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HARD MACHINING OF P235GH STEEL WITH DIFFERENT PARAMETERS USING GSRS MODELLING

MEHANSKA OBDELAVA JEKLA VRSTE P235GH Z UPORABO RAZLIČNIH PROCESNIH PARAMETROV IN GSRS MODELIRANJA

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The high-strength and heat-resistant P235GH steel finds wide applications in pressure vessels and heat exchangers. It is a difficult-to-handle material, which reduces the life of the tool during machining, hence spoiling the finish of machined surface. Cutting fluids can improve the life of tools and surface finish. The current investigation observes the effect of machining parameters (revolution and feed rate) and different cutting environments (SAE-40 oil with 5 % boric acid, soybean oil and nanofluid) on the surface finish and flank wear in hard turning of P235GH steel. Machining trials are designed using an L_{18} orthogonal array with replications. A hybrid approach of grey system based response surface (GSRS) modelling is employed to study the effects of various parameters and their interactions. The chip morphology and flank wear are analysed using scanning electron microscopic images and the predicted optimal machining condition for a better surface finish and reduced tool wear is also validated.

Keywords: hard machining, nanofluid, P235GH steel, grey response surface

Jeklo vrste P235GH je zelo trdo in odporno proti povišanim temperaturam. Uporabja se na mnogih področjih; predvsem pa za visoko tlačne posode in toplotne izmenjevalnike. To je material, katerega se zelo težko oblikuje in mehansko obdeluje, kar zelo skrajšuje življenjsko dobo orodij za njegovo oblikovanje in mehansko obdelavo. Hitra obraba orodja pa lahko tudi poslabša kakovost površine obdelovanca. Ustrezne kapljevine (fluidi), ki se uporabljajo med mehansko obdelavo lahko izboljšajo življensko dobo rezalnih orodij in kakovost mehansko obdelane površine. V pričujočem članku so avtorji opazovali vpliv parametrov mehanske obdelave (število obratov in globino reza) pri različnih pogojih mazanja orodja med mehansko obdelavo. Uuporabljali so olje SAE-40 s 5 % borove kisline, olje zrn soje in nano fluida in ocenjevali končno kakovost mehansko obdelane površine in bočno obrabo rezala med trdim struženjem jekla vrste P235GH. Preizkuse so dizajnirali z uporabo ortogonalne matrike L_{18} z replikami. Uporabili so modeliranje na osnovi hibridnega pristopa sistema zabrisane (sive) logike na osnovi metode odziva površine (GSRS; angl.: Grey System based Response Surface) za študij vpliva različnih procesnih parametrov in njihovega medsebojnega vpliva (interakcij). S pomočjo uporabe posnetkov narejenih z vrstičnim elektronskim mikroskopom (SEM) so analizirali morfologijo ostružkov in bočno obrabo stružnih nožev. Napovedali so optimalne pogoje mehanske obdelave za doseganje boljše površine obdelovancev in ocenili pogoje za zmanjšanje obrabe rezalnega orodja.

Ključne besede: mehanska obdelava, nanofluid, jeklo P235GH, metoda odzivne površine

1 INTRODUCTION

The P235GH steel finds applications in heat-exchanger tubes, pressure vessels and boilers. It can retain strength at elevated temperatures but it is a hard-to-machine material. Excessive tool wear and surface roughness of a machined surface pose difficulties in machining. Turning is an important machining operation for complex profiles, providing reasonable accuracy. The important cutting parameters in turning include the revolution, feed and depth of cut. However, the selection of an appropriate tool and cutting fluid becomes essential for controlling the heat generated, economy and accuracy of the cut.[1] The force components observed in turning are the cutting force, feed force and radial force, with the surface finish being the most decisive response for evaluating the process. A machined surface with a good finish can improve the fatigue strength, corrosion resistance and creep failure.[2]

