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Multi Response Optimization for Turning AISI 1040 Steel with Extreme Pressure Additive included Vegetable Oil Based Cutting Fluids using Grey Relational Analysis

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Abstract – *The present work focuses on finding the optimal machining parameters in turning AISI 1040 steel with multiple performance characteristics using Grey-based Taguchi method. The multi-response problem is converted into an equivalent single-response problem using Grey Relational Analysis (GRA). A Grey grade obtained from GRA is analysed to get optimal machining parameters using the Grey grade as the performance index. The performance characteristics selected in this work are cutting force, cutting tool temperature, tool flank wear and surface roughness. These performance characteristics are analysed to obtain the optimal machining parameters for type of vegetable oil based cutting fluid, proportion of extreme pressure (EP) additive, cutting speed and feed. The results reveal that type of vegetable based cutting fluid is found to be the major factor along with feed, proportion of EP additive and cutting speed that influences the multiple performance characteristics.*

Keywords: turning, vegetable oils, extreme pressure additive, Taguchi method, grey relational analysis

1.0 INTRODUCTION

Workpiece quality and dimensional accuracy is very much affected by high temperatures generated in machining. These high temperatures are the result of friction between tool-workpiece and tool-chip interface. This can be controlled with the help of effective lubrication in machining zone. Cutting fluids (CFs) play the dual role of lubricants and coolants in reducing the friction as well as dissipating the heat. In production shops mineral oil based cutting fluids are traditionally used due to their reusability and chemical stability. However, dermatitis to operators, environmental and water pollution are the adverse effects due to the application of conventional CFs. Soil contamination also occurs during their disposal [1-4]. These factors have promoted investigations to probe into use of eco-friendly coolants in machining. Researchers have started using vegetable oils as an alternative to conventional CFs. Vegetable oil based cutting fluids (VBCFs) are better substitute for conventional CFs due to renewable properties, higher biodegradability and lower environmental impact [5]. Molecular structure of

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vegetable oils is termed as triacylglicerides. They contain medium fatty acid chain (MFAC) and long fatty acid chain (LFAC) which are joined at the hydroxyl groups (OH) through ester linkages. The length of the chain of these fatty acids ranges 6-12 (medium carbon chain) and 14-22 (long carbon chain) carbons [6]. Due to LFAC triglyceride structure provides desirable boundary lubrication which in turn provide high strength lubrication film when that interacts strongly with metallic surface thereby reducing friction and wear [5]. The chemical composition and fatty acid profiles of vegetable oils are the primary reasons behind their performance as cutting fluid. It is reported that good absorption properties, better pitting resistance, lower coefficient of friction and excellent boundary lubrication on the metal surface in contact were achieved by the application of VBCFs [6, 7].

Chemical additives like emulsifiers and extreme pressure (EP) additives when added to CFs result in reducing corrosion, odour prevention and improving flash point. EP additives are additives for lubricants to reduce friction between tool-chip interface and heat caused by plastic deformation of the metal. In these oils an additive used is largely confined to sulfur or sulfurized fats. Sulfur additives are well-known for their anti-wear and strong EP characteristics. Performance is enhanced in terms of reducing cutting forces and tool wear and improving surface finish and part accuracy by using CFs with EP additives [8]. Researchers are investigating to develop new bio based CFs from different vegetable oils. With the use of VBCFs various studies have been focused on different machining processes like drilling [9-11], turning [11,12] and reaming [10,11,13,14]. In these studies, cutting force, tool wear, tool life and surface finish were examined. Huseyin et al. [15] examined the performance of VBCFs (canola and sunflower oils) with EP additive, semi-synthetic and mineral oil based CFs for cutting and feed forces and surface finish in turning AISI 304L with carbide tool. Type of cutting fluid, cutting speed, feed and depth of cut are the machining parameters considered in this work. Analysis of variance (ANOVA) results reveals that feed has greater effect on surface roughness (97% contribution) while depth of cut has more effect on feed force (95% contribution) and cutting force (82% contribution). Further, VBCFs with EP additive has more significant effect in reducing cutting and feed forces compared to cutting speed and feed.

