15	50	80	0.5
16	50	135	0.1
17	50	135	0.3
18	50	135	0.5

A fuzzy model was set up for the normalized values for the *S*/*N* ratios of the Taguchi experiment, shown in Fig. 4.

The fuzzy model consists of a fuzzifier, an inference engine, the membership functions, the fuzzy rules, and defuzzifier (Klir & Yuan, 2005). In the study, the fuzzifier uses membership functions to fuzzily the normalized values of the *S*/*N* ratios, and the inference system completes a fuzzy based on fuzzy rules to create the fuzzy index. The fuzzy rules are generated from the group IF&THEN rules of the parameter inputs.

The fuzzy rules can be shown as:

Rule i: If x_1 is A_{i1}; x_2 is A_{i2}; x_3 is A_{i3}...; and x_j is A_{ij} then y_i is C_i;
$i = 1; 2; \ldots ; N$;

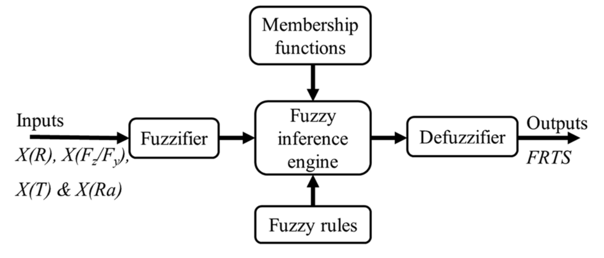

Fig. 4 Fuzzy model for FRTS

where N is the total number of fuzzy rules, x_j ($j = 1,2,\ldots,s$) are the normalized values, y_i are the fuzzy values, and A_{ij} and C_i are fuzzy sets defined by membership functions $\mu_{Aij}(x_j)$ and $\mu_{Ci}(y_j)$, respectively. The Mamdani implication method is chosen to perform for the inference of a set of different rules; the collected output for the N rules is

$$\mu_{C_i}(y_i) = \max\{\min_i[\mu_{A_{i1}}(x_1), \mu_{A_{i2}}(x_2), , \mu_{A_{is}}(x_j)]\} \tag{7}$$

And then, the defuzzifier converts the fuzzy outputs into the absolute values. The defuzzification method is used to find non-fuzzy value y_0 (in this paper, the non-fuzzy value is FRTS): $y_o = \frac{\sum y_i \cdot \mu_{C_i}(y_i)}{\sum \mu_{C_i}(y_{i.})}$

Results and discussion

Multi-objective optimization

The *S*/*N* ratio is used to determine the optimal parameter settings. The values *S*/*N* for the total cutting forces, the ratio forces F_z/F_y, the cutting temperatures, and the surface roughness were calculated by Minitab 16, shown in Table 4. The normalized input parameters were calculated by the formulas (5) and (6), shown in Table 4. In this study, the fuzzy model has been designed by MATLAB 9, in order to optimize multi-responses for the fly hobbing process, illustrated in Fig. 5. There are three fuzzy sets for variables of input parameters: small (S), medium (M) and high (H). The membership functions of the output variable are illustrated in Fig. 6. With four inputs and their three fuzzy sets, there are 34 (81) fuzzy rules used for this model. And there are seven fuzzy sets for variables of FRTS: very very small (VVS), very small (VS), small (S), medium (M), high (H), very high (VH), and very very high (VVH). The fuzzy rules are determined and shown in Table 4. The final FRTS output values were calculated by the defuzzification method applying the fuzzy rules in Table 5 with the Mamdani inference of MATLAB 9 software and shown in Fig. 7. The maximum value of FRTS has the highest ranking and the minimum value of FRTS has the lowest ranking as also shown in Table 6. The maximum average FRTS for minimum total cutting force, maximum ratio force F_z/F_y, minimum cutting temperature, and minimum surface roughness are obtained at a level 1 (38 mpm) of cutting speed, level 1 (20 nm) of nanoparticle size, and level 3 (0.5%) of nanoparticle concentration is A1B1C3.

