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Optimization Cutting Fluids and Parameters for Minimizing Cutting Force in Fly-Hobbing

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Abstract: Applying nanofluid formulates using dispersions of nano Aluminum Oxide (Al_2O_3) in normal oil may decrease the Total Cutting Force (TCF) in the gear hobbing because the nearly spherical Al_2O_3 nanoparticles easily entry into the contact area friction to decrease the friction. However, the gear hobbing is very complicated, difficult to measure TCF and has the high cost for an experience. Therefore, a fly-hobbing process was used to perform cutting on a milling machine so that the size of chip produced was the same as the largest cutting chips produced during the hobbing process. This study focused on the fly cutting process of SCM420 steels using cutting fluid mixed Al_2O_3 nanoparticles. The influence of the parameters on TCF was evaluated through the mean value and ratio (S/N) by Taguchi's method. The results indicated that nanoparticles size, nanoparticles concentration and interaction between them were the most significant parameters that influenced TCF of fly hobbing. The nanoparticle size 20 nm showed a minimum TCF lower 13.2% than nanoparticle size 135 nm. Using cutting fluids added 0.5% Al_2O_3 nanoparticles can reduced the TCF by 17.6% as compared with 0.1% Al_2O_3.

Key words: Cutting fluid, nanofluid, SCM420, nanoparticle, gear hobbing, parameters

INTRODUCTION

Gear hobbing is one of the processes to make many kinds of cylinder gears. In the gear hobbing process a hob tool is used to remove material of work gear with complex kinematic motions. Thus, the gear machining processes cause complex action frictions and wear on the cutting tool and high temperature as well. Those factors lead to the reduction of gear accuracy, surface quality and tool life so using an appropriate cooling lubricant is very important. The use of cutting fluids in gear machining results in increasing demand for enhancing machining productivity as well as machining accuracy, the extensive application of cutting fluid in gear hobbing has been found in many industries. In recent years, the use of cutting fluids comprising nanoparticles such as Al_2O_3, WS_2, MoS_2 and so forth, called nanofluids has attained much attention in the machining field. Many researchers showed that nanofluid exhibits the promising results as reducing cutting force, temperature, improving surface finish and decreasing tool wear in the machining process. In recent studies. Sarhan *et al.* (2012) reported that new nano lubrication SiO_2 exhibits the promising results as reducing the friction and cutting force compared to the normal lubrication. Owing to spherical morphology, the Al_2O_3 nanoparticles have many properties consistent with adding to the industrial oils (Vasu and Pradeep, 2011). Bizhan Rahmati studied the effects of the parameters of cutting fluid added MoS_2 nanoparticles on the force, temperature and surface roughness in CNC milling of aluminum alloy (Khalil *et al.*, 2015). M. Amrita added nano graphite into water SO and studied their effects on cutting forces, temperature, tool wear and roughness of machined surface (Amrita *et al.*, 2014). Roja Abraham Raju M Tech opined that multi-walled carbon nano tubes suspended in water and sodium dodecyl sulfate surfactant help to decrease in surface roughness, reduces tool wear and cutting forces turning operation (Abraham *et al.*, 2017). Khalilpourazary and Meshkat, studied the influences of nanofluids on surface roughness and tool wears in the hobbing process and 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 (Khalilpourazary and Meshkat, 2014). But the effect of Al_2O_3 nanoparticle size and concentration that mixed with cutting fluids in gear

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hobbing on TCF has not been published yet. However, 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 very difficult to measure TCF during the machining process. Hence, the different substitute experiences are developed as fly-hobbing experiences for modeling the actual hobbing process (Rech, 2006; Umezaki *et al*., 2012; Stein *et al*., 2012). In this report, the impaction of parameters such as cutting speed, Al_2O_3 nanoparticles size, nanoparticle concentration and the interaction between them in the TCF of the hobbing process was considered in the fly-hobing modern. SCM420 steels are very popular steels used in the manufacture of the transmission gear and were used in this study. The results showed that Al_2O_3 nanoparticle mixed into the cutting fluid has reduced TCF by fly hobbing significantly. This is an important prerequisite for improving the processing efficiency of gear hobbing using Al_2O_3 nanoparticle in the cutting fluid.