Cambiella et al. [16] evaluated the influence of different oil-in-water emulsions in machining operations which were considered as lubricating as well as cooling fluids in EP tests. The EP properties of the oil-in-water emulsions were studied by considering various proportions of anionic, non-ionic and cationic emulsifiers. The results proved that the effectiveness of oil-in-water emulsions was similar to base oils. Further in making the metal surface wet, the ability of oil droplets played a major role in tribological behaviour. In addition, the type of emulsifier and variation in emulsifier concentration affected the performance of lubrication. Virgin coconut oil (VCO) is reported good quality physio-chemical properties and antioxidant nature [17]. The presence of ZDDP additive in the Refined, Bleached and Deodorized (RBD) palm stearin cutting fluid experienced less coefficient of friction and wear scar diameter [18]. Mohd Marsin et al. [19] carried out investigation on Purple Sweet Potato (PSP) starch by adding glycerol as plasticizer and kappa carrageenan as gelling agent and observed improvement in the formation of the edible film. Robin and Hariom [20] analyzed the effect of machining parameters on surface roughness and material removal rate in a turning operation to get the optimal values using Taguchi method. Gokul and Smitha [21] conducted a comparative study of dry machining and wet machining where rice bran oil and coolant oil are used as the cutting fluids. The results obtained with conventional flood cooling method are compared with that of dry cutting. The experiment is carried out in a CNC lathe for turning operation on plain carbon steels EN8 and EN9 for surface roughness and tool life by varying parameter like cutting speed and feed keeping depth of cut constant. Amit and Kadam [22] employed Response surface method technique and Grey relation method for optimization of the process parameters in

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SS316L steel etching of Photochemical machining process for the prediction of material removal rate, surface roughness and undercut. Kuram et al. [23] evaluated the effect of EP additive added to VBCFs for reducing cutting force, surface roughness and increasing tool life during milling of AISI 304 steel. The experimentation was carried out with canola and sunflower oils with 8% EP additive and the results were compared with semi-synthetic cutting fluid. Improvement in performance was achieved with canola based cutting fluid with 8% EP additive.

From the literature it is observed that investigations related to VBCFs have shown better performance compared to conventional CFs. Addition of EP additive to cutting fluids enhanced their performance due to the favourable properties of EP additives along with vegetable oils. However, combination of different vegetable oils with addition of EP additive performance and its optimization in machining is seldom found. Owing to this reason, coconut oil, canola oil, sesame oil are used as lubricants in the present work. In the present work different vegetable oils with addition of EP additive is used in machining operation and the optimum conditions for better performance are investigated. Multi response optimization problem is converted into an equivalent single response optimization problem using Grey Relational Analysis (GRA).

2.0 EXPERIMENTATION

All the machining experiments are conducted on PSG-124 lathe with coated carbide tool insert (CNMG120408NC6110) in turning AISI 1040 steel workpiece having hardness of 30±2 HRC (Rockwell Hardness). Figure 1 shows the experimental setup for turning process. Chemical composition of AISI 1040 workpiece material in percentage by weight is given Table 1. The experimental details are depicted in Table 2. Table 3 shows the percentage of saturated fatty acids (SFA), unsaturated fatty acids (U-SFA) and Table 4 shows the profiles of fatty acids in three types of vegetable oils considered in the present work [24]. Sulfur based EP additive (HiTEC343) is used to prepare VBCFs because it is less viscous, possesses good solubility in water and has high lubricating ability [25]. Cutting fluid is prepared by adding EP additive in canola, coconut and sesame oils at a proportion of 5%, 10% and 15% by weight. Initially emulsifier and vegetable oil are mixed in the ratio of 15% and 85% by weight respectively. Then premeasured quantity of EP additive is taken in a beaker and the required quantity of emulsifier and vegetable oil mixture is added while manually mixing both to obtain a uniform mixture. Finally VBCF is prepared by adding water to the mixture in oil to water as 9:100 ratio.

