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Optimization of Cutting Condition in the Turning of AISI D2 Steel by using Carbon Nanofiber Nanofluid

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Abstract

In this research, the parameter design of the Taguchi-Response Surface Methodology (RSM) was integrated and applied to set the optimal parameters for multi-response in turning D2 steel. In this research work, the nanofluid was prepared by mixing 0.1g carbon nanofiber with 1.0 litre deionized water by adding gum arabic as a stabilizing agent using a two-step method. A coated carbide insert was used as the cutting tool. It was found that cutting speed is the most dominant factor affecting tool wear. Meanwhile, for surface roughness, the most significant factor is feed rate. The optimum condition for multi-responses (Flank wear, Vb, and surface roughness, Ra) was at the cutting speed of 144.58 m/min, feed rate of 0.14 mm/rev using carbon nanofiber (CNF) nanofluid as a coolant.

Keywords: Turning, D2 steel, Nanofluid, Taguchi method, Response Surface Methodology, Gum Arabic

INTRODUCTION

AISI D2 steel (57-62 HRc) is an air hardening, high-carbon, high-chromium tool steel that has high wear and abrasion resistant properties. It is widely used in industries for stamping or forming dies and punches, molds and etc. [1]. Hard turning is one of the processes widely used to machine AISI D2 steel. Hard turning is defined as turning hardened steel which has hardness above 45 HRc [2–5]. During the hard turning process, the contact surface between the tool and the work piece creates friction causing heat to accumulate and leading to high surface temperature. This problem can result in poorly finished product. In order to reduce and overcome this problem, many researchers have come out with various solutions such as manipulating the cutting parameter and tool materials, as well as changing the coolant type and technique.

In the recent year, Srithar et al. [6] investigated and analysed surface roughness on hard turning of AISI D2 steel using coated carbide insert. From the analysis, they found that by increasing cutting speed, the surface roughness in the machining of hardened steel is decreased. Their results also showed that feed rate is the most significant control parameter. For enhanced tool life, Chinchanikar and Choudhury [7] remarked that cutting speed followed by the depth of cut were found to be the most influencing factors on tool life, especially when turning harder materials. In the hard turning of AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel, Lima et al. [8] said that the flank wear increases with cutting speed and depth of cut. Meanwhile, in an investigation, Gaitonde et al. [9] found that the maximum tool wear occurs at a cutting speed of 150m/min for all values of feed rate. For a specified value of cutting speed or feed rate, the tool wear increases with the increase in machining time.

Nalbant et al. [10] conducted an investigation on the optimization of cutting parameters for surface roughness in turning using AISI 1030 steel and TiN coated tool using the Taguchi method. From their experiment, it was found that greater insert radius (1.2 mm), low feed rate (0.15 mm/rev), and low depth of cut (0.5 mm) are recommended to obtain better surface roughness for specific test range. In the recent year, to predict the surface roughness of AISI 4340 steel, Agrawal et al. [11] used the multiple regression model and revealed that the most significant parameter is feed rate followed by cutting speed and depth of cut.

Dureja et al. [12] found that for simultaneously optimizing both tool wear and surface roughness, the most optimal solution is as follows: speed = 130 m/min, feed rate = 0.13 mm/rev and DOC = 0.21 mm in turning AISI D3 by using the Taguchi and RSM methods. Meanwhile, other researchers, Das et al. [13] used the Grey based Taguchi and regression methodology to find the optimal result for multi-response in hard turning using coated carbide insert. The result showed that the optimal parametric combination is at the depth of cut of 0.4 mm, feed of 0.04 mm/rev and cutting speed of 130 m/min, respectively for both Ra (arithmetic surface roughness average) and Rz (maximum peak-to-valley height). Another method to find the optimization for multi-response is by using the Taguchi based utility concept coupled with principal component analysis like what was done by Singarvel et al. [14]. It showed that the combination of machining parameters for this investigation is the cutting speed of 244 m/min, feed rate of 0.10 mm/rev and depth of cut of 1.0 mm with CVD coated tool for the minimization of surface roughness and cutting force, and maximization of metal removal rate. Kumar and Singh [15] also used the Taguchi approach and utility concept in multi-response optimization for the dry turning process and found that all of the parameters have significant effects on axial force, radial force, cutting force, and material removal rate. Using the desirability function, Aggarwal et al. [16] found that the optimum in turning AISI P20 steel under cryogenic cooling can be obtained at low cutting speed, feed, depth of cut, and high nose radius. In the optimization of cutting parameters and fluid application parameters during the turning of oil hardened non-shrinkable steel (OHNS) steel, Johnson et al. [17] observed that feed rate has more influence on surface roughness, and turning with minimal cutting fluid application can enhance cutting performance when compared with dry turning and conventional wet turning. Sharma et al. [18] studied the effect of CNT nanofluids in turning AISI D2 steel using the Taguchi method and found that the optimal process parameter for temperature is at 51 m/min for cutting speed, 0.10 mm/rev for feed rate and 5 bars for air pressure. It was also found that the cutting zone temperature can be decreased while surface quality and tool wear improved using nanofluid MQL compared to normal MQL.

Based on the comprehensive literature review, although some researchers have carried out many optimizations in turning, the use of carbon nanofiber (CNF) as the lubricant additive surprisingly has rarely been reported. Therefore, the main objective of this research work is to optimize the process parameter using the Taguchi approach based on the response surface methodology on turning D2 steel using CNF nanofluid.

EXPERIMENTATION

Formulation of nanofluid

In this investigation, a two-step method [19] has been employed in producing nanofluid. CNF was commercially available, and used without any further purification. The nanofluid was formulated by using 20-30 nm diameter CNF (Figure 1) suspension in deionized (DI) water as the base fluid. Gum Arabic (GA) surfactant was used to stabilize the suspension of nanoparticles. Approximately 0.1g GA was dissolved into one litre DI water using ultrasonic homogenizer at 50 amplitudes and 0.5 cycles for 15 minutes. Then CNF was dispersed into the mixture for another 45 minutes at the same amount of GA. The stability of the nanofluid was investigated through observation. The observation was done two weeks later and it was found that the particles distributed uniformly without agglomeration and precipitation of CNF with the addition of GA surfactant (Figure 2).

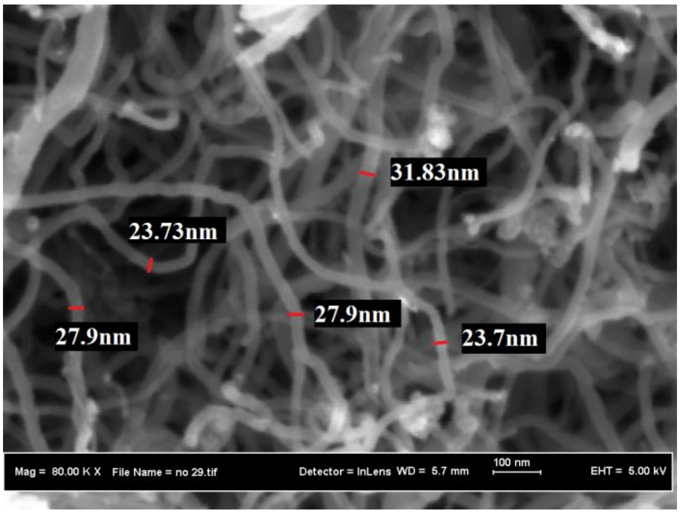


Figure 1: FESEM photographs of carbon nanofiber

Initial After 2 weeks

Figure 2: Nanofluid by adding GA after 2 weeks period

Machining

AISI D2 cold work tool steel of 50 mm diameter was used as the work piece material. D2 steel falls under the difficult to cut material as it has hardness of 62 HRc. Experiments were carried out on HAAS SL-20 CNC lathes machine. For increasing the rigidity of the machining system, D2 steel bar was held by chuck and tailstock, while the tool overhang was maintained at the minimum possible, whereby the L/D ratio is less than 2; it was one-fifth more than the recommendation by ISO 3685. The coated carbide insert of DNMG 150408N with chip breaker was used throughout the investigation. The insert has a multilayer PVD coating of nanometre thick TiAlN and

AlCrN layer. The DDJNR2525M15 type tool holder was used to employ the insert.

The experiment was conducted under two different cutting fluid conditions which were base fluid (deionized water) and CNF nanofluid. The coolant was supplied to the cutting area by using the Masterflex pump at a flow rate of 200 ml/min. The experiment was set up as shown in Figure 3. The coolant type, cutting speed and feed rate were the input parameters for turning D2 steel. The output responses for both cutting fluids were then compared to find the optimum parameter.

For measuring the machining performance, the surface roughness (Ra) of the machined surface and tool wear (Vb) were considered. The Ra value was measured by using a Mitutoyo portable surface roughness tester. Seven measurements were done on each surface and the arithmetic mean was calculated. Meanwhile, the tool wear was measured by using a Mitutoyo tool-maker microscope. The admissible flank wear was measured at at the flank area (Vb) according to the ISO 3685 standard (1993). The Ra and Vb values were taken after 400 mm tool travelled for each run.

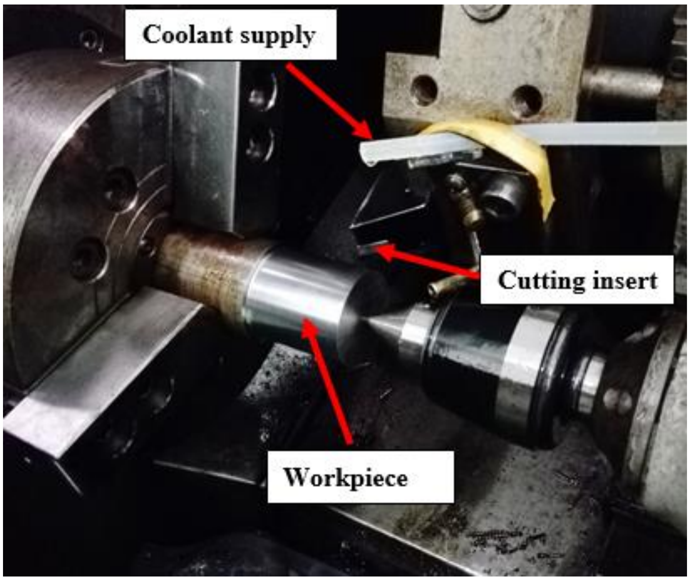


Figure 3: Experimental set up

Design of experiment

The Taguchi method and mixed level design for mixed 2-3 level were selected to determine the effect of coolant type, cutting speed and feed rate on surface roughness and tool wear in hard turning of AISI D2 steel, conducted in the MINITAB software. This method was selected as it can reduce the number of experiments [20]. There were two numerical and one categorical variable factors used for this experiment. The coolant type has two levels while the cutting speed and feed rate have three levels, and thus the L18 design was selected. The depth of cut remained constant at 0.25 mm. The selected machining parameters are shown in Table 1. The 18 runs were replicated three times and the average data were taken as the result.

Table 1: Cutting parameters and their levels

Factors	Level 1	Level 2	Level 3
Type of coolant	CNF nanofluid	Deionized water	-
Cutting speed (m/min)	100	150	200
Feed Rate (mm/rev)	0.1	0.15	0.2

In the Taguchi method, the experimental results were transformed into S/N signal-noise ratios to measure the quality characteristics deviating from the desired value. Regardless of the category of the quality characteristic, a greater S/N ratio corresponded to better quality characteristics. In this study, the S/N ratio was computed using equation 1 which is the lower-the-better for each 18 run. The negative sign in Eq. (1) is used to show the smaller-the-better quality characteristic.

$$S/N = -10 log\left[\frac{1}{n}(y_1^2 + y_2^2 \dots y_n^2)\right] \quad (1)$$

The orthogonal array experiment was conducted to economically obtain the response measurements. Analysis of variance (ANOVA) and the main effect plot of S/N ratio were used to determine the significant parameters and set the optimal level for each parameter. The Response Surface Methodology (RSM) was then used to build the relationship between the input parameters and output responses in order to find the optimal parameters for multiple responses in turning D2 steel. RSM provides a systematic procedure to determine the relationship between independent input process parameters and output (process response) [21].

RESULT AND DISCUSSION

Tool wear

In the present study, S/N ratio was calculated based on the smaller-the-better criterion for flank wear, Vb as smaller tool wear value means prolonged tool life. Table 2 shows the experimental results and corresponding S/N ratios for flank wear. The rank of the parameters was obtained from the response table of S/N ratio (Table 3). Therefore, the optimal level of the process parameter is the level with the highest delta. From Table 3, it is shows that feed rate was ranked 1, cutting speed 2 and type of coolant 3, according to the significance of the parameters.

Table 2: Experimental results and corresponding S/N ratios for flank wear

No	Cutting speed (m/min)	Feed rate (mm/rev)	Type of coolant	Flank Vb wear, (mm)	S/N ratio for Vb
1	100	0.10	CNF	0.100	20.0000
2	100	0.15	CNF	0.065	23.7417
3	100	0.20	CNF	0.067	23.4785
4	150	0.10	CNF	0.106	19.4939
5	150	0.15	CNF	0.095	20.4455
6	150	0.20	CNF	0.083	21.6184
7	200	0.10	CNF	0.147	16.6537
8	200	0.15	CNF	0.114	18.8619
9	200	0.20	CNF	0.086	21.3100
10	100	0.10	DI-water	0.109	19.2515
11	100	0.15	DI-water	0.095	20.4455
12	100	0.20	DI-water	0.081	21.8303
13	150	0.10	DI-water	0.126	17.9926
14	150	0.15	DI-water	0.100	20.0000
15	150	0.20	DI-water	0.086	21.3100
16	200	0.10	DI-water	0.162	15.8097
17	200	0.15	DI-water	0.121	18.3443
18	200	0.20	DI-water	0.096	20.3546

Table 3: Response Table for Signal to Noise Ratios (Smaller is better) for Vb

Level	Cutting speed	Feed rate	Type of Coolant
1	21.46	18.20	20.62
2	20.14	20.31	19.48
3	18.56	21.65	
Delta	2.90	3.45	1.14
Rank	2	1	3

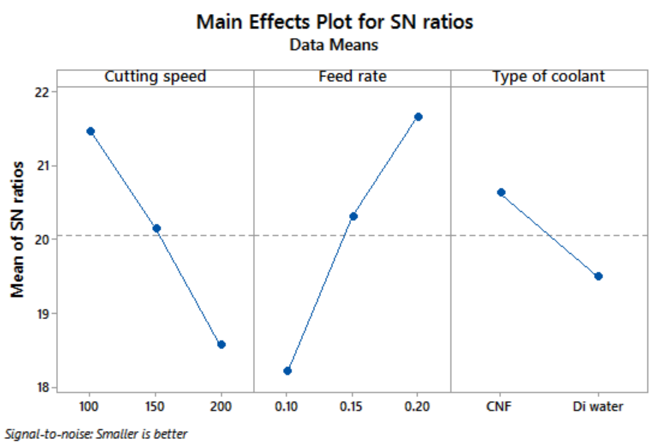


Figure 4: Main effects plot for S/N ratios for tool wear

Figure 4 shows the main effect plots for S/N ratios for tool wear. In the main effect plots, the one which has the highest inclination will have the most significant effect on the responses. From Figure 4, it shows that feed rate was the most significant factor, followed by cutting speed and coolant type. Taguchi also recommended that larger S/N ratio corresponded to the best quality characteristics, regardless of the category of the performance characteristic which was at the highest point on the graph. From the figure, the highest S/N ratio obtained was level-1 for cutting speed (A), level-3 for feed rate (B) and level 1 for the type of coolant (C), respectively. Therefore, the optimal condition for process parameters was found to be A1-B3-C1.

As seen in Figure 4, tool wear increased with the increase of cutting speed. When speed increased the contact produced a higher friction, thus increasing wear. This result is consistent with that reported by Padmini et al. [22]. In terms of feed rate, it was shown that higher feed rate resulted in lower tool wear. However, this phenomenon contradicts the finding by some researchers such as Kilickap et al. [23] who found that tool wear was higher when higher feeds were used. Meanwhile, CNF nanofluid was better in reducing wear compared to DI water. This might be due to the tribological behaviour of CNF particles where it can reduce friction and wear as it prevents direct contact between tool and work piece because of the protective film it produces. As supported by Sayuti et al. [24], the protective film exists when a strong chemical interaction forms between nanofluid and the new surface where the nanoparticles continuously rub on the work piece during machining. Besides that, Sharma et al. [25] said that nanofluid improved machining performance by reducing tool wear up to ~ 58.1% and ~35.85% when compared to dry and conventional machining, respectively.

The optimization of the Taguchi approach gives extreme value of parameter range. In order to get finer optimal parameter for multi-responses, the analysis was further conducted by using RSM. The adequacy of the response surface quadratic model was further justified through ANOVA and the results are presented in Table 4.

An ANOVA table consists of the sum of squares and degrees of freedom (Df). The sum of squares is performed into contributions from the polynomial model and experimental error. The mean square is the ratio of the sum of squares to the degrees of freedom and F-ratio is the ratio of the mean square of the regression model to the mean square of the experimental error. As per ANOVA, the calculated value of F-ratio of the developed model should be more than that of the F-table for the model to be adequate for a specified confidence interval [26].

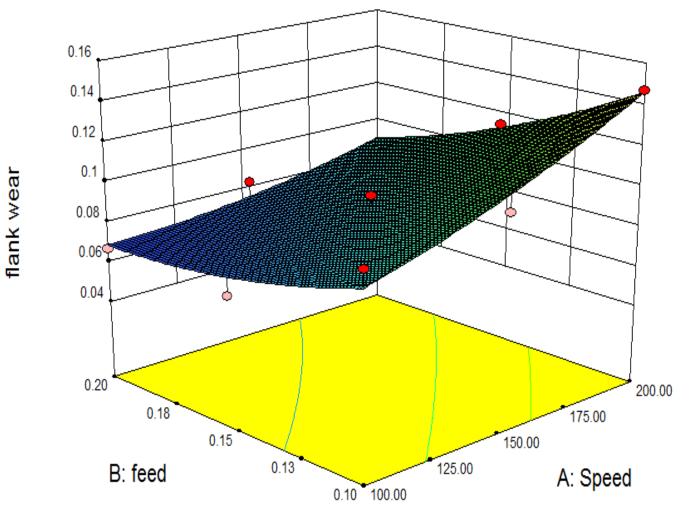
In Table 4, a model F-value of 28.49 implies that the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The values of p (Prob > F) was also less than 0.0500 indicating that the model terms are significant with 95% confidence level. Therefore, in this investigation, factors A, B, C, and the interaction between AB are significant model terms. As can be seen in Table 4, besides the specified effective parameters, other parameters also had some effects that could be spotted based on their respective ratios. However, these effects are relatively low and hence neglected in the analysis.

Table 4: ANOVA of quadratic response surface design for Vb

Source	Sum of squares	Df	Mean square	F value	p-value
Model	0.010	8	1.301×10^{-3}	28.49	< 0.0001
A-cutting speed	3.64×10^{-3}	1	3.64×10^{-3}	79.69	< 0.0001
B-feed rate	5.25×10^{-3}	1	5.25×10^{-3}	114.93	< 0.0001
C-type of coolant	7.094×10^{-4}	1	7.094×10^{-4}	15.53	0.0034
AB	5.445×10^{-4}	1	5.445×10^{-4}	11.92	0.0072
AC	3.675×10^{-5}	1	3.675×10^{-5}	0.80	0.3931
BC	2.408×10^{-5}	1	2.408×10^{-5}	0.53	0.4862
A^2	7.225×10^{-5}	1	7.225×10^{-5}	1.58	0.2402
B^2	1.323×10^{-4}	1	1.323×10^{-4}	2.90	0.1231
Residual	4.111×10^{-4}	9	4.568×10^{-5}		
Cor Total	0.011	17			

The tool wear prediction models have been obtained through regression. The developed machinability models were used to predict the value of flank wear at any point by substituting within the range of the process parameter selected. The equation models can be used to predict tool wear when CNF nanofluid is used:

Flank wear = +0.10597 + (3.68333×10^{-4}) x Speed - 0.58500 x feed – (3.3×10^{-3}) x Speed x feed + (1.7×10^{-6}) x Speed^2 + 2.30000 x feed^2……. (2)



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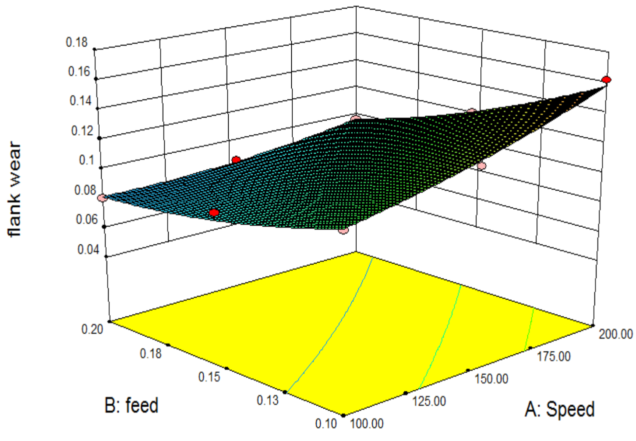

(b)

Figure 5: Response surface plot which showing the interaction between feed rate and cutting speed on tool wear: (a) CNF nanofluid (b) DI-water

According to ANOVA, only the interaction between cutting speed (A) and feed rate (B) was significant (0.0072). Figure 5 illustrates the effect of varying the two factors on tool wear for both CNF nanofluid and DI-water. For both cutting fluids, it can be seen that lower cutting speed and higher feed rate resulted in lower tool wear.

Surface roughness

Table 5 shows the experimental results and corresponding S/N ratios for surface roughness. For surface roughness (Ra), the smaller-the-better criterion was also selected as for better surface quality. From Table 6, it shows that feed rate was ranked 1, cutting speed 2 and type of coolant 3, according to the significance of the parameters.

Table 5: Experimental results and corresponding S/N ratios for surface roughness

No	Cutting speed (m/min)	Feed rate (mm/rev)	Type of coolant	Surface roughness, Ra (µm)	S/N ratio for Ra
1	100	0.10	CNF	0.84	1.51441
2	100	0.15	CNF	1.85	-5.34343
3	100	0.20	CNF	2.01	-6.06392
4	150	0.10	CNF	0.78	2.15811
5	150	0.15	CNF	0.81	1.83030
6	150	0.20	CNF	1.35	-2.60668
7	200	0.10	CNF	0.43	7.33063
8	200	0.15	CNF	0.68	3.34982
9	200	0.20	CNF	1.24	-1.86843
10	100	0.10	DI- water	0.84	1.51441
11	100	0.15	DI-water	0.97	0.26457
12	100	0.20	DI-water	1.93	-5.71115
13	150	0.10	DI-water	0.50	6.02060
14	150	0.15	DI-water	1.07	-0.58768
15	150	0.20	DI-water	1.98	-5.93330
16	200	0.10	DI-water	0.46	6.74484
17	200	0.15	DI-water	1.30	-2.27887
18	200	0.20	DI-water	2.27	-7.12052

Table 6: Response Table for Signal to Noise Ratios (Smaller is better) for Ra

Level	Cutting speed	Feed rate	Type of coolant
1	-2.30418	4.21384	0.03342
2	0.14689	-0.46088	-0.78745
3	1.02625	-4.88400	
Delta	3.33043	9.09783	0.82088
Rank	2	1	3

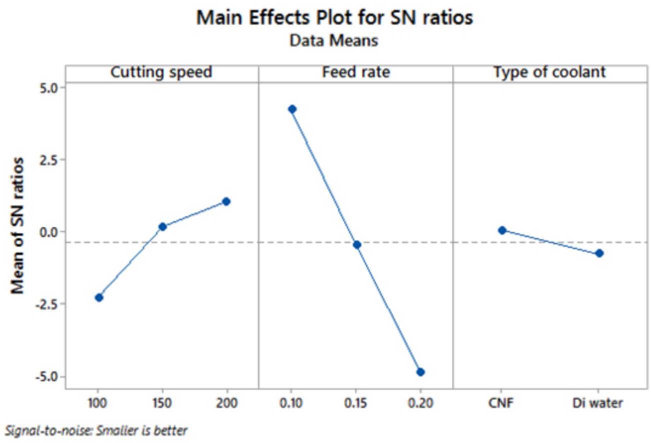

Figure 6: Main effects plot for S/N ratios for Ra

The same approach was adopted to determine the optimum result of Ra. The highest S/N ratio was obtained at level-3 for cutting speed (A), level-1 for feed rate (B), and level-1 for the type of coolant (C), respectively. Therefore, the optimal combination of process parameter was found as A3-B1-C1.

It can be noticed from Figure 6 that surface roughness is better when speed increases and feed rate reduces. The surface roughness increases with the higher feed rate which may be caused by higher temperature in the cutting zone. With reference to turning, experimental results revealed that surface roughness was initially reduced and then increased with increasing cutting speed at all lubricating conditions [27].

From this figure also, it is shown that CNF nanofluid gives better finishing surface compared to pure DI-water. This is due to the fact that the presence of CNF which has high thermal conductivity compared to conventional fluid and advanced tribological properties can transfer the heat produced in the machining area [28]. Krishna et al. [27] also suggested that the reduction in surface roughness may be attributed to better lubricating action of nanoparticles present in the cutting fluid which reduces the frictional forces between the tool and work piece by reducing the temperature developed, ultimately preventing tool wear, and resulting in surface quality improvement.

Table 7 shows the analysis of variance for Ra. A P value less than 0.05 indicates that the parameter is significant at 95% confidence level. Therefore, from Table 7, it shows that A, B, and the interaction between AC are significant factors for surface roughness, while the type of coolant gives insignificant effect toward Ra response.

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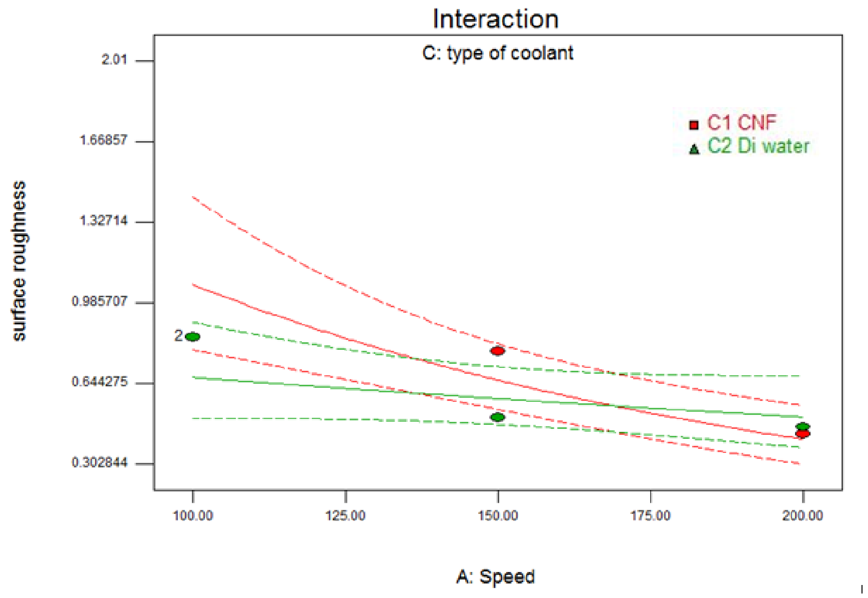
Table 7: ANOVA for Response Surface 2FI Model for Ra.

Source	Sum of squares	df	Mean square	F value	p-value
Model	4.37	6	0.73	22.38	< 0.0001
A-Speed	0.44	1	0.44	13.56	0.0036
B-feed	3.29	1	3.29	101.19	< 0.0001
C-type of coolant	0.040	1	0.040	1.24	0.2900
AB	0.11	1	0.11	3.48	0.0892
AC	0.34	1	0.34	10.31	0.0083
BC	0.15	1	0.15	4.49	0.0576
Residual	0.36	11	0.033		
Cor Total	4.73	17			

The develop equation of response (equation 3) was used to predict the surface roughness after machining by substituting it within the range of the process parameter selected. The equation models can be used to predict Ra when CNF nanofluid is used:

Surface roughness = +0.903 - 0.0143 x Speed + 1.134 x feed + 0.0476 x Speed x feed -----(3)



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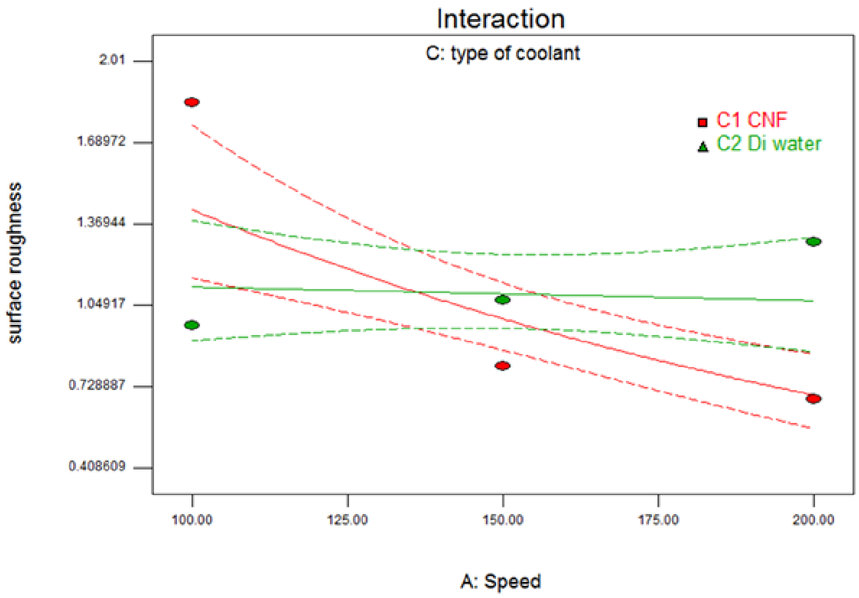

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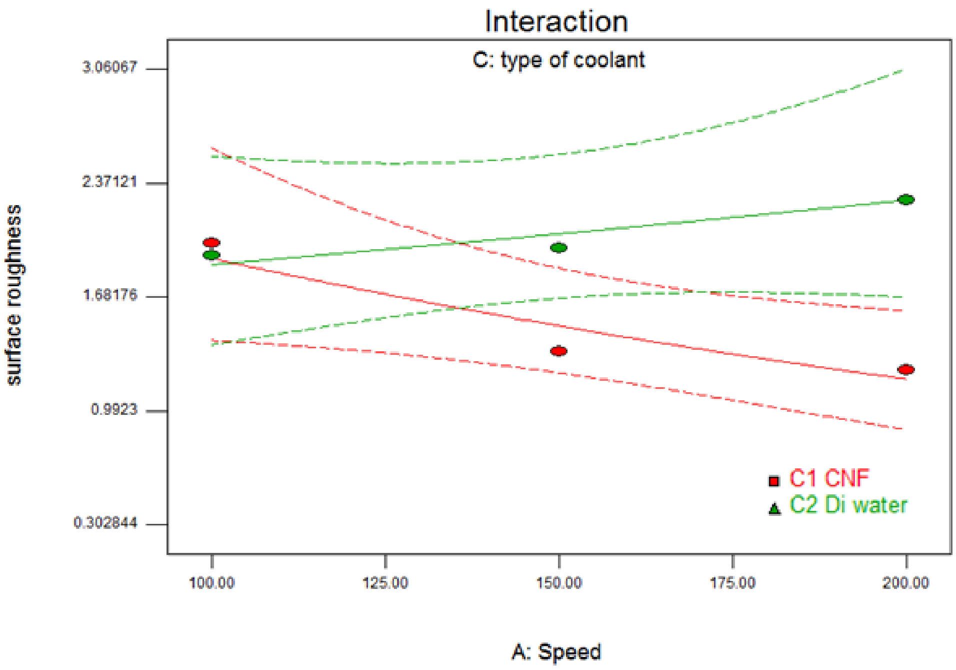

(c)

Figure 7: Interaction model between cutting speed and type of coolant (a) feed rate of 0.1 mm/rev (b) feed rate of 0.15 mm/rev (c) feed rate of 0.2 mm/rev

Figure 7 shows the interaction between cutting speed and coolant type on surface roughness. As can be seen in Figure 7, CNF nanofluid gives better surface finish by increasing cutting speed compared to DI water. Besides that, it also shows that DI water gives rougher surface when cutting speed increased at each feed rate. From this result, it was also proven that adding CNF can give finer surface as it can reduce and transfer the heat produced during machining because increasing cutting speed also increases the temperature at the cutting zone. This finding is supported by Hussien et al. [29] who investigated heat transfer enhancement using nanofluids and found that nanofluid produces higher heat transfer enhancement than pure water. Padmini et al. [22] also found similar results where the cutting temperature increased with time and was reduced to 21% by applying nanofluid, and 39% effective in reducing surface roughness.

Confirmation test

Three experiments were performed at optimal settings (for multi-responses) of process parameters in the turning of D2 steel for confirmation test as given in Table 8. The result was selected from RSM when lower tool wear and surface roughness were as desired. The results of the confirmation test are tabulated in Table 9. It shows that the average measured values of Vb and Ra are varied within the predicted optimal range of the respective responses at 95% confidence interval of confirmation test. The error percentage of the experimental overall mean (confirmation test) lies within 2.19% and 2.21% for both Vb and Ra, respectively. The values also give a close result to each other among experimental overall and estimated means. Thus, it validated the combination of the obtained optimal process parameters for multi-characteristics optimization in the turning of D2 steel.

Table 8: Parameters used in confirmation test

Speed	Feed	Type of coolant	Flank wear	Surface roughness	Desirability	
144.58	0.14	CNF	0.090993	0.958769	0.722	Selected

Table 9: Results of confirmation test

Response	Predicted	Experimental			Average	Error %
		1	2	3		
Vb	0.090993	0.09	0.087	0.091	0.089	2.19
Ra	0.958769	0.96	0.99	0.98	0.98	2.21

CONCLUSION

The present study was designed to determine the optimum parameters in the turning of D2 steel by using the Taguchi method and Response Surface Methodology. Based on this study, the following conclusions can be made:

1. The optimum parameters for Vb according to Taguchi are A1 (cutting speed 100 m/min), B3 (feed rate 0.2 mm/rev), and C1 (a type of coolant CNF).
2. For surface roughness, Ra, the optimized control factor settings according to Taguchi are A3 (cutting speed 200 m/min), B1 (feed rate 0.1 mm/rev), and C1 (a type of coolant CNF).
3. The optimal tool wear and surface roughness were found to be at a cutting speed of 144.58 m/min, feed rate of 0.14 mm/rev and use of CNF nanofluid as coolant.

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