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ORIGINAL ARTICLE

Investigating the effects of vegetable oil-based cutting fluids with minimum quantity lubrication on machining performance of low-alloyed carbon steels: an optimization study

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Abstract

This work investigated the influence of Spindle Speed (N), Cutting Feed (CF), Depth of Cut (DC), Workpiece Type (WP) and Fluid Types (FT) on MQL-assisted turning of low-alloyed steels. Core interest in fluid types employed is the fatty acid unsaturation difference. Machining was conducted using Taguchi L_{27} design of experiment with N, CF, DC, WP and FT defined in the range of 435–870 rpm, 0.08–0.18 mm/rev, 0.3–0.7 mm, 84.00–109.00 HRB, and Rubber-Seed-Oil (RSO), Neem-Seeds-Oil (NSO) and Jatropha-Seeds-Oils (JSO) respectively. Response parameters measured are surface roughness, cutting temperature, chip thickness ratio and metal removal rate. Measured parameters were subjected to Analysis of Variance (ANOVA) at 5% significance, Taguchi analyses and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Results obtained showed WP was statistically significant with 48.77% contribution on surface roughness while difference in fluid types unsaturated fatty acid compositions has no significant effect on surface roughness. However, JSO having linoleic acid, thermal resistivity and viscosity values 27.87–34.87%, 664.40 ± 14.35 and 140.0 cP respectively, gave optimum value of surface roughness. All factors except N had significant effect on chip thickness ratio with WP having the most dominant with 50.91% contribution and RSO with lowest viscosity value of 125.5 cP gave rise to optimum chip thickness ratio due to the most efficient flowability occasioned by high linoleic acid (34.70–37.45%) present. N and CF were the only statistically significant factors on metal removal rate. TOPSIS proved that 870 rpm, 0.18 mm/rev, 0.5 mm, RSO and LAMCS-109 HRB optimized the MQL-assisted turning.

Keywords Low-alloyed steel · Turning operation · Minimum quantity lubrication · Cutting fluids · Machining parameters

Abbreviations

AHP	Analytical hierarchy process
ANOVA	Analysis of variance
CC_i	Closeness coefficients of alternatives
CF	Cutting feed
ChT	Chip thickness
CTR	Chip thickness ratio
CT	Cutting temperature
DC	Depth of cut
FT	Fluid type
JSO	Jatropha seed oil
LAHCS	Low-alloy high carbon steel
LALCS	Low-alloy low carbon steel
LAMCS	Low-alloy medium carbon steel
MiWNV	Minimum weighted normalized value
MaWNV	Maximum weighted normalized value
MQL	Minimum quantity lubrication
MRR	Metal removal rate
N	Spindle speed
NIS	Negative ideal solution

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NSO	Neem seed oil
OES	Optical emission spectroscope
PIS	Positive ideal solution
RSO	Rubber seed oil
D^+ & D^-	Separation measure
SR	Surface roughness
TOPSIS	Technique for order preference by similarity to ideal solution
WP	Workpiece type