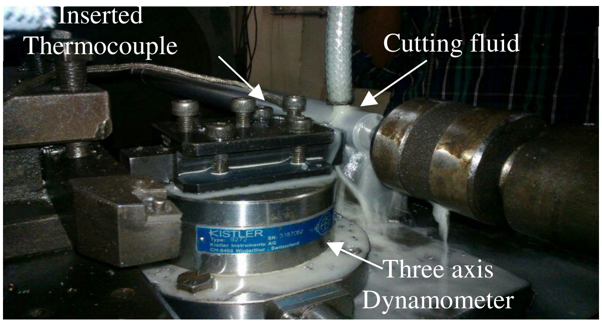

Figure 1: Experimental set up

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Table 1: Chemical composition of AISI 1040 steel (wt. %)

C	Si	Mn	S	P	Fe
0.36-0.45	0.2-0.3	0.60-1.00	0.025	0.015	Balance

Table 2: Experimental Details

Workpiece Material:	AISI 1040 (C: 0.36–0.45%, Mn: 0.6–1%, Si: 0.2–0.3%, S: 0.025%, P: 0.015%)
Hardness	30 ±2 HRC
Tool holder	PSRNR12125F09
Cutting tool (insert)	CNMG120408NC6110 coated carbide (TiCN/Al_2O_3 coating)
Cutting speed	60, 80 and 100 m/min
Feed rate	0.14, 0.17 and 0.20 mm/rev
Depth of cut	0.5 mm (constant)
Cutting fluids	Coconut, canola and sesame based cutting fluids
% EP additive inclusion	5, 10 and 15

Table 3: Saturated and Unsaturated Fatty Acids in vegetable oils

Vegetable oil	% Saturated	% Mono-unsaturated	% Poly-unsaturated
Sesame oil	7	65	28
Canola oil	15	41	44
Coconut oil	91	6	3

Table 4: Fatty acids profiles of three types of vegetable oils

Vegetable oil	Linoleic Acid (U-SFA)	Oleic Acid (U-SFA)	Palmatic Acid (SFA)	Stearic Acid (SFA)	Fatty Acids (length)
Sesame oil	41	39	8	5	LFAC [14-22 Carbons]
Canola oil	21	61	4	2	LFAC [14-22 Carbons]
Coconut oil	2	8	11	3	MFAC [8-12 Carbons]

The effectiveness of a cutting fluid as a lubricant is judged by its kinematic viscosity. In the present work, kinematic viscosity of EP additive included in different VBCFs is estimated using Redwood viscometer-I. Thermal conductivity of EP additive included in VBCFs is measured at different temperatures using steady-state thermal conductivity apparatus (P A Hilton Ltd, England; temperature range: 25^0C-65^0C). Cutting fluid is supplied at the rate of 3.5 lit/min at the machining zone. All the machining experiments are conducted at variable cutting conditions with nine different VBCFs formulated from canola, coconut and sesame oils (including 5%, 10% and 15% of EP additive) for recording the responses such as cutting force (F_c), cutting tool temperature (T), tool flank wear (V_b) and surface roughness (R_a). The cutting forces are tracked online using DynoWare software by fixing Kistler 9272 dynamometer to the lathe tool post. Cutting temperatures are sensed online by an embedded thermocouple (K-type) calibrated in the range of 0^0C–1200^0C. GX51 optical microscope offline is employed for measuring tool flank wear. For measuring surface roughness offline Surf test, SJ-301, MITUTOYO, diamond stylus with tip radius of 5 μm is employed. Response value is considered by calculating the average of measurements taken at three different locations. In this study, type of cutting fluid, proportion of EP additive, cutting speed and feed are considered as parameters in turning AISI 1040 steel. The four factors with different levels are presented in Table 5. The prepared CFs are notated as sesame based cutting fluid (SCF), canola based cutting fluid (CNCF) and coconut based cutting fluid (CCF).