Table 4 The *S*/*N* ratio and normalized values for input parameters

Exp. no.	The cutting force						Temperature		Surface roughness	
	F_y (*N*)	F_z (*N*)	*R*	*S*/*N* (*R*)	F_z/F_y	*S*/*N* (F_z/F_y)	*t*	*S*/*N* (*t*)	Ra	*S*/*N*(Ra)
1	277.8	78.3	288.62	− 49.2066	0.282	− 10.9994	32.6	− 30.2644	0.1817	14.8129
2	232.6	73.6	243.97	− 47.7466	0.316	− 9.99464	29.3	− 29.3374	0.1175	18.59924
3	190.8	61.7	200.53	− 46.0435	0.323	− 9.80586	24.7	− 27.8539	0.2022	13.88438
4	282.9	77.3	293.27	− 49.3454	0.273	− 11.2691	32.1	− 30.1301	0.3705	8.624236
5	255.2	72.1	265.19	− 48.4711	0.283	− 10.9789	27.6	− 28.8182	0.312	10.11691
6	235.6	70.1	245.81	− 47.8119	0.298	− 10.5291	24.1	− 27.6403	0.5125	5.806123
7	293.3	82.2	304.60	− 49.6746	0.280	− 11.0488	34.7	− 30.8066	0.5888	4.600644
8	282.8	80.8	294.12	− 49.3704	0.286	− 10.8814	30.9	− 29.7992	0.4327	7.276262
9	260.1	74	270.42	− 48.6408	0.285	− 10.9182	27.0	− 28.6273	1.0337	− 0.28789
10	282.4	75.2	292.24	− 49.3148	0.266	− 11.4929	34.8	− 30.8316	0.1423	16.9359
11	246.3	72.3	256.69	− 48.1883	0.294	− 10.6465	30.1	− 29.5713	0.0894	20.97325
12	222	69.1	232.51	− 47.3287	0.311	− 10.1375	25.1	− 27.9935	0.161	15.86348
13	296.2	78.3	306.37	− 49.7251	0.264	− 11.5565	34.0	− 30.6296	0.3059	10.28841
14	262.8	74.1	273.05	− 48.7247	0.282	− 10.9961	29.1	− 29.2779	0.25	12.0412
15	242.9	70.9	253.04	− 48.0636	0.292	− 10.6956	27.7	− 28.8496	0.57	4.882503
16	295	84.6	306.89	− 49.7397	0.287	− 10.849	36.2	− 31.1742	0.3565	8.958809
17	283	80.8	294.31	− 49.3761	0.286	− 10.8875	32.3	− 30.1841	0.4319	7.292336
18	263.5	76.2	274.30	− 48.7644	0.289	− 10.7765	28.2	− 29.0050	0.9397	0.540215

The analysis of variance (ANOVA)

The ANOVA analysis results with 96.8% confidence intervals were used to determine the impact of the coefficient on the multiple responses (FRTS) and shown in Table 7. The values of critical *F* ratio were determined and shown in Table 7. The result indicates that control parameters *B* (nanoparticle size) and *C* (nanoparticle concentration) are the greatest effect parameters to the FRTS values (Table 8).

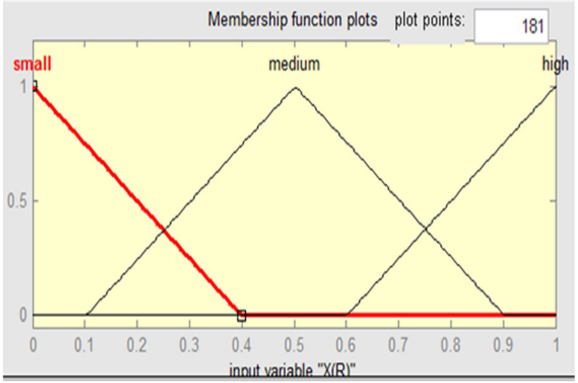

Fig. 5 The membership functions for the input parameters

Applying the optimal conditions on the actual hobbing process

The flank wear of hob with optimal conditions and normal conditions were measured by the Zeiss optical microscope after the 500th gears were machined, shown in Fig. 8. Figure 8a shows the flank wear of the hob under the normal conditions using the normal oils (177.84 μm), and the result shows that the TiN coating was cracked and stripped; the great mechanism wears of the HSS material were detected. Figure 8b shows the flank wear of the hob under the optimal conditions using the