MATERIALS AND METHODS

Experiments: As the mechanism and conditions in hobbing are complicated and the cost for experience is very high, so the hob teeth were replaced by a fly cutter for simplification. A fly cutter having a single tool on a milling machine is used and the fly tool has the same profile as a hob tooth. The fly cutter used in the first test is coated with the TiN film and a workpiece is fixed on a horizontal milling (Knuth) (Fig. 1).

The cutting conditions such as cutting depth and feed rate are fixed as becoming the same conditions with the hob tooth carrying the biggest load on the hobbing process used in a gear production line at the Machinery Spare Parts No. 1 Joint Stock (FUTU1) Company. And maximum chip thickness and chip length are calculated from the characteristics of the hobbing process by using equations as presented by Hoffmeister (1970). 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. It can be seen from these figures that by suitable cutting depth h and feed f', it is possible to perform cutting with a fly cutter to give chips of the same size and shape as those produced by a hob ($L = r.\theta$, $h = r\ (1\text{-}\cos\theta)$ and $f' = S/\sin\theta$, $r = 30$ mm) shown in Fig. 2. Thus, the characteristics of fly-hobbing are calculated and also showed in Table 1. The workpiece made with chromium molybdenum steel (SCM420) was fixed on a kistler dynamometer. The kistler dynamometer mounted on the work table of milling machine allowed three dynamic

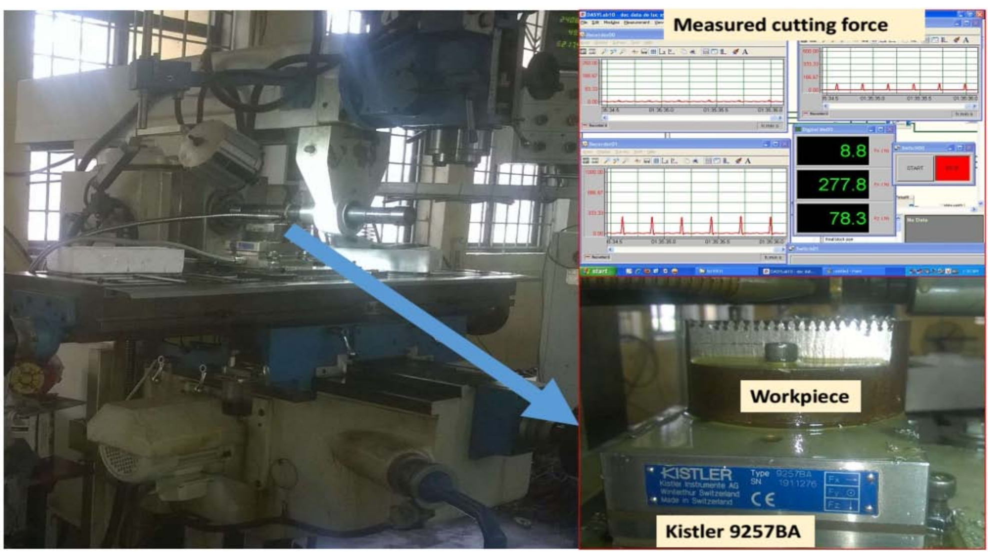

Fig. 1: Experimental setup

Table 1: The dimensions of maximum chips produced during hobbing and the cutting condition required to produce the same chips in fly-hobbing on milling machine

Hobbing process				Fly-hobbing process on milling machine	
No. of threads of hob	Feed of hob f (mm/rev)	Length of chips (mm)	Maximum thickness of chip S (mm)	Depth of cut (mm)	Feed of table f' (mm/rev)
1	1.27	12.92	0.108	2.74	0.259

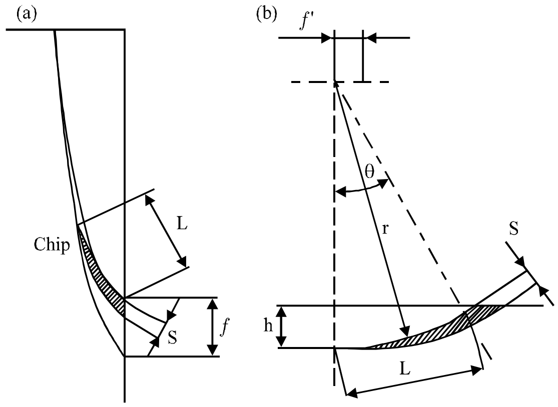

Fig. 2: a) The size of chip in gear hobbing process and b) in fly-hobbing process