Cutting fluids play an important role, reducing the tool-workpiece interface temperature, providing lubrication and flushing the chips away from the interface.[3] A vegetable oil-based nanofluid could be an ideal cutting fluid for high-strength alloys like Inconel. Further, the concept of minimum quantity lubrication (MQL) proved to be good in terms of economy and environmental compatibility.[4] A study on fast turning of a hard material under different cutting conditions proved the effectiveness of a MQL environment, particularly with the coated tools.[5] During dry machining of Inconel 718, using an uncoated WC tool, the cutting parameters were found to play a vital role in influencing the surface finish and tool wear.[6] Solid lubricants like PTFE, hBN and WS_2 were also applied in machining with a reasonable success.[7] Ceramic carbide inserts could provide for better machined surface in hard turning of tool steels. Though

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flank wear was identified as a mode of failure of a cutting tool, multiple coated tools could be employed at higher revolutions.[8] In addition to the wear of cutting tools, residual stresses were also generated in the machined surfaces.[9] Flank wear was found to be higher at elevated revolutions and built up edges (BUEs) play a significant role in generating a wear land.[10] The feed rate was an important parameter in influencing the surface roughness during machining of hardened AISI H11 steel with a CBN tool.[11] The feed rate, revolution and cutting environment were found to have significant effects on the tool wear and roughness of a machined surface. The formation of BUEs can spoil the finish of a machined surface, hence a lower revolution and feed rate are desired when machining stainless steel.[12]

The optimal hard-turning conditions can be found using the grey relational analysis (GRA), genetic algorithm (GA), response surface methodology (RSM), principal component analysis (PCA) and fuzzy logic. The RSM and desirability analysis were effectively used in the machining of nanocomposites to find the optimal levels of machining parameters.[13] An orthogonal array with a Taguchi based methodology could be used to perform turning trials and identify the optimal machining conditions. The analysis of variance (ANOVA) was used to find the significant process inputs for a better finish and reduced tool wear.[14] The GRA was used for optimizing multiple responses in machining. It uses the grey relational grade as the performance measure along with the signal-to-noise ratio (S/N ratio) to find the optimal machining condition.[15] The RSM was generally used to design a quadratic model and study the interaction effects among the parameters via response-surface plots. The methods like complex proportional assessment or grey incidence combined with the fuzzy and PCA in hybrid formats were also employed to design the input parameters for different manufacturing processes.[16–18] Machining trials using orthogonal array and an application of the Taguchi method could be effective to find the optimal turning parameters.[19] The MANOVA was also used successfully to find the contribution of parameters in an investigation of machining performance.[20] Hence, the Taguchi method along with the grey theory, RSM or PCA was found to be effective for optimizing the multiple responses in machining processes.

The present work provides an insight into the hard turning of P235GH steel, whose coverage in the existing literature is limited. Optimal turning conditions were also predicted using the methodology of grey system based on response surface modelling. The results provide guidance for machining P235GH steel in industries with good quality standards.

2 MACHINING AND OBSERVATIONS

High-strength P235GH steel was procured in the form of circular rods with a diameter of 12 mm and longitudinal turning was done for a length of 30 mm. A CBN insert (CNGA 120412-R2) with a designated tool holder (DSSNR-2525-M12) was used to perform turning. The range of parameters like revolution and feed were chosen from the literature[9] and pilot turning trials. Three different cutting fluids were used in machining trials (SAE-40 oil with 5 % boric acid, soyabean oil and nanofluid). A binary mixture of 80 % ethylene glycol and 20 % water with suspended nanoparticles of alumina and magnesium oxide was used as the nanofluid. The levels of turning parameters and cutting environment are shown in **Table 1**.