1 Introduction

The in-service performances of materials most especially steels, are solely reliant on processing parameter sets. It is note-worthy to say that various methods have been developed to control response parameter measures that affect performances of components produced via machining, one of which is Minimum Quantity Lubrication (MQL). The MQL technique is one method that has proven to be a sustainable machining method as disadvantages associated with conventional wet, dry, high pressure cooling and cryogenic machining are eliminated. Kumar et al. [1] expressed that conventional flood cooling system does not meet expected outcome as much as MQL because coolant is restricted from reaching the tool/chip interface. MQL provides both cooling and lubrication to the cutting tool/workpiece and cutting tool/chip interfaces by penetrating these interfaces in mist condition. Cooling via MQL occurs in two modes which are convective and evaporative [2]. A study by Kedare et al. [3] showed that the cooling effect of MQL oil resulted in better surface finish of End-Milled bright mild steel over the conventional wet system at 225 rpm and it was attributed to lubricating capacity of the oil. Besides high cutting speed, high depth of cut and low feed rate that produced highest degree of chip formation in the work of Darsin et al. [4], it was also recorded that cutting fluid application mode had greater influence. Consequently, the authors showed that MQL oil application mode produced lower chip serration degree and this means lower plastic deformation or shearing stress occurred at the workpiece/tool interface. However, Bhosetty et al. [5] made it known that the quantity of fluid dispensed through MQL nozzle orifice has little effect on milling response parameters whereas the type of fluid was most influential. Lisowicz et al. [6] corroborates Bhosetty et al. [5] statement that oil/fluid type in MQL system has much influence on response parameters and stated further that MQL assisted turning using oil made by mixing vegetable oil and diester performed better than two other pure vegetable oil types in terms of surface roughness. Similarly, Yuan et al. [7], Sen et al. [8] and Liu et al. [9] reported that castor oil-ethanol blend (31–69%), castor-palm oil blend and castor oil-ethanol blend (1:2) respectively, performed better than respective individual base fluid in MQL assisted turning. In another study by Sadeghifar et al. [10], it was established that MQL flow rate during turning operations has influence on response parameters such as surface roughness where it was noted that lower flow rates of 3.5 and 10.0 ml/min gave the least surface roughness values at low feed rate. They also noted that flow rate had no effect on chip forms generated. Increase in flow rate from 70 to 100 ml/h was rather recorded by Pervaiz et al. [11] as a contributory factor to decreased surface roughness and thermal softening for a MQL variant which incorporated both cooling and lubrication, at low turning operation feed rate of 0.1 mm/rev. Gurbuz et al. [12] report that MQL flow rate had no significant effect on surface roughness has been refuted by earlier stated studies by Sadeghifar et al. [10] and Pervaiz et al. [11], though the authors [12] claimed it had effect on main cutting forces tool flank wear. According to the work of Ghuge et al. [13], MQL has the capability to reduce surface roughness by average of 47% and 3% compared to dry and flood cooling respectively. The authors as well gave value for cutting temperature reduction by average of 16% and 5% in the respective order of cutting condition stated previously. Same decline in surface roughness values was recorded in Hossain and Abedin [14] over the entire depth of cut range and cutting time considered for MQL assisted turning operation, against that obtained for dry and flood cooling. Yildirim et al. [15] in their turning experiment conducted revealed the preference of MQL over Cryogenic assisted MQL cooling-lubrication system such that MQL reduced surface roughness and tool wear by 13.8 and 50.67% respectively, contrary to what was stated in Urmi et al. [16]. Kumar et al. [17] comparatively studied the performances of coconut and castor oils applied via MQL and emulsified mineral oil in flood cooling for turning of Aluminium AA 150 and found that both MQL oils which are vegetable based, outperformed mineral counterpart by generating better surface finish. Nguyen et al. [18] opined that increasing feed rate or cutting speed leads to increase in metal removal rate while the surface quality is compromised for milling process aided by MQL. Feed rate was found by Mumtaz et al. [19] and Nguyen et al. [20] to be the most significant process parameter for surface roughness in milling operation. It was further explained by Mumtaz et al. [19] that increase in feed rate led to corresponding increase in surface roughness while increase in spindle speed and depth of cut resulted in decrease in surface roughness. Increasing machining speed has direct influence on decrease in surface roughness as a result of prevention in built-up-edge formation [21]. According to the study by Mia et al. [22], minimum surface roughness can be attained when machining is done at medium cutting speed, low feed rate and high depth of cut under dry cutting condition relative to

Table 1 Fatty acid compositions of fluid type

Fluid type	Saturated fatty acid		Unsat. fatty acid		Total Unsat. FA	References
	Palmitic	Stearic	Oleic	Linoleic		
RSO	9.10–13.78	7.49–12.63	22.18–25.31	34.70–37.45	73.94–82.67	[40–43]
NSO	15.12–25.36	11.40–27.65	34.09–48.12	9.37–20.56	40.41–64.18	[44–48]
JSO	13.07–16.69	5.15–7.67	40.39–52.27	27.87–34.87	74.29–80.59	[49–52]