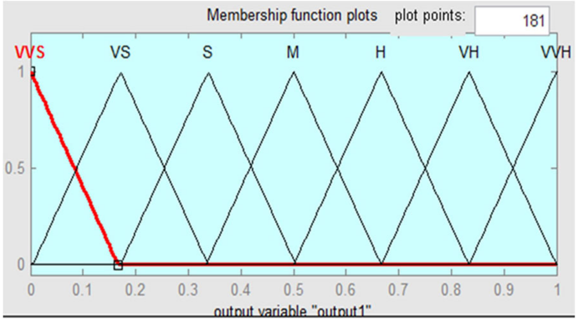

Fig. 6 The membership functions for FRTS

Table 5 Fuzzy rule table

TT	X (R)	X (F_z/F_y)	X (T)	X (Ra)	FRTS
1	S	S	S	S	VVS
2	S	S	S	M	VS
3	S	S	S	H	VS
4	S	S	M	S	VS
5	S	S	M	M	VS
6	S	S	M	H	S
7	S	S	H	S	S
8	S	S	H	M	S
9	S	S	H	H	S
10	S	M	S	S	S
11	S	M	S	M	S
12	S	M	S	H	S
13	S	M	M	S	S
14	S	M	M	M	S
15	S	M	M	H	S
16	S	M	H	S	M
17	S	M	H	M	M
18	S	M	H	H	M
19	S	H	S	S	S
20	S	H	S	M	S
21	S	H	S	H	S
22	S	H	M	S	M
23	S	H	M	M	M
24	S	H	M	H	M
25	S	H	H	S	M
26	S	H	H	M	M
27	S	H	H	H	M
28	M	S	S	S	S
29	M	S	S	M	S
30	M	S	S	H	S
31	M	S	M	S	S
32	M	S	M	M	M
33	M	S	M	H	M
34	M	S	H	S	M
35	M	S	H	M	M
36	M	S	H	H	M
37	M	M	S	S	M
38	M	M	S	M	M
39	M	M	S	H	M
40	M	M	M	S	M
41	M	M	M	M	M
42	M	M	M	H	M
43	M	M	H	S	M
44	M	M	H	M	M
45	M	M	H	H	M
46	M	H	S	S	H
47	M	H	S	M	H
48	M	H	S	H	H
49	M	H	M	S	H
50	M	H	M	M	H
51	M	H	M	H	H
52	M	H	H	S	VH
53	M	H	H	M	VH
54	M	H	H	H	VH
55	H	S	S	S	M
56	H	S	S	M	M
57	H	S	S	H	M
58	H	S	M	S	M
59	H	S	M	M	M
60	H	S	M	H	H
61	H	S	H	S	H
62	H	S	H	M	H
63	H	S	H	H	H
64	H	M	S	S	H
65	H	M	S	M	H
66	H	M	S	H	H
67	H	M	M	S	H
68	H	M	M	M	H
69	H	M	M	H	H
70	H	M	H	S	VH
71	H	M	H	M	VH
72	H	M	H	H	VH
73	H	H	S	S	VH
74	H	H	S	M	VH
75	H	H	S	H	VH
76	H	H	M	S	VH
77	H	H	M	M	VH
78	H	H	M	H	VH
79	H	H	H	S	VH
80	H	H	H	M	VH
81	H	H	H	H	VVH

nanolubricants (107.98 μm). This result indicated that the width of flank wear using the optimal conditions using nanofluids is smaller than that using the normal condition of the FUTU 1 Company. It clearly reveals that the width of flank wear reduces about 39.3% under the optimal condition with the nanolubricant compared to the normal conditions.

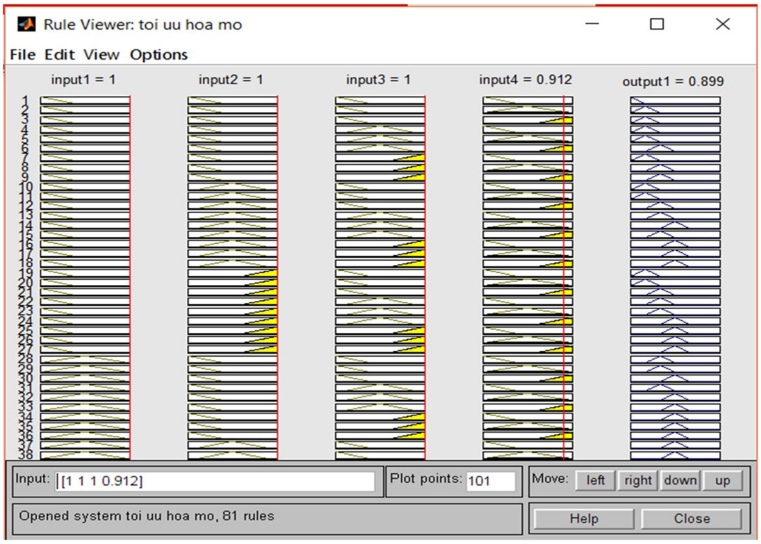

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Fig. 7 Calculating the final FRTS outputs on MATLAB 9