Table 1: Turning parameters and cutting environment

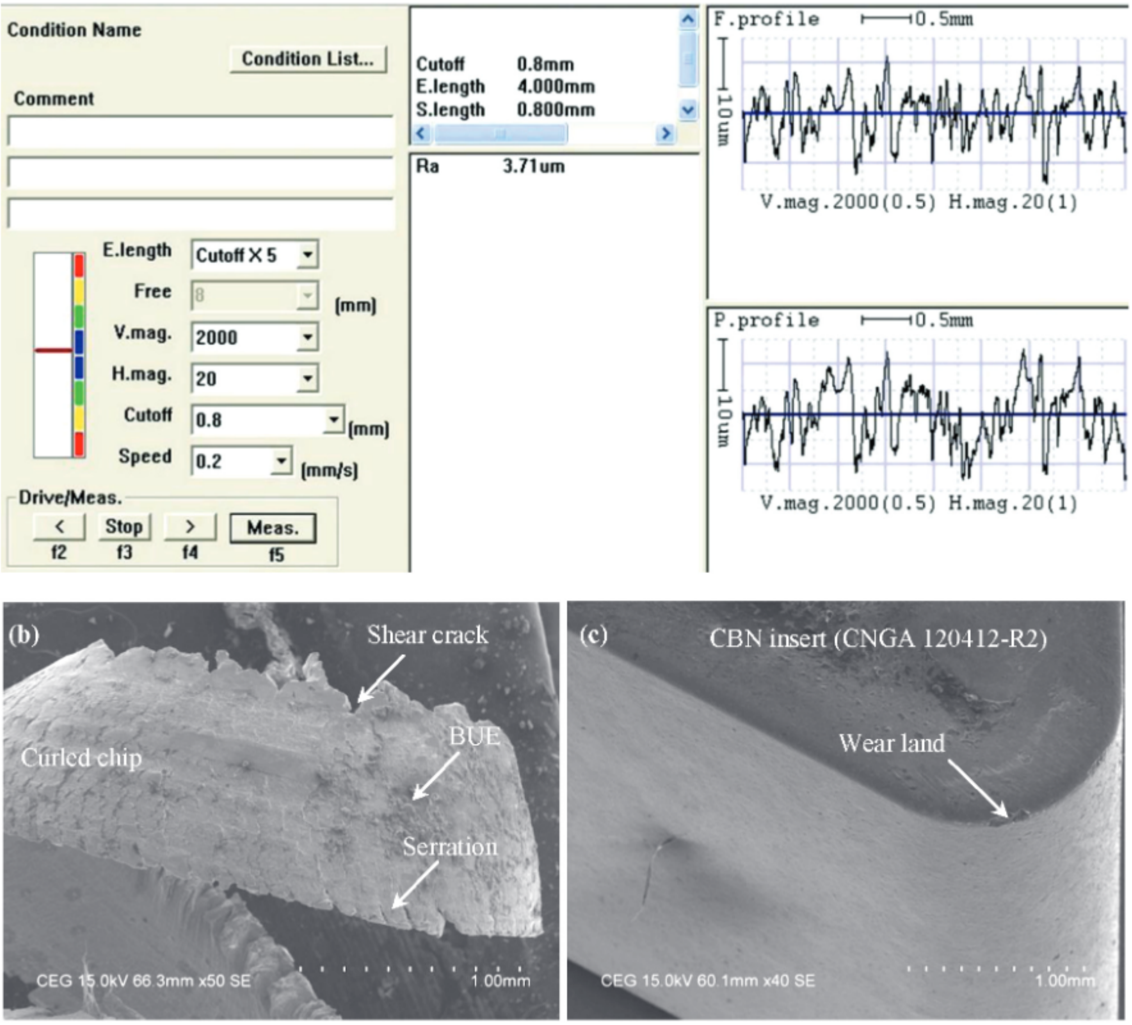
Factors	Units	levels		
		1	2	3
Revolution (*R*)	min^{-1}	1500	2000	2500
Feed rate (*FR*)	mm/rev	0.03	0.09	0.15
Cutting environment (*CE*)	–	SAE-40 oil + 5 % H_3BO_3	Soybean oil	Nanofluid ($C_2H_6O_2$ (80 %)+H_2O (20 %)+nanoparticles of Al_2O_3 + MgO)