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Table 5: Levels of turning factors

Parameters	Symbol	Unit	Level	Level 2	Level
Cutting fluid	*CF*	--	SCF	CNCF	CCF
EP additive	*EP*	%	5	10	15
Cutting speed	*V*	m/min	60	80	100
Feed	*f*	mm/rev	0.14	0.17	0.20

Taguchi's L_{27} orthogonal array shown in Table 6 is utilized for experimental design. MINITAB 14 version is used for design of experiments. The four factors type of vegetable based cutting fluid, proportion of EP additive, cutting speed and feed are considered in the present analysis. The influence of these factors at various levels on F_c, T, V_b and R_a is examined by applying GRA. Optimal value for each machining parameter is obtained by analysing the Grey grade. ANOVA is carried out to detect the most influencing factors for F_c, T, V_b and R_a in turning AISI 1040 steel.

Table 6: Orthogonal array (L_{27}) of experiments and measurements

Trial No.	*CF*	EP	*V*	*f*	F_c	*T*	V_b	R_a
1	SCF	5	60	0.14	101.0961	29	91.8	4.14
2	SCF	5	80	0.17	157.9813	33	130.5	5.16
3	SCF	5	100	0.20	123.2514	42	239.18	4.53
4	SCF	10	60	0.17	91.8209	29	87.2	3.91
5	SCF	10	80	0.20	156.168	34	209.53	6.13
6	SCF	10	100	0.14	58.4193	38	105.05	3.80
7	SCF	15	60	0.20	127.3058	32	155.68	5.22
8	SCF	15	80	0.14	162.694	32	125.68	5.35
9	SCF	15	100	0.17	125.8062	41	154.73	4.54
10	CNCF	5	60	0.17	90.3875	29	88.45	3.69
11	CNCF	5	80	0.20	156.9662	33	162.11	5.54
12	CNCF	5	100	0.14	62.2729	38	92.14	3.42
13	CNCF	10	60	0.20	90.0264	29	99.87	3.94
14	CNCF	10	80	0.14	89.6116	29	77.64	3.92
15	CNCF	10	100	0.17	68.3976	39	102.24	3.26
16	CNCF	15	60	0.14	98.0550	29	84.45	3.86
17	CNCF	15	80	0.17	124.4871	33	119.07	4.81
18	CNCF	15	100	0.20	95.1379	42	185.13	4.35
19	CCF	5	60	0.20	88.0967	29	84.6	3.63
20	CCF	5	80	0.14	82.1692	28	61.65	3.44
21	CCF	5	100	0.17	60.3194	38	91.45	2.94
22	CCF	10	60	0.14	66.2509	26	53.52	2.63
23	CCF	10	80	0.17	79.0149	29	74.52	3.50
24	CCF	10	100	0.20	61.1302	39	83.60	3.20
25	CCF	15	60	0.17	86.974	29	87.56	3.45
26	CCF	15	80	0.20	142.3296	32	98.33	4.96
27	CCF	15	100	0.14	57.887	39	73.45	3.06

CF: cutting fluid; *EP*: EP additive in %; *V*: cutting speed in m/min; *f*: feed in mm/rev; F_c: cutting force in N; *T*: cutting tool temperature in ^{0}C; V_b: tool flank wear in µm; R_a: surface roughness in µm.

3.0 GREY RELATIONAL ANALYSIS (GRA)

Multi response optimization is done by integrating Taguchi method and GRA to identify the optimum process parameters [26-28]. The objective is to obtain the optimum process parameters for multi response characteristics. Correlation between the desired and actual experimental data is represented by the Grey relational coefficients. In GRA multi-response problem is converted into an equivalent single-response problem by calculating Grey grade. Grey relational coefficient is calculated by normalizing all the responses from '0' to '1'. The Grey grade is obtained by averaging Grey relational coefficients of selected response. Initially the responses are normalized using Eq. (1) based on smaller-the-better criterion and it is known as Grey relational generation.

$$\left[x_i(r) = \frac{\max y_i(r) - y_i(r)}{\max y_i(r) - \min y_i(r)} \right] \tag{1}$$

where, $x_i(r)$ is grey relational generation

$\min y_i(r)$ is smallest value of $y_i(r)$ for the r^{th} response

$\max y_i(r)$ is largest value of $y_i(r)$ for the r^{th} response

r = 1,2,….m ('m' is the number of responses)

i = 1,2,….n ('n' is the number of experiments)