Unsat. FA = unsaturated fatty acid

other conditions considered. Low surface roughness is usually characterized by low feed rate and high cutting speed [2, 23] but the work of Mia et al. [24] showed that minimum surface roughness and maximum metal removal rate can be achieved with MQL technique at maximum cutting speed, feed rate and depth of cut set; tool flank wear became minima at the minimum cutting parameters settings with cutting speed having most influence on surface roughness. The work of Martowibowo [25] showed that surface roughness can be reduced by a factor of 5.3 while metal removal rate can be increased by multiple of 6.6 when MQL technique is employed than dry machining. More efficient heat transfer is attainable using MQL as demonstrated by Mia et al. [22], where oil droplets from MQL spray reduced cutting zone temperature than other techniques of dry, flood and solid lubricant with compressed air respectively. Singh et al. [26] noted that percentage temperature reduction by MQL is dependent on nozzle distance from the cutting zone. Nozzle position (rake and flank faces), workpiece hardness and tool type has also been reported by Masoudi et al. [27] to be of significant influence on output turning parameters. Benkai et al. [28] made it known that the higher viscosity vegetable oils for MQL possess the capability to lower cutting force but becomes non beneficial in terms of heat exchange capacity as it reduces heat exchange potentials of vegetable oils. Also, the authors propounded that saturated fatty acids in oils are more efficient in their lubricating influence than unsaturated fatty acids. Strain hardening or phase transformation of titanium alloy material machined under MQL condition is eliminated due to cooling effect offered by the technique [29]. Revankar et al. [2] reported that machining results in increased surface hardness higher than the as-received specimen due to strain hardening effect but below the top surface, reduced hardness was obtained as a result of aging. However, specimen subjected to MQL had lower hardening effect than dry machining. Results from Revankar et al. [2] corroborates that obtained in Kaynak et al. [29] who observed that MQL had the least hardening effect on specimen among the three methods of cutting fluids application systems considered. Commonly used MQL fluid types by researchers are of plant seeds sources making this technique environment friendly, cost effective and poses no health hazard. These oils offer promising alternative to petroleum based oil as they are less toxic, renewable and eco-friendly [30]. It has been recorded that vegetable oils possess polar atoms and groups such as S, O, N, –COOR, –COOH and OH which have high affinity for metals, bonding on surface of workpiece to form a molecular film layer that enhances lubrication at the cutting point [31]. Lubricating properties of vegetable oils are determined by their molecular structure and chemical compositions [31]. Best lubricating performance from vegetable oil can be obtained from oil with higher straightness and longer carbon chain length [33]. Joshy et al. [34] confirmed that the oleic acid in vegetable oils produced lowest coefficient of friction at lower load as the unsaturation caused adsorption that allowed formation of thin lubricating film. Contrarily, Xu et al. [35] established a correlation index of 0.83 between coefficient of friction and degree of fatty acid unsaturation with the assertion that the greater the degree of fatty acid unsaturation, the greater the coefficient of friction. As noted in Wang et al. [36] and corroborated by the results of Yin et al. [37], palm oil contains high level of saturated fatty acid (80%) which makes it better than other oils but as pointed out in Joshy et al. [34], this assertion is only true when it is operating at high load condition. Jatropha curcas oil as metal working fluid, has better friction coefficient than palm oil and palm fatty acid fraction under extreme pressure condition as reported in Zhang et al. [31], in respective of fatty acid saturation of palm oil. In this work, the influences of three pure vegetable oils i.e., Rubber Seed Oil (RSO), Neem Seed Oil (NSO) and Jatropha Seed Oil (JSO) with varying degree of fatty acid unsaturation, are evaluated in application as cutting fluids using MQL technique for turning operation. The fatty acid compositions of the oils are as defined in Table 1 where RSO and JSO can be seen to posse more unsaturated fatty acid than NSO. However, RSO has more of Linoleic than Oleic, compared to other fluid types and this means RSO is most fluidic as increase in Linoleic content of vegetable oil leads to decrease in viscosity[38, 39]. Other machining parameters also considered include spindle speed, cutting feed, depth of cut and workpiece type; the workpiece type is defined by the composition and hardness value. It is noteworthy that to the best of our understanding, this is probably the first time such work will be conducted as previous works have only carried out study using pure vegetable oil, synthetic oil and mixture of pure vegetable oil and ethers. Also, the fatty acid compositions of vegetable oil types employed in MQL machining are rarely studied for their effects on machining processes.

2 Materials and methods

2.1 Characterization of specimens

Specific gravity of each fluid type was determined using a density bottle and measurement made against distilled water as a standard liquid in conformity with ASTM D1217 [53]. The thermal resistivity measurement was conducted using thermal property analyzer by Decagon Devices Inc and followed procedure contained in KD2 Pro [54]. Oil was poured in a tube, thermal needle sensor KS-1 inserted in the oil, knob was rotated to on position while the needle supplied heat to the liquid for 10 min before the process was stopped for each reading to be taken. Dynamic viscosity of each fluid type was measured using a Brookfield viscometer (Model No.: RVDVE230) with a rotary disc marked spindle 2. Measurement of dynamic viscosity was carried out in accordance with ASTM D2983-09 [55] by filling the beaker up to the marked point on the disc spindle and the spindle rotated at speed of 60 rpm. The pH measurement was performed using a digital pH meter after re-calibration using distilled water as reference. The elemental compositions of the low-alloyed carbon steel samples, categorized as Low-Alloyed Low Carbon Steel (LALCS), Low-Alloyed High Carbon Steel (LAHCS) and Low-Alloyed Medium Carbon Steel (LAMCS) were determined using Arc Spark Optical Emission Spectroscope (OES) in accordance with ASTM E415 [56] while the hardness of the samples was determined according to ASTM E18 [57] via Rockwell Hardness tester.

2.2 Experimental setup and turning operation

The turning operation was conducted on the three different grades of low-alloyed carbon steel materials designated as LALCS, LAMCS and LAHCS, with chemical compositions presented in Table 2. Each of the turned pieces was of diameter 25 mm. Controllable turning parameters applied are spindle speed, cutting feed, depth of cut, cutting fluid type and workpiece type at three different levels as coded in Table 2. The experimental design for the turning operation was based on Taguchi L_{27} Orthogonal Array, determined using Minitab 7, a statistical analysis software. At different level of parameters settings as defined by in the L_{27} orthogonal array, individual fluid type was applied using MQL technique. The controllable machining parameters employed are spindle speed, cutting feed, depth of cut, fluid type and workpiece type while the response parameters measured are surface roughness, tool temperature, chip thickness/thickness ratio and metal removal rate. The machining operation was plain turning on center lathe "Graziano Tortona" (Model No.: SAG 508) using carbide tool of 6° rake angle, fed to the workpiece at an approach angle 90°. Oil was delivered to cutting zone at flow rate 50 mL/hr through a nozzle of orifice diameter 0.2 mm positioned at an angle 45° and distance 70 mm from the tool cutting point, driven by air pressure 2 bar from a pneumatic compressor, nozzle position angle and air pressure are adopted from the work of Krishman et al. [58]. Basis for selection of the spindle speed, cutting feed and depth of cut ranges is that the present MQL turning experiment conducted considering rough turning operation.

2.3 Response parameter measurement

Cutting temperature at the tool cutting point for each experimental run was measured using a handheld infrared thermometer. The laser target of the thermometer enabled accurate targeting of laser beam to the cutting zone. Maximum temperatures attained during each turning experiment was displayed on the LED screen and recorded accordingly. Average surface roughness (R_a) of each machined piece was measured using surface profilometer (Model: SRT-6200) at a cut-off point of 0.8 μm and taken at three distinct points on each sample. Chips collected during cutting process for each experimental run was measured for their thickness using micrometer screw gauge. Subsequently, chip thickness ratios were determined based on Eq. 1.

$$r = \frac{t_o}{t} = \frac{F \sin\theta}{t} \tag{1}$$

where t_o is uncut chip thickness; t is cut chip thickness; F is cutting feed; θ is approach angle.

Metal removal rates, generally defined mathematically as in Eq. 2 [59], were determined by measuring the initial diameter of each workpiece before commencement of turning operation and the final diameter measured as well after each cutting operation and Eq. 3 [60] was applied.

$$MRR = \frac{\text{Volume of metal removed}}{\text{Cutting time}} \tag{2}$$

$$\begin{aligned} MRR &= \frac{\pi L(D^2 - d^2)}{\frac{4L}{FN}} = \frac{\pi}{4}(D^2 - d^2)FN \\ &= \frac{\pi}{2}D_m(D - d)FN \quad mm^3/min \end{aligned} \tag{3}$$

where L is workpiece length; F is Cutting Feed; N is Spindle Speed; D is Initial workpiece diameter; d is Final workpiece diameter; D_m is Mean workpiece diameter.

Table 2 Controllable parameter value level and level codes

Controllable Factors	Unit	Level		
		1	2	3
Spindle speed	rev/min (rpm)	435	620	870
Cutting feed	mm/rev	0.08	0.12	0.18
Depth of cut	mm	0.3	0.5	0.7
Fluid type	–	RSO	NSO	JSO
Workpiece type	HRB	LALCS-84.00	LAHCS-89.23	LAMCS-109.00

2.4 Response data analysis

Response data obtained based on factor level settings in the Taguchi orthogonal array experimental design were analyzed using Analysis of Variance (ANOVA) at significance level of 5%, Taguchi signal-to-noise ratio (S/N) and mean-of-means. The ANOVA was conducted in order to test significance and obtain contributions of input machining parameters on response parameters. Furthermore, Taguchi signal-to-noise ratio and mean-of-means analysis were conducted to rank influence of input machining parameter on response parameter and obtain optimal value of each input parameter. The parameters' response data generated were checked for their normal distribution at confidence interval of 99% by employing normal probability plots. Since minimum surface roughness, minimum cutting temperature, high chip thickness/thickness ratio and high metal removal rate are desired in any machining processes, objectives set for the Taguchi signal-to-noise ratio (S/N) and mean-of-means analysis are 'Smaller is Better', 'Smaller is Better', 'Lager is Better' and 'Lager is Better' respectively. These objective set for S/N are as defined mathematically in Eqs. 4 and 5 [61]. A multi-criteria optimization scheme known as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was adopted in order to obtain single optimum machining parameter rather than the individual optimum parameter based on each response. Employing the scheme, the response parameters were made into a single response parameter. TOPSIS is based on the idea that alternatives should possess the least distance to the ideal positive solution while having the farthest distance to the ideal negative solution and it has been executed in the present work according to Parida and Routara [62]. Decision matrix formulated according to the number of experimental runs by number of response parameters, was normalized using vector normalization [63] as in Eq. 6. Weights were applied to these normalized values (Eq. 7) to obtained weighted value Vij. Positive and negative ideal solutions were evaluated by employing scheme in Eqs. 8 and 9. Consequently, the distances of the weighted values to ideal solutions were obtained in accordance with Eqs. 10 and 11. Finally, the coefficients of closeness for each distance to ideal solutions were determined using Eq. 12 and the value closest to unity was found as the optimum.

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad \text{(Larger is Better)} \tag{4}$$

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad \text{(Smaller is Better)} \tag{5}$$

where y_i is performance characteristics value; n is number of y_i values

$$x_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{m} y_{ij}^2}} \tag{6}$$

$$v_{ij} = w_i \times x_{ij} \tag{7}$$

$$I^+ = \{V_1^+, V_2^+ \ldots\ldots\ldots\ldots\ldots\ldots\ldots, V_m^+\} = \{(\operatorname{Max} V_{ij} | j \in J), (\operatorname{Min} V_{ij} | j \in J')\} \tag{8}$$

$$I^- = \{V_1^-, V_2^- \ldots\ldots\ldots\ldots\ldots\ldots\ldots, V_m^-\} = \{(\operatorname{Min} V_{ij} | j \in J), (\operatorname{Max} V_{ij} | j \in J')\} \tag{9}$$

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \tag{10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{11}$$

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{12}$$

where i is 1, ……, m; j is 1,……., n; y_{ij} is actual value of ith value of jth experimental run; x_{ij} is corresponding normalized value of ith value of jth experimental run; W_i is weigth of jth criteria; V_{ij} is weigthed normalized value of ith value of jth experimental run; I^+ is positive ideal solution (PIS); I^- is negative ideal solution (NIS); D_i^+ is distance from PIS; D_i^- distance from NIS; CC_i is closeness coefficients of alternatives.

Table 3 Physiochemical properties of rubber, neem and jatropha seeds oils

Fluid type	Specific gravity	Thermal resistivity ($^{o}C^{-cm/w}$)	Dynamic Viscosity at 25 °C (cP)	pH
RSO	0.896 ± 0.01	700.23 ± 33.94	125.5	6.67
NSO	0.902 ± 0.01	668.63 ± 15.28	176.0	5.57
JSO	0.904 ± 0.01	664.40 ± 14.35	140.0	6.91

Table 4 Elemental compositions of low-alloyed carbon steel samples

Element (wt %)	Steel sample		
	LALCS [68]	LAHCS	LAMCS [67]
Fe	98.1000	97.6000	96.8800
C	**0.0724**	**0.5440**	**0.3182**
Si	0.1820	0.2320	0.1537
Mn	0.9790	1.1100	0.7130
P	0.0102	0.0121	–
S	0.0051	0.0262	–
Cr	0.1160	0.1130	1.0580
Ni	0.1240	0.0816	0.0870
Mo	0.0425	0.0160	0.3278
Cu	0.2440	0.1130	0.0896
Al	0.0188	0.0262	0.0472
V	0.0027	0.0024	0.0020
Co	–	–	0.0063
W	–	–	0.2215
Sn	0.0087	0.0122	–
Zn	0.0045	0.0026	–
As	0.0054	0.0053	–
Sb	0.0023	0.0027	–
Se	0.0031	0.0027	–
Te	0.0043	0.0039	–
Ta	0.0717	0.0509	–

Bold in this table is to stress the classification assigned to each material as contained in each column

Table 5 Rockwell hardness of low-alloyed carbon steels

Low alloy steel type	Rockwell hardness value (HRB)
LALCS	84.00 ± 0.50
LAHCS	89.23 ± 0.40
LAMCS	*109.00 ± 0.00

* converted from C scale

3 Results and discussion

3.1 Some physicochemical properties of rubber, neem and *jatropha* seeds oils; composition and rockwell hardness of low-alloyed steel

Contained in Table 3 are the results of specific gravity, thermal resistivity, dynamic viscosity and pH for the respective raw vegetable oil. It can be seen that rubber seed oil has the least of specific gravity value while jatropha seed oil has the highest. Based on the average values of specific gravity obtained which may not be significantly different and in order RSO < NSO < JSO, JSO has highest density. This indicates presence of higher Oleic fatty acid in JSO as shown previously in Table 1 and closely followed by NSO, as higher degree of unsaturation resulting from increased Oleic acid means higher density [64]. Unsaturated fatty acid contributes to enhanced lubricity by forming adherent thin film to prevent metal-to-metal contact [65], making JSO of higher potential to improve machinability when used as MQL oil. Highest thermal resistivity possessed by rubber seed oil showed that it is least conductive, may not be able to effectively cause cooling at the tool cutting point as the other two. Dynamic viscosity measured for the oils as indicated in Table 3 shows that value obtained for RSO < JSO < NSO and this indicates best spread-ability and penetration of RSO from the MQL nozzle into tool/chip interface and cutting zone [66]. This assertion as relating to RSO is supported by value of Linoleic acid presented previously in Table 1. The pH values of these non-edible vegetable oils are below neutral, though jatropha and rubber seeds oils tend to be close to being neutral in pH which may quite favourable for use as cutting fluids. Nevertheless, it has been confirmed in the work of Adesusi et al. [67] that these oils contain free fatty acids whose constituents are of carbonyl and hydroxyl groups that contributed to enhancement in corrosion resistance of low-alloyed steel in corrosive solution by acting as active centres. Hence, the respective pH value obtained may not be a thing of concern, even as rubber seed and jatropha seeds oils are near being neutral. Tables 4 and 5 show elemental compositions and Rockwell hardness values respectively, of low-alloyed steels as obtained.

3.2 Response data and normal probability plots of response data

Contained in Table 6 are the results of Taguchi L_{27} experimental design showing input parameters variables combinations with their corresponding response parameters. These input parameters are spindle speed, cutting feed, depth of cut, fluid type and workpiece type differentiated by their compositions and Rockwell hardness value as given in Tables 4 and 5 respectively, as presented above. The abbreviations to these parameters are as defined in footnote of Table 6. Probability plots of response parameters SR, CT, CTR and MRR

Table 6 Experimental design based on Taguchi L_{27} (3^5) orthogonal array

Run No	Factors (input parameters)						Response parameters			
	N (rpm)	CF (mm/rev)	DC (mm)	FT	WP	SR (μm)	CT (°C)	ChT (mm)	CTR	MRR (mm^3/min)
1	435	0.08	0.3	RSO	LALCS	2.200	37.2	0.410	0.195	683.30
2	435	0.08	0.3	RSO	LAHCS	4.587	50.7	0.130	0.615	1780.24
3	435	0.08	0.3	RSO	LAMCS	1.847	50.2	0.150	0.533	683.30
4	435	0.12	0.5	NSO	LALCS	3.493	44.0	0.195	0.615	1639.91
5	435	0.12	0.5	NSO	LAHCS	3.167	41.6	0.265	0.453	2152.38
6	435	0.12	0.5	NSO	LAMCS	1.870	51.0	0.190	0.632	922.45
7	435	0.18	0.7	JSO	LALCS	2.403	45.8	0.607	0.297	3997.28
8	435	0.18	0.7	JSO	LAHCS	4