Taguchi's L_{18} orthogonal array was used to conduct the turning experiments on P235GH steel at a constant depth of cut (0.4 mm). The turning trials were performed in a random order with two replications (Re_1 and Re_2) by varying the parameters as prescribed by the L_{18} array.[16] A CNC lathe (Ikegai TU-30) with a spindle revolution range of 30–2500 min^{-1}, feed range of 0.01–3.0 mm/rev and motor rating of 30 kW was used to perform the turning of the P235GH steel rods. A surface roughness tester (model: Surfcoder SE:3500) was used to measure the roughness at a speed of 0.5 mm/s for a cut-off length of 0.8 mm. VMS-2020F was used to measure the maximum wear land width (flank wear). A few turned samples are shown in **Figure 1**. The responses such as the surface

Figure 1: A few samples of turned P235GH steel rods

Table 2: L_{18} array showing the observed surface roughness and flank wear

Exp. No	Run order	Levels of control factors			Responses			
		R	*FR*	*CE*	Surface roughness (μm)		Flank wear (mm)	
		(min^{-1})	(mm/rev)	–	Re_1	Re_2	Re_1	Re_2
1	4	1500	0.03	SAE-40 + 5 % H_3BO_3	4.206	4.2141	0.1012	0.1021
2	10	1500	0.09	soybean oil	3.905	3.9131	0.0995	0.0995
3	7	1500	0.15	nanofluid	3.845	3.8531	0.1124	0.1138
4	1	2000	0.03	SAE-40+5% H_3BO_3	3.208	3.208	0.1026	0.1017
5	15	2000	0.09	soybean oil	3.501	3.5091	0.0812	0.0803
6	11	2000	0.15	nanofluid	3.841	3.8329	0.0954	0.0949
7	18	2000	0.03	soybean oil	2.402	2.4101	0.1135	0.1144
8	13	2000	0.09	nanofluid	2.145	2.1287	0.1024	0.1019
9	5	2000	0.15	SAE-40 + 5 % H_3BO_3	2.997	2.9807	0.1498	0.1498
10	16	1500	0.03	nanofluid	3.973	3.973	0.0345	0.0345
11	8	1500	0.09	SAE-40 + 5 % H_3BO_3	3.710	3.6867	0.1042	0.1047
12	2	1500	0.15	soybean oil	4.452	4.4764	0.0931	0.0931
13	12	2000	0.03	soybean oil	3.492	3.5164	0.0985	0.0994
14	17	2000	0.09	nanofluid	2.491	2.5154	0.0965	0.097
15	14	2000	0.15	SAE-40+5% H_3BO_3	4.375	4.3831	0.1067	0.1072
16	9	2000	0.03	nanofluid	1.274	1.2821	0.0885	0.0876
17	6	2000	0.09	SAE-40 + 5 % H_3BO_3	2.904	2.9203	0.1018	0.1022
18	3	2000	0.15	soybean oil	2.026	2.026	0.1153	0.1167



Cutoff 0.8mm
E.length 4.000mm
S.length 0.800mm

Ra 3.71um

E.length: Cutoff X 5
Free: 8 (mm)
V.mag.: 2000
H.mag.: 20
Cutoff: 0.8 (mm)
Speed: 0.2 (mm/s)

Figure 2: a) Measurement of the surface roughness, b) chip morphology and c) flank wear land

roughness (SR) and flank wear (FW) obtained with the turning trials are listed in **Table 2**.