Table 6 The fuzzy value FRTS

Exp. no.	*V* (mpm)	Size (nm)	Nano con. (%)	*x*(*R*)	$x(F_z/F_y)$	*x*(*T*)	*x*(Ra)	FRTS	Ranks	
1	38	20	0.1	0.144	0.318	0.257	0.710	0.348	11	
2	38	20	0.3	0.539	0.892	0.520	0.888	0.657	3	
3	38	20	0.5	1.000	1.000	0.940	0.667	0.837	1	
4	38	80	0.1	0.107	0.164	0.295	0.419	0.285	13	
5	38	80	0.3	0.343	0.330	0.667	0.489	0.418	6	
6	38	80	0.5	0.522	0.587	1.000	0.287	0.5	4	
7	38	135	0.1	0.018	0.290	0.104	0.230	0.269	14	
8	38	135	0.3	0.100	0.386	0.389	0.356	0.365	10	
9	38	135	0.5	0.297	0.365	0.721	0.000	0.406	7	
10	50	20	0.1	0.115	0.036	0.097	0.810	0.224	15	
11	50	20	0.3	0.420	0.520	0.454	1.000	0.5	4	
12	50	20	0.5	0.652	0.811	0.900	0.760	0.714	2	
13	50	80	0.1	0.004	0.000	0.154	0.497	0.177	16	
14	50	80	0.3	0.275	0.320	0.537	0.580	0.384	8	
15	50	80	0.5	0.453	0.492	0.658	0.243	0.5	4	
16	50	135	0.1	0.000	0.404	0.000	0.435	0.336	12	
17	50	135	0.3	0.098	0.382	0.280	0.357	0.366	9	
				18	50	135	0.5		0.264	0.446

Table 7 Analysis of variance (ANOVA) for the FRTS

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Cutting speed (*A*)	1	0.0112	0.0112	0.0112	12.13	0.025
Nanoparticle size (*B*)	2	0.125357	0.125357	0.062679	67.87	0.001
Nanoparticle concentration (*C*)	2	0.259467	0.259467	0.129734	140.47	0.000
$A \times B$	2	0.020931	0.020931	0.010466	11.33	0.023
$A \times C$	2	0.000827	0.000827	0.000413	0.45	0.668
$B \times C$	4	0.071170	0.071170	0.017792	19.27	0.007
Error	4	0.003694	0.003694	0.000924	–	–
Total	17	0.492647	–	–	–	–

Table 8 Response table for FRTS

Level	Cutting speed (*A*)	Nanoparticle size (*B*)	Nanoparticle con. (*C*)
1	0.4539	0.5467	0.2732
2	0.4040	0.3773	0.4483
3	–	0.3628	0.5653
Delta	0.0499	0.1838	0.2922
Rank	3	2	1

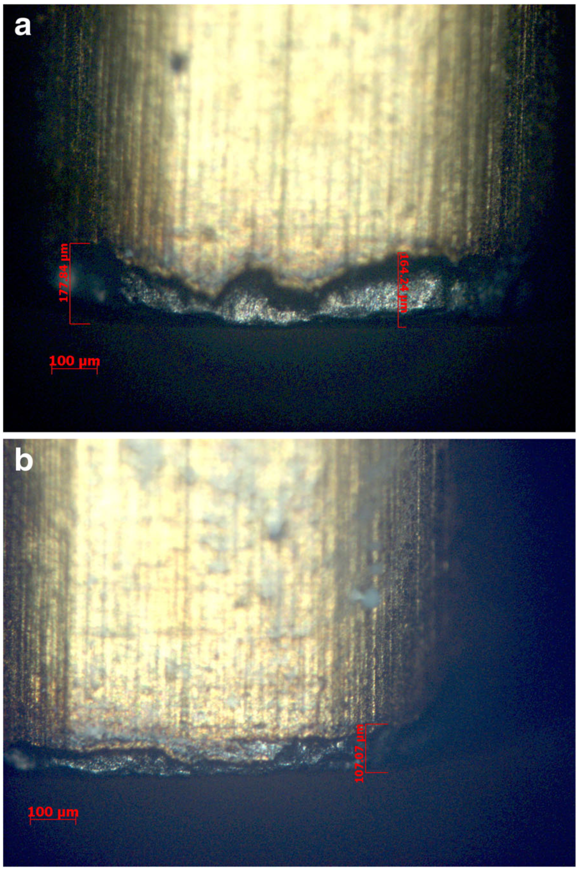

Fig. 8 Flank wear of the hob with **a** normal conditions using normal lubricant and **b** optimal conditions using nanolubricant (0.5% Al_2O_3, 20 nm*)*

After 500 gears were machined, the crater wear of the rake surface of hob was taken by the Zeiss optical microscope at three positions on the rake face (right, center, and left), shown in Figs. 9 and 10. The result revealed that a portion of the TiN coating is removed from the rake face. Figure 9 shows the crater wear of hob (right 154.72 µm, center 163.22 µm, and left 158.98 µm position on rake face) after machining 500 gears with the normal conditions using a normal lubricant (Fig. 10) and the crater wear on hob (right 66.28 µm, center 63.38 µm, and left-53.88 µm position on rake face) after machining 500 gears with the optimal conditions using the nanolubricant. The result indicated that the width of the crater wear area under the nanolubricant is clearly smaller than that under the normal lubricant. Hence, some dents can be found on the rake surface under normal oils, while nothing on the rake face under nano oils.