Grey relational coefficient $\xi_i(r)$ can be calculated using Eq. (2):

$$\xi_i(r) = \frac{\Delta\min + \psi\Delta\max}{\Delta_{0i}(r) + \psi\Delta\max} \tag{2}$$

where,

$\Delta_{oi} = \left\| x_o(r) - x_j(r) \right\|$ is the absolute difference between $x_o(r)$ and $x_j(r)$

$x_o(r)$ is the reference sequence ($x_o(r)$= 1 for r= 1,2,….m)

$x_j(r)$ is the specific comparison sequence

$\Delta_{\min} = \min_{\forall j \in j} \min_{\forall r} \left\| x_o(r) - x_j(r) \right\|$ is smallest value of $x_j(r)$

$\Delta_{\max} = \max_{\forall j \in j} \max_{\forall r} \left\| x_o(r) - x_j(r) \right\|$ is largest value of $x_j(r)$

ψ is the distinguishing coefficient (lies between 0 and 1)

The Grey grade $(\overline{\gamma_i})$ for each experimental run can be obtained by calculating the average of the grey relational coefficients by using Eq. (3):

$$\overline{\gamma_i} = \frac{1}{m} \sum_{r=1}^{m} \xi_i(r) \tag{3}$$

The higher Grey grade indicates that parameter combination is very close to optimum value.

4.0 RESULTS AND DISCUSSION

4.1 Basic properties of VBCFs

The values of kinematic viscosity of VBCFs with varying EP additive proportion are shown in Table 7. It is found that as %EP additive is increased viscosity of the VBCF is decreased. Sulfur based EP additive added to vegetable based cutting fluid possess low viscosity values [15]. When viscosity is low, heat dissipation capacity of EP additive increases and when it is high the ability of EP additive to form a consistent film between contact surfaces gets enhanced [23]. Referring to Table 8, it is observed that thermal conductivity increased with increase in proportion of EP additive. Among all the samples considered coconut based cutting fluid with

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EP additive possess higher values of thermal conductivity. Owing to higher thermal conductivity of coconut oil the phenomenon is more significant in coconut oil compared to canola and sesame oils as shown in Table 8.

Table 7: Physical properties of vegetable oil based cutting fluids

Cutting fluid / EP additive	Temperature (^{0}C)	Kinematic Viscosity (cm^2/sec) EP additive inclusion in cutting fluid (%)			
		0	5	10	15
SCF + EP	30	2.952	2.869	2.753	2.625
	35	2.943	2.931	2.748	2.569
	40	2.928	2.920	2.739	2.557
	45	2.932	2.865	2.726	2.549
CNCF + EP	30	2.196	2.159	1.968	2.036
	35	2.183	2.137	1.824	2.013
	40	2.164	2.111	1.805	1.997
	45	2.158	2.125	1.947	1.982
CCF + EP	30	2.381	2.395	2.293	2.346
	35	2.379	2.385	2.286	2.297
	40	2.385	2.373	2.261	2.186
	45	2.376	2.352	2.136	2.173

Table 8: Thermal conductivity of vegetable oil based cutting fluids

Cutting fluid / EP additive	Thermal Conductivity (W/m-K) EP additive inclusion in cutting fluid (%)			
	0	5	10	15
SCF + EP	0.1764	0.1767	0.1772	0.1775
CNCF + EP	0.1786	0.1789	0.1795	0.1802
CCF + EP	0.1815	0.1821	0.1827	0.1832

4.2 Grey relational analysis

The experimental data (Table 6) obtained for the responses cutting force, cutting tool temperature, tool flank wear and surface roughness is normalized based on smaller-the better criteria using Eq. (1). The normalized values for each of the response is presented in Table 9. GRA is performed for the normalized values to calculate Grey relational coefficients. Grey relational coefficient for each experimental run of performance characteristic is calculated by giving equal weight ($\psi_{F_c} = 0.25, \psi_T = 0.25, \psi_{V_b} = 0.25$ and $\psi_{R_a} = 0.25$) using Eq. (2). Grey grade is obtained by averaging the Grey relational coefficients. Thus, the multi-objective problem has been converted into an equivalent single objective problem by integrating Taguchi method and GRA.