The scheme of measuring the surface roughness is shown in **Figure 2a**, which corresponds to trial number 11 (revolution – 1500 min^{-1}, feed rate – 0.09 mm/rev, an environment of SAE-40 + 5 % H_3BO_3). The F-profile and P-profile measured for an evaluation length of 4 mm and sampling length of 0.8 mm were clearly evident. The free surface of a chip suffering from serration was visible on the top side of the chip. The severe plastic deformation giving rise to shear cracks was also seen in the chip morphology (**Figure 2b**). The formation of cracks can also be attributed to elevated compressive stresses.[22] These cracks created chip segments and new chips were formed, while the elevated temperature and plastic deformation resulted in saw-tooth chips.[21] The abrasion marks on the tool due to severe rubbing between the machined surface and tool flank causes flank wear. Broken BUEs also contribute to the flank wear.[22] The flank wear observed in **Figure 2c** could be due to the compressive-stress concentration in the rake face of the tool that increases significantly at elevated temperatures.

3 OPTIMIZATION OF FLANK WEAR AND SURFACE ROUGHNESS

The simultaneous optimization of responses (flank wear and surface roughness) was performed using techniques including the grey theory, Taguchi method and RSM. The responses were made into a single characteristic representing the quality, using the GRA. The calculation of the S/N ratio and further normalization were done to reduce the noise and bring the responses to a common scale.[14] The *'smaller-the better'* quality characteristic shown in Equation (1) was used for both responses, where *r* denotes the number of replications and y_{ij} indicates the value of observed responses. The data variability was eliminated using Equation (2).

$$S/N \text{ ratio } (\eta) = -10 \lg_{10}\left(\frac{1}{r} \cdot \sum_{i=1}^{r} y_{ij}^{2}\right) \tag{1}$$

$$Z_{ij} = \frac{\eta_{ij} - \min(\eta_{ij}, i = 1, 2, \ldots n)}{\max(\eta_{ij}, i = 1, 2, \ldots n) - \min(\eta_{ij}, i = 1, 2, \ldots n)} \tag{2}$$

The relation between the ideal and actual experimental result was found and expressed as a grey relational coefficient (GRC) and grey relational score (GRS) using Equations (3) and (4), respectively[18]:

$$\gamma_i^j = \frac{\Delta\min + \xi\Delta\max}{\Delta_{oj}(i) + \xi\Delta\max} \tag{3}$$

$$GRG_i = \frac{\sum_{i=1}^{n}(\delta_i)}{n} \tag{4}$$

where *n* is the number of trials, z_{ij} is the normalized S/N ratio, $\Delta\min = \min |z_o(i)-z_j(i)|$ for all *i* values and $j \in i$ is the least value of z_j(i); $\Delta\max = \max |z_o(i)-z_j(i)|$ for all *i* values and $j \in i$ is the highest value of $z_j(i)$; ξ is the distinguishing coefficient with a value of 0.5, applying an equal weightage to the responses. A mathematical model (polynomial second-order equation) was formed using Design Expert software (Version-7.1) to predict the responses in terms of the GRS. The ANOVA was performed to find the influence of the turning parameters on the flank wear and surface roughness. Finally, a desirability function was used to achieve the optimal combination of the turning inputs.

4 RESULTS AND DISCUSSION

The grey system based response surface (GSRS) modelling was used to process the experimental data and identify the optimal turning inputs.

4.1 Data processing using the grey theory

The S/N ratios were obtained and normalized to reduce the variability among the responses. The relationships between the ideal and actual response values were obtained in terms of the GRG and finally the GRS was calculated for each trial. The processed data is displayed in **Table 3** and the variation in the GRS values for various turning trials is shown in **Figure 3**. Though both responses were of a *'smaller-the-better'* characteristic, the larger GRS value became essential for producing better responses.[18] A good deviation in the GRS values was observed, justifying the selection of the levels of parameters. The value of GRS was the largest for the sixteenth trial, showing its closeness to the optimal turning condition.

Table 3: Processed data displaying values of the grey relational score (GRS)

Exp. No	*S/N* ratio		Normalized S/N ratio		Grey relational coefficient		GRS
	SR	FW	SR	FW	SR	FW	
1	–12.486	19.858	0.047	0.264	0.344	0.405	0.374
2	–11.841	20.044	0.106	0.279	0.359	0.409	0.384
3	–11.707	18.932	0.119	0.192	0.362	0.382	0.372
4	–10.125	19.815	0.264	0.261	0.405	0.403	0.404
5	–10.894	21.857	0.193	0.421	0.383	0.463	0.423
6	–11.680	20.430	0.121	0.309	0.363	0.420	0.391
7	–7.626	18.866	0.494	0.186	0.497	0.381	0.439
8	–6.596	19.813	0.589	0.261	0.549	0.403	0.476
9	–9.510	16.490	0.321	0.000	0.424	0.333	0.379
10	–11.982	29.244	0.093	1.000	0.355	1.000	0.678
11	–11.352	19.624	0.151	0.246	0.371	0.399	0.385
12	–12.995	20.621	0.000	0.324	0.333	0.425	0.379
13	–10.892	20.091	0.194	0.282	0.383	0.411	0.397
14	–7.970	20.289	0.463	0.298	0.482	0.416	0.449
15	–12.828	19.418	0.015	0.230	0.337	0.394	0.365
16	–2.131	21.105	1.000	0.362	1.000	0.439	0.720
17	–9.284	19.830	0.342	0.262	0.432	0.404	0.418
18	–6.133	18.712	0.632	0.174	0.576	0.377	0.476

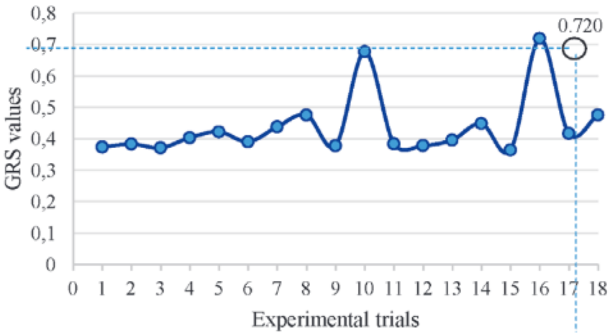


Figure 3: Variation in GRS values for various trials

4.2 Fit and adequate second-order polynomial model

A quadratic model was formed using Design Expert software to study the relationships among the parameters and outputs (surface finish and flank wear). The interaction effects were also studied from the model generated for the GRS (Equation (5)). Taguchi's L_{18} array was preferred over the central composite design to reduce the turning trials. Insignificant higher-order terms were removed from the model. The final equations were also represented in terms of the actual factors (Equations (6–8)).

$$GRS = 0.45 + 0.025 \cdot R - 0.052 \cdot FR - 0.053 \cdot CE\,[1] - 8.46\ \mathrm{X}10^{-3} \cdot CE\,[2] - 5.659 \cdot 10^{-3} \cdot R{\cdot}FR - 4.662 \cdot 10^{-3} \cdot R{\cdot}CE\,[1] + 0.046 \cdot R \cdot CE\,[2] + 0.037 \cdot FR \cdot CE\,[1] + 0.073 \cdot FR \cdot CE\,[2] \tag{5}$$

Cutting Environment (CE): SAE-40 + Boric acid

$$GRG = 0.30331 + 5.70940 \cdot 10^{-5} \cdot R + 0.12551 \cdot FR - 1.88635 \cdot 10^{-4} \cdot R \cdot FR \tag{6}$$

Cutting Environment (CE): Soybean oil

$$GRG = 0.090544 + 1.58381 \cdot 10^{-4} \cdot R + 0.72828 \cdot FR - 1.88635 \cdot 10^{-4} \cdot R \cdot FR \tag{7}$$

Cutting Environment (CE): Nanofluid

$$GRG = 0.78258 - 1.62222 \cdot 10^{-5} \cdot R - 2.30936 \cdot FR - 1.88635 \cdot 10^{-4} \cdot R \cdot FR \tag{8}$$

The ANOVA was performed for the GRS (**Table 4**), showing the model significance (f–value of 11.97). The adequacy of the generated model was shown by the

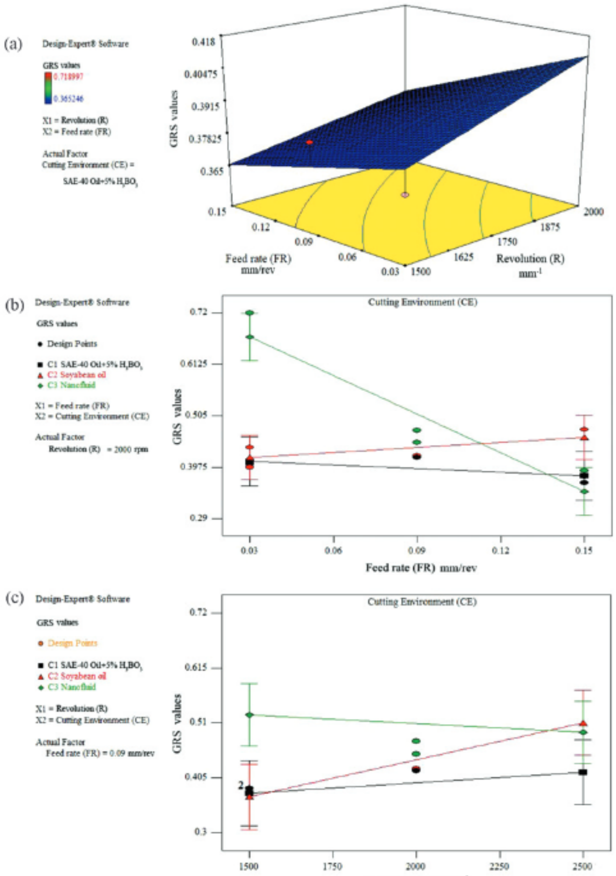


Figure 4: Response-surface diagrams

Table 4: Analysis of variance

Source	Sum of squares	Degrees of freedom	Mean square	*f*–value	*p*–value	remarks
Model	0.1600	9	0.018	11.97	0.0009	significant
Revolution (*R*)	0.00166	1	0.00166	1.12	0.3208	
Feed rate (*FR*)	0.03500	1	0.0350	23.81	0.0012	
Cutting environment (*CE*)	0.05600	2	0.0280	18.79	0.0009	
R–FR	0.000059	1	0.000059	0.04	0.8466	
R–CE	0.00436	2	0.00218	1.47	0.2859	
FR–CE	0.06	2	0.0300	20.13	0.0008	
Residual	0.012	8	0.00148			
Lack of fit	0.011	5	0.00212	5.07	0.106	not significant
Pure error	0.00125	3	0.000418			
Cor. total	0.17	17				
Model fitness statistics						
Std. dev.	0.038	R-squared	0.931			
Mean	0.439	Adj. R-squared	0.853			
C.V. %	8.764	Pred. R-squared	0.659			
PRESS	0.058	Adeq. precision	11.621			

Table 5: Predicted optimal conditions

Factor	Name	Optimal level	Low level	High level
R	Revolution (min^{-1})	1837.84	1500	2000
FR	Feed rate (mm/rev)	0.051	0.03	0.15
CE	Cutting environment	Nanofluid	SAE-40 + 5 % H_3BO_3	Nanofluid
Response	Prediction	SE Mean	95 % CI low	95 % CI high
GRG	0.74823	0.0242	0.6911	0.8003