Conclusions

A single fuzzy multi-response performance index (FRTS) was determined by using a fuzzy logic model based on the Taguchi methods to optimize multiple responses in the fly hobbing process. The research results show that the fly hobbing test can be used to study the gear hobbing process before applying in the actual hobbing process. The results also indicate that the nanoparticle concentrations and the nanoparticle size are the greatest effect factors to fuzzy multi-response performance index (FRTS) by using the fuzzy logic model based on the Taguchi method with the fly hobbing process. The optimum parameter values for different control parameters have been suggested as nanoparticle concentration 0.5%, nanoparticle size 20 nm, and cutting speed

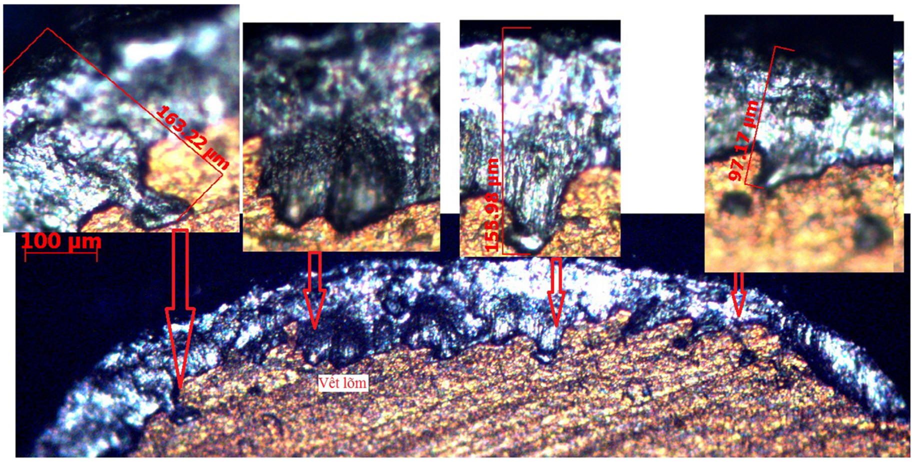

Fig. 9 The crater wear of hob with the normal conditions using normal lubricant

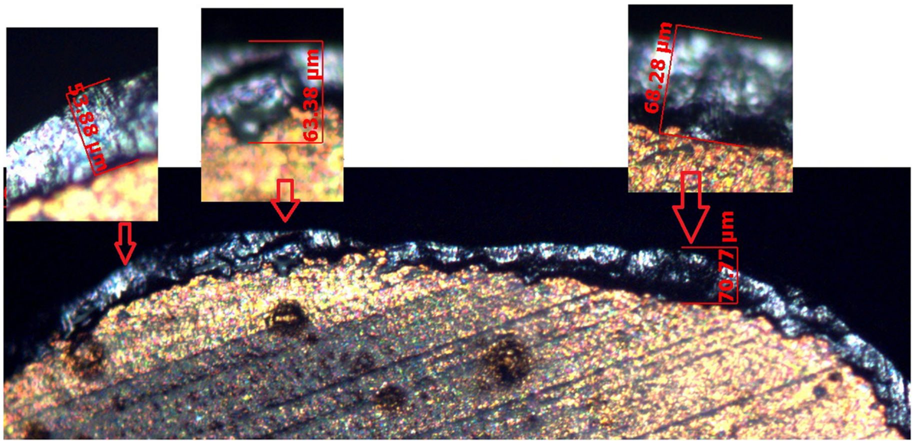

Fig. 10 The crater wear of hob with the optimal conditions using nanolubricant

38 nm. Applying the optimal conditions in the actual hobbing process was investigated in the FUTU 1 Company and reduced 39.3% the flank wear and 59.4% the width of crater wear. This result initially indicated the efficiency of using nanoparticles in the gear hobbing process with the actual conditions of the FUTU1 Company in Vietnam.

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Authors' contributions
NT and HV set up the experiment model and performed the design of the Taguchi experiment. HS used MATLAB software to set up the fuzzy logic optimization model. NT, HV, and HS participated in the analysis and discussion of results. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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