For identifying the optimum process conditions signal-to-noise ratio is determined. Analysis of variance is applied for investigating the significant influence of process parameters on the responses considered in this study.

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Table 9: Normalized values, Grey relational coefficients and Grey grades of responses

Trial No.	Normalized values of $x_i(r)$				Grey relational co-efficient				Grey grade	S/N ratio
	F_c	T	V_b	R_a	F_c	T	V_b	R_a		
1	0.5877	0.8125	0.7938	0.5686	0.3775	0.5714	0.5480	0.3669	0.4660	-6.6323
2	0.0450	0.5625	0.5854	0.2771	0.2075	0.3636	0.3761	0.2570	0.3011	-10.4258
3	0.3763	0.0000	0.0000	0.4571	0.2862	0.2000	0.2000	0.3153	0.2504	-12.0273
4	0.6762	0.8125	0.8186	0.6343	0.4357	0.5714	0.5795	0.4060	0.4982	-6.0519
5	0.0623	0.5000	0.1597	0.0000	0.2105	0.3333	0.2293	0.2000	0.2433	-12.2772
6	0.9949	0.2500	0.7224	0.6657	0.9801	0.2500	0.4739	0.4279	0.5330	-5.4655
7	0.3377	0.6250	0.4497	0.2600	0.2740	0.4000	0.3124	0.2525	0.3097	-10.1812
8	0.0000	0.6250	0.6113	0.2229	0.200	0.4000	0.3914	0.2434	0.3087	-10.2093
9	0.3520	0.0625	0.4549	0.4543	0.2784	0.2105	0.3144	0.3142	0.2794	-11.0755
10	0.6899	0.8125	0.8119	0.6971	0.4464	0.5714	0.5706	0.4522	0.5101	-5.8469
11	0.0547	0.5625	0.4151	0.1686	0.2091	0.3636	0.2994	0.2312	0.2758	-11.1881
12	0.9582	0.2500	0.7920	0.7743	0.8566	0.2500	0.5458	0.5255	0.5445	-5.2800
13	0.6933	0.8125	0.7504	0.6257	0.4491	0.5714	0.5004	0.4005	0.4803	-6.3697
14	0.6973	0.8125	0.8701	0.6314	0.4523	0.5714	0.6580	0.4042	0.5215	-5.6549
15	0.8997	0.1875	0.7376	0.8200	0.7137	0.2353	0.4879	0.5814	0.5046	-5.9411
16	0.6167	0.8125	0.8334	0.6486	0.3948	0.5714	0.6001	0.4157	0.4955	-6.0991
17	0.3645	0.5625	0.6469	0.3771	0.2823	0.3636	0.4145	0.2864	0.3367	-9.4551
18	0.6446	0.0000	0.2911	0.5086	0.4129	0.2000	0.2607	0.3372	0.3027	-10.3798
19	0.7118	0.8125	0.8326	0.7143	0.4645	0.5714	0.5989	0.4667	0.5254	-5.5902
20	0.7683	0.8750	0.9562	0.7686	0.5190	0.6667	0.8509	0.5193	0.6390	-3.8900
21	0.9768	0.2500	0.7957	0.9114	0.9151	0.2500	0.5503	0.7384	0.6134	-4.2451
22	0.9202	1.0000	1.0000	1.0000	0.7580	1.0000	1.0000	1.0000	0.9395	-0.5421
23	0.7984	0.8125	0.8869	0.7514	0.5536	0.5714	0.6885	0.5014	0.5787	-4.7509
24	0.9691	0.1875	0.8380	0.8371	0.8899	0.2353	0.6068	0.6055	0.5844	-4.6658
25	0.7225	0.8125	0.8167	0.7657	0.4739	0.5714	0.5769	0.5162	0.5346	-5.4394
26	0.1943	0.6250	0.7586	0.3343	0.2368	0.4000	0.5088	0.2730	0.3547	-9.0028
27	1.0000	0.1875	0.8927	0.8771	1.0000	0.2353	0.6996	0.6705	0.6513	-3.7244

4.3 Signal-to-noise ratio

Based on larger-the-better criterion signal-to-noise (S/N) ratio is calculated for Grey grade values using Eq. (4) and the results are presented in Table 9.

$$\text{S/N ratio} = -10 \log_{10} \frac{1}{y_i^2} \quad (4)$$

where y_i is measured performance characteristic value.

A graphical representation of the main effects plot for Grey grade values is shown in Figure 2. Also, the response table for means of Grey grade values is presented in Table 10. It is clear that the optimal conditions for turning AISI 1040 steel becomes $CF_3\ EP_2\ V_1\ f_1$.

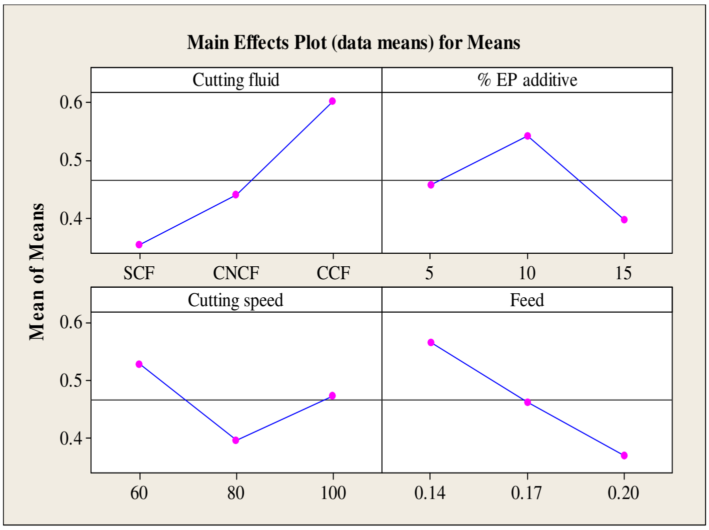

Figure 2: Main effects plot of means for Grey grade

Table 10: Response table for Grey grades

Levels	Factors			
	CF	***EP***	***V***	***f***
1	0.3544	0.4584	**0.5288**	**0.5666**
2	0.4413	**0.5426**	0.3955	0.4619
3	**0.6023**	0.3970	0.4737	0.3696
Optimum	CF_3	EP_2	V_1	f_1

The optimum level of process parameters for multiple performance characteristics are coconut based cutting fluid (level 3), 10% of EP additive (level 2), 60 mm/rev of cutting speed (level 1) and 0.14 mm/rev of feed (level 1). The reason behind decrease in cutting force with 10% of EP additive is due to formation of lead sulphide as EP additive which reacts with the surface and eases up plastic deformation [15]. With high proportion of EP additive in cutting fluid built up edge increases as shear force decreases on the surface causes increase in cutting forces [29]. The reduction in cutting tool temperature is due to better viscosity property of coconut based cutting fluid. Fatty acid chain in vegetable oils provides desirable boundary lubrication reduces friction which results in reduced tool flank wear. Cooling and lubricating effect of EP additive is also added to vegetable oil. Under high cutting temperatures EP additive creates a thin lubricating film on tool and workpiece. When the mixture of EP additive and vegetable oil flows at the interface causes decrease in plastic contact results in reduction of tool flank wear [30]. This is more effective with 10% EP additive in coconut oil for reduction of tool flank wear. The reduction in tool flank wear is due to low viscosity property of coconut based cutting fluid which reduced friction at tool-chip and tool-workpiece interfaces. With further increase in proportion of EP additive to 15%, tool flank wear increased due chemical attack at tool-workpiece interface [8]. When high proportion of EP additive passing through chip surface forms lubricating layer which accelerates abrasive wear mechanism and the same is indicated by 15% EP additive in cutting fluid [15]. The reason behind reduction in surface roughness is due to low viscosity property of coconut based cutting fluid compared to canola and sesame based cutting fluids which reduced friction between tool-chip and tool-workpiece interfaces.

4.4 Analysis of variance

Analysis of variance (ANOVA) is used for investigating the significant effect of process parameters on performance characteristics in the turning process. This is measured by the sum of the squared deviations of each parameter from the total sum of squares of the machining parameters and error. Thus:

$$SS_T = SS_F + SS_e \tag{5}$$

where,

$$SS_T = \sum_{j=1}^{p} \left(\gamma_j - \gamma_m\right)^2 \tag{6}$$

SS_T – Total sum of squares
SS_F – Sum of squares due to each factor
SS_e – Sum of squares due to error
p – Number of experiments in the orthogonal array
γ_j – Mean value of response for j^{th} experiment
γ_m – Grand mean value of response

In addition percent contribution is utilized to determine the significant influence of process parameter's effect on the performance characteristics. Table 11 presents the ANOVA for Grey grade. Percent contribution is the ratio sum of squares of each factor to total sum of squares. The extent of influence is higher for a factor with high percentage contribution on performance characteristic. The percent contribution of each machining parameter on performance characteristic is depicted in Table 11. The type of cutting fluid has major effect on multi-response characteristics (42.92%) compared to feed (26.33%), % EP additive (14.49%) and cutting speed (12.17%).

Table 11: ANOVA for process parameters

Source of variation	Degrees of freedom	Sum of squares	% contribution
Cutting fluid	2	0.28482	42.92
% EP additive	2	0.09615	14.49
Cutting speed	2	0.08078	12.17
Feed	2	0.17474	26.33
Error	18	0.02716	4.09
Total	26	0.66364	100

4.5 Confirmation test

Confirmation test is conducted for predicting and verifying the enhancement of performance characteristics after identifying the optimum process parameters. Grey grade $\hat{\gamma}$ is estimated under optimum process conditions using Eq. (7):

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$$\hat{\gamma} = \gamma_r + \sum_{i=1}^{s} \left(\bar{\gamma}_i - \gamma_r \right) \tag{7}$$

where γ_r is total of mean Grey grade

$\bar{\gamma}_i$ is mean Grey grade value at optimum condition

s indicates the number of process parameters

The comparison of predicted values with experimentally measured values at optimum machining parameter conditions is presented in Table 12. The predicted values are found to be very close to the experimental results. The results show that lower cutting force, cutting tool temperature, tool flank wear and better surface finish are obtained using the optimal parameter settings ($CF_3\ EP_2\ V_1\ f_1$). Hence, Taguchi based GRA is a very useful tool for predicting and obtaining optimum performance characteristics in turning AISI 1040 steel.

Table 12: Results of comparison test

	Optimal process condition	
	Prediction	**Experiment**
Facto levels	$CF_3\ EP_2\ V_1\ f_1$	$CF_3\ EP_2\ V_1\ f_1$
Cutting force (N)	--	66.2509
Cutting tool temperature (^{0}C)	--	26.0000
Tool flank wear (µm)	--	53.5200
Surface roughness (µm)	--	2.6300
S/N ratio of Grey grade	−1.4907	– 0 .5421
Grey grade	0.8423	0.9395

5.0 CONCLUSION

In the present research work, Taguchi method and Grey relational analysis (GRA) are combined to evaluate optimum levels for type of vegetable based cutting fluid, proportion of EP additive, cutting speed and feed in turning AISI 1040 steel. Taguchi method is used for experimental plan. GRA is applied for converting multi-objective problem into an equivalent single-objective problem by calculating Grey grade. The multiple responses considered in this work are cutting force, cutting tool temperature, tool flank wear and surface roughness. In turning experiments, level of influence for machining parameters on multiple performance characteristics is determined by S/N ratio and ANOVA. The results reveal the following conclusions:

- The optimum parameter setting ($CF_3\ EP_2\ V_1\ f_1$) causes lower values of multiple performance characteristics.
- Base oil has more influence on multiple performance characteristics in turning process compared to feed, % EP additive addition and cutting speed.
- Type of vegetable oil is the major factor (42.92%) affecting multiple performance characteristic compared to feed (26.33%), % EP additive (14.49%) and cutting speed (12.17%).
- It is also shown that the machining performance is greatly enhanced by reduction of performance characteristics by using Grey-based Taguchi method.

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