Table 6: Confirmation experiments at the optimal conditions

Responses	Initial setting (Trial 16)	Predicted optimal setting	Improvements	
			Value	Percentage
Surface roughness (μm)	1.2812	1.157	0.1242	9.694
Flank wear (mm)	0.0885	0.0525	0.036	40.678
GRG	0.7212	0.7423	0.0223	3.097
Parameter settings	$A_3{\cdot}B_1{\cdot}C_3$	*R* = 1837.84 min^{-1} *FR* = 0.051 mm/rev CE – nanofluid		

f–value (5.07) for the lack of fit. The terms in the model were significant as the p–value was less than 0.5, excluding the interaction term *'R-FR'*. The results display the ability of the polynomial equation to represent the turning conditions for the P235GH steel. The fitness of the model was further strengthened by the closeness of the predicted and adjusted R-squared values. The value of adequate precision (11.6) was larger than 4.0.

4.3 Interaction plots

The response plots are shown in **Figure 4**. The effects of different parameters can be understood from the graphs. A moderate level of revolution was desired as it removes the BUEs formed at the elevated temperature and compressive stresses (**Figure 4c**). A high speed enhances the tool wear, while a low speed spoils the surface finish. Hence, a low feed rate combined with a moderate level of revolution could improve the finish and reduce the tool wear, as seen from **Figure 4a**. This was indicated by an improvement in the GRS value. Less apparent feed marks at a relatively low level of the feed rate improved the surface finish and reduced the tool wear (**Figure 4b**); hence, we obtained an improved GRS value. The nanofluid used in the cutting environment improved the responses and hence, we obtained an increased GRS value. The improvement was clearly well ahead of that achieved with the other two cutting fluids (**Figure 4b** and **4c**).

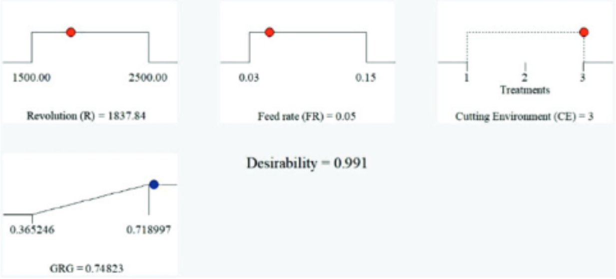


Figure 5: Ramp diagram

4.4 Desirability graph and validation

Among the various types of desirability functions, the *'larger-the-better'* type was used in the analysis. The turning input closer to the highest desirability value was predicted as the optimal condition (**Table 5**). The predicted optimal parameters for turning P235GH steel included a revolution of 1837.84 min^{-1} and feed rate of 0.051 mm/rev in a nanofluid cutting environment. The dot on each ramp (**Figure 5**) indicates the extent of desirability[13] and the optimal inputs are shown in the ramp diagram.

The approach used to predict the optimal turning parameters and environment requires a proper validation for providing the necessary guidelines to the industries handling P235GH steel. Hence, the responses obtained with the optimal conditions were compared with the turning inputs that gave the largest GRS value during the initial experimentation (Trial 16). Good improvements in the responses were observed as shown in **Table 6**.

5 CONCLUSIONS

The surface finish and flank wear were studied during the hard turning of P235GH steel, using a CBN insert. The turning trials were designed using Taguchi's L_{18} array and the following conclusions were drawn:

A hybrid methodology of grey system based response surface (GSRS) modelling was effectively used to predict the optimal turning conditions including a revolution of 1837.84 min^{-1} and feed rate of 0.051 mm/rev in a nanofluid ($C_2H_6O_2$ (80%) + H_2O (20%) + nanoparticles of Al_2O_3 + MgO) cutting environment.

The turning inputs as well as the cutting fluid environment were found to affect both the surface finish and tool wear significantly. The reduced roughness of the machined surface and flank wear of the tool, observed at the optimal turning conditions, demonstrated the effectiveness of the combined methodology.

The multi-response problem of turning P235GH steel, using a CBN insert, was reduced to the optimization of a single response in terms of the GRS.

The results of the study can provide the required guidelines for hard turning P235GH steel, used in heat-exchanger tubes, pressure vessels and boilers.

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