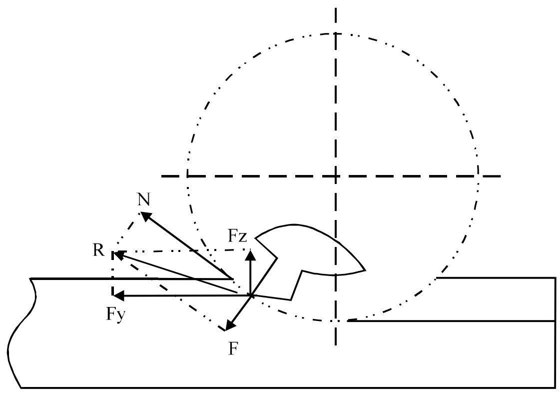

Fig. 3: The cutting force of the fly-hobbing process

forces to be measured. TCF R is calculated from two measured forces Fy and Fz (Fig. 3). Depending on the existing system, the ISO VG46 industrial lubricant was popularly used to gearing processes in FUTU1 Company due to its economical characteristics. The Al_2O_3 nanoparticles made by US Research Nanomaterials is a ceramic material consisting of such many significantly physical and chemical properties as wear resistance, easy to process and low cost. On the other hand, the Al_2O_3 nanopowder has a high sintering temperature, heat resistance, spherical structure and a high coefficient of heat transfer. These properties could be made the Al_2O_3 nanopowder improve the cooling and lubricating process during machining. According to Khalilpourazary and Meshkat (2014) nanopowder was mixed with lubricant following the weight ratio with 0.1÷0.2% the weight of the lubricant in order to produce the nano lubricant. To compare and evaluate the cooling-lubrication effectiveness of the nanofluid, Al_2O_3 nanoparticles with

Table 2: The parameters and their level in Taguchi design

		Level			
Factors	Symbols	1	2	3	df
Cutting speed (mpm)	A	38	50	-	1
Nanoparticle size (nm)	B	20	80	135	2
Nanoparticle concentration (%)	C	0.1	0.3	0.5	2
Interaction of cutting speed and nanoparticle size	A×B	-	-	-	2
Interaction of cutting speed and nanoparticle con	A×C	-	-	-	2
Interaction of nanoparticle size and concentration	B×C	-	-	-	4
Total					13

the size of 20, 80 and 135 nm was selected according to the economical requirement. The mixing ratio is 0.1, 0.3 and 0.5%.

Design experimental and ANOVA: With the purpose of applying the nanofluid for the hobbing process in the FUTU1 Company at Vietnam, this study focused research the effects of some parameters on the total cutting force in the fly hobbing process. Hence, an experimental Taguchi design is chosen for the fly-hobbing process as very simple and decreasing the number of experiments. In this study, the cutting speeds were selected based on the actual hobbing process in FUTU1, the Al_2O_3 nanoparticle sizes and concentrations were selected following the published reports. The effect parameters and interaction between them that were estimated are shown in Table 2. Thus, the total Degree of Freedom (DOFs) was 13 DOFs (Table 3) and an L18 orthogonal array can indeed be used to design the experiment as it had 17 DOFs (Table 3).

Taguchi method popularly uses the signal to noise ratio (S/N) to consider the influence of the survey parameters on the output parameter. Higher values of the S/N ratio identify control factor settings that minimize the effects of the noise factors. The S/N ratio as determined as follows (Roy, 1990). Smaller is better: $S/N = -10 \, Log_{10} [MSD]$:

$$MSD = \sum_{i=1}^{n} y_i^2 \tag{1}$$

Where:

MSD = The mean-square deviation
y_i = The total cutting force in the experiment
n = The number of experiments

Table 3: Experimental design based on L18 orthogonal array and the results of TCF

Exp. No.	V (mpm)	Size (nm)	Nanoparticle con. (%)	F_y (N)	F_z (N)	R (N)	S/N
1	38	20	0.1	277.8	78.3	288.62	-49.2066
2	38	20	0.3	232.6	73.6	243.97	-47.7466
3	38	20	0.5	190.8	61.7	200.53	-46.0435
4	38	80	0.1	282.9	77.3	293.27	-49.3454
5	38	80	0.3	255.2	72.1	265.19	-48.4711
6	38	80	0.5	235.6	70.1	245.81	-47.8119
7	38	135	0.1	293.3	82.2	304.60	-49.6746
8	38	135	0.3	282.8	80.8	294.12	-49.3704
9	38	135	0.5	260.1	74.0	270.42	-48.6408
10	50	20	0.1	282.4	75.2	292.24	-49.3148
11	50	20	0.3	246.3	72.3	256.69	-48.1883
12	50	20	0.5	222.0	69.1	232.51	-47.3287
13	50	80	0.1	296.2	78.3	306.37	-49.7251
14	50	80	0.3	262.8	74.1	273.05	-48.7247
15	50	80	0.5	242.9	70.9	253.04	-48.0636
16	50	135	0.1	295.0	84.6	306.89	-49.7397
17	50	135	0.3	283.0	80.8	294.31	-49.3761
18	50	135	0.5	263.5	76.2	274.30	-48.7644

RESULTS AND DISCUSSION

Results of the experiments: The total cutting forces were calculated from two measured forces (F_y and F_z) determined by the Kistler dynamometer 9257BA in the duration of the experiment. The experimental results were analyzed by the Software Minitab 16. Table 3 shows the TCFs and the S/N ratio for the TCFs.

Effect on the total cutting force: The data of experiment should be checked the ANOVA assumptions before concluding about the effect of the parameter to the TCF. The level effect of survey parameter to TCF in fly-hobbing was considered by basing on the results of ANOVA analysis with 95.2% confidence intervals as shown in Table 4. The result show that the Seq SS and Adj SS are the same, so the using Taguchi experimental is suitable. In addition, Fisher ratio (F) is determined from the effection parameter's adj MS and DF. The greater the Fisher ratio of the input factor is the more effective to output factor. ANOVA indicated that nanoparticle concentration (F = 101.49), nanoparticle size (F = 54.04), cutting speed (F = 9.34), the interaction between nanoparticle concentration and nanoparticle size (F = 4.93) were the greatest effect factors to TCF (R). Figure 4 and 5 shows the influence of the factors and the interactions between them (A×B, A×C and B×C) on the TCF in the fly-hobbing process using the cutting fluid added Al_2O_3 nanoparticles. The TCF slightly increases while the cutting speed increases in the low cutting speed ranges (Fig. 4a). A decrease in the nanoparticle size with the cutting fluid reduces the TCF (Fig. 4b). The lower cutting speed (38 mpm) has a higher influence on the TCF than the higher cutting speed while the nanoparticle sizes or concentrations are unchanged (Fig. 5a, b). A decrease in the nanoparticle size from 80-20 nm reduces the total cutting force with a rate higher than in the nanoparticle size from 135-80 nm (Fig. 4b). The small size (20 nm) has

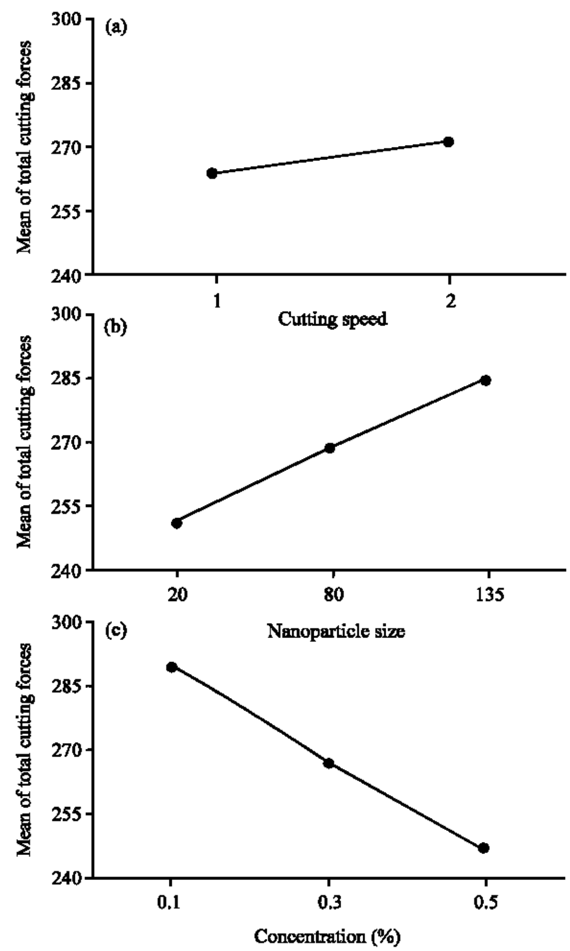

Fig. 4: Main effects plot for the total cutting forces: a) cutting speed; b) nanoparticle size and c) concentration

Table 4: ANOVA of the total cutting force

Sources	df	Seq SS	Adj SS	Adj MS	F-values	p-vlaues
Cutting speed (A)	1	381.5	381.50	381.50	9.34	9.340
Nanoparticle size (B)	2	4417.0	4417.00	2208.49	54.04	0.001
Nanoparticle Concentration (C)	2	8295.5	8295.50	4147.75	101.49	0.000
A×B	2	146.8	146.82	73.41	1.80	0.270
A×C	2	60.0	60.00	30.00	0.73	0.535
B×C	4	912.0	912.00	228.00	4.93	0.027
Residual error	8	370.3	370.30	46.29	-	-
Total	17	14376.3	-	-	-	-

Table 5: ANOVA for S/N ratio for the total cutting force

Sources	df	Seq SS	Adj SS	Adj MS	F-values	p-vlaues
Cutting speed (A)	1	0.4719	0.4719	0.47186	7.36000	0.053
Nanoparticle size (B)	2	5.0110	5.0110	2.50552	39.10000	0.002
Nanoparticle Concentration (C)	2	8.9327	8.9327	4.46635	69.70000	0.001
A×B	2	0.2262	0.2262	0.11309	0.11309	1.760
A×C	2	0.1205	0.1205	0.06026	0.94000	0.463
B×C	4	1.3204	1.3204	0.33011	5.15000	0.071
Error	4	0.2563	0.2563	0.06408	-	-
Total	17	16.3391	-	-	-	-

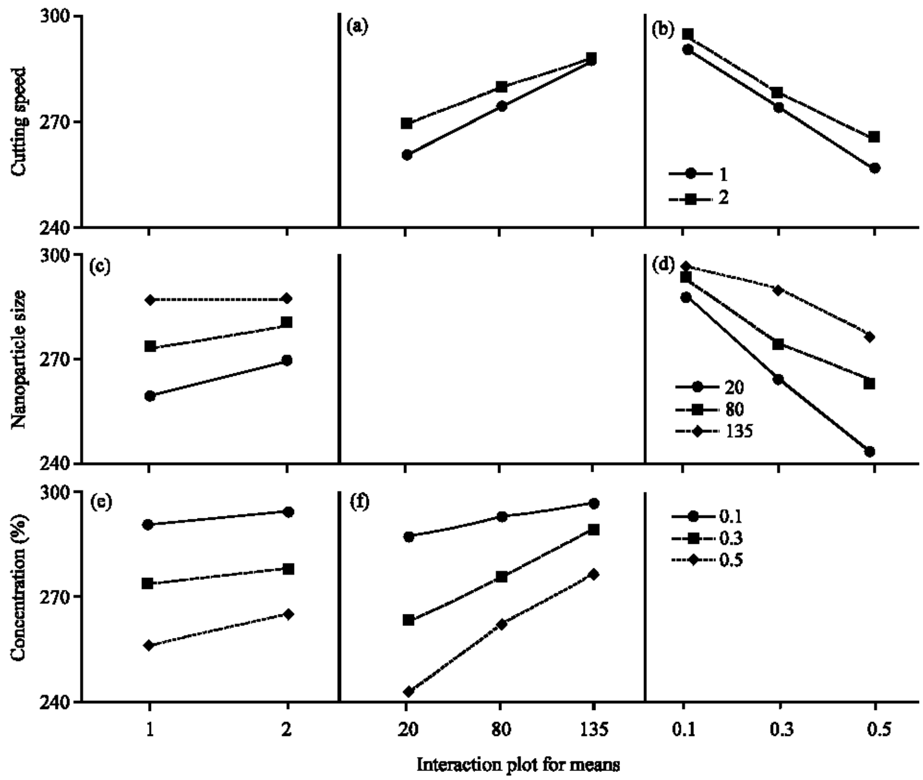

Fig. 5: a-f) interraction plot for the total cutting force (R)

the highest influence on the total cutting force while the nanoparticle concentration or the cutting speeds are unchanged (Fig. 5c and d). With increasing concentrations of nanoparticles from 0.1-0.5%, the total cutting force reduces but the bigger nanoparticle size uses, the slowlier the total cutting force reduces with increasing concentrations of nanoparticles from 0-0.5%. At a nanoparticle concentration of 0.1%, the maximum cutting force is obtained with the minimum the total cutting force at a powder concentration of 0.5% (Fig. 4c). Figure 5e and f shows that the total cutting force for 0.5% is affected the most by the change in the cutting speed and the nanoparticle sizes.

Optimization of the total cutting force: In Taguchi method, the S/N ratio is used to determine the optimal parameter settings. The values S/N for the TCF were calculated as shown in Table 3. Table 5 shows the results

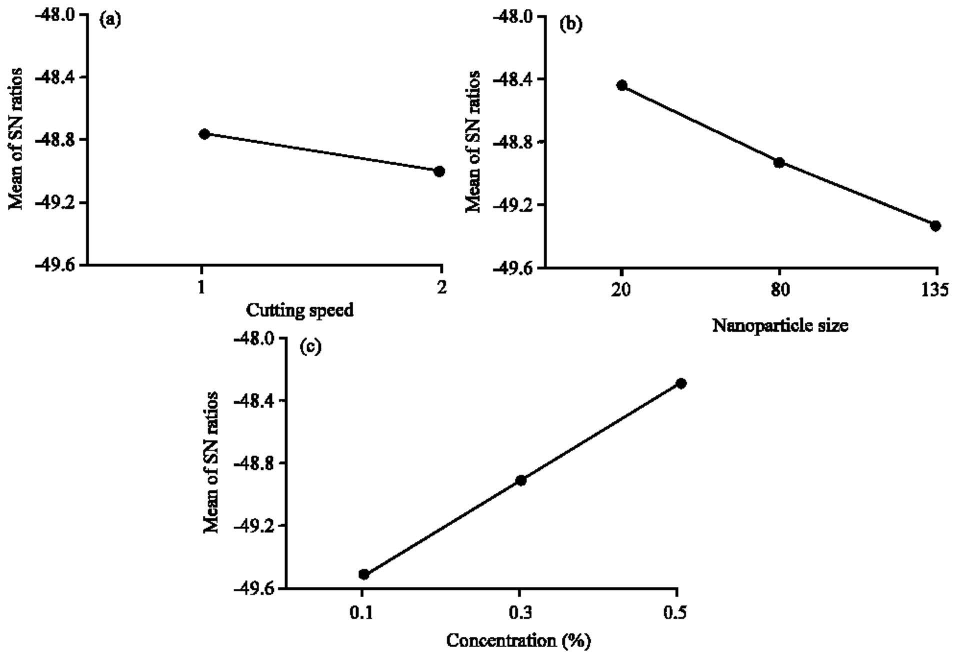

Fig. 6: Main effects plot for S/N of the total cutting force: a) cutting speed; b) nanoparticle size and c) concentration (%)

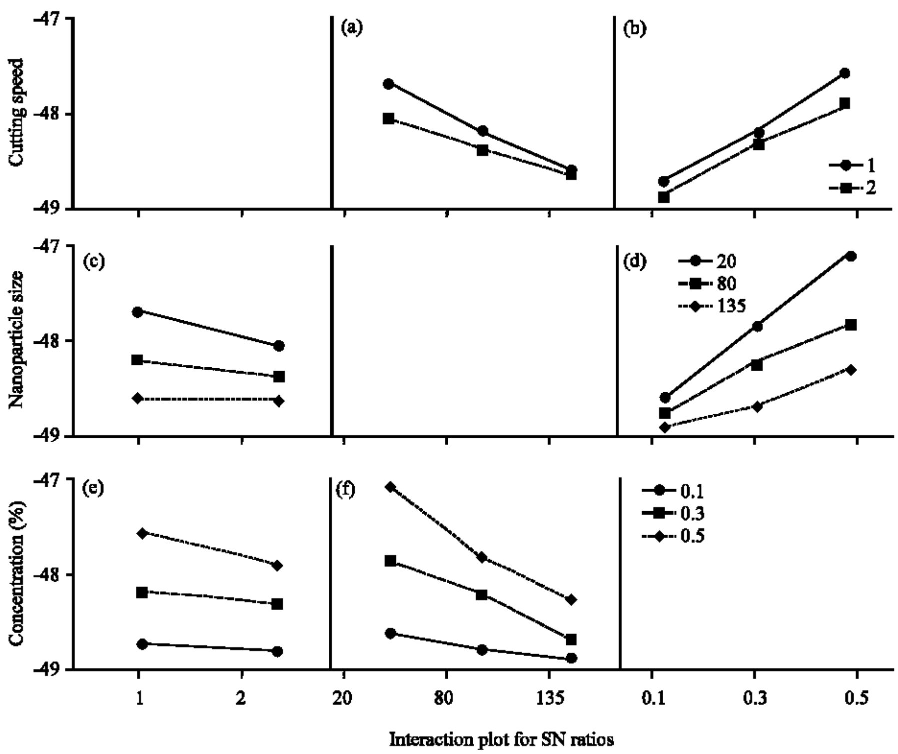

Fig. 7: a-f) interraction plot for S/N of the total cutting force

of ANOVA S/N ratio of TCFs with 93.3% confidence intervals. This results indicated that the nanoparticle concentration (F = 69.7), nanoparticle size (F = 39.1), cutting speed (F = 7.36) and the interaction between the size and concentration (B×C, F = 5.15) are parameters that influence the S/N ratio of the total cutting forces. Figure 6 shows the effect of the factor on the S/N ratio for the TCF. These evinced that the lower cutting speed (38 mpm, A_1), the nanoparticle size 20 nm (B_1) and the nanoparticle concentration of 0.5% (C_3) contributed to the largest S/N ratio. The graph given in Fig. 7 proved the interacted effect of the factors on the S/N ratio for the total cutting force. These results evince that the interaction between the cutting speed (38 mpm) and the nanoparticle size 20 nm ($A_1 \times B_1$), the cutting speed 38 mpm and the nanoparticle concentration 0.5% ($A_1 \times C_3$) and the nanoparticle size 20nm and the nanoparticle concentration 0.5% ($B_1 \times C_3$) are the interactions which have the most effect on the largest S/N ratio.

CONCLUSION

Research has shown that nanoparticle Al_2O_3 mixed into the cutting fluid in the fly cutting process has reduced the total cutting force while increasing the concentration and decreasing the nanoparticle size. In this research, optimizing the TCF is obtained by applying Taguchi method to determine the most effective factors. Based on the experimental and statistical results, the cutting speed, nanoparticle size, nanoparticle concentration and the interaction between nanoparticle size and nanoparticle concentration were the main factors that influenced the cutting speed. Aluminum nanoparticle mixed with the cutting fluid decreased the total cutting force with increasing the concentration. The maximum decrease in the total cutting force was 17.6% with a nanoparticle concentration of 0.5%. The nanoparticle size 20 nm showed a minimum cutting force lower than nanoparticle size 135 nm with a 13.2% decrease. This has improved the efficiency of the fly-cutting process. Thus, nanofluid using dispersions of nano aluminum oxide (Al_2O_3) in normal oil may be applied for the gear hobbing process in FUTU1. However, further research is needed on the temperature, tool wear in the fly cutting process and also the gear hobbing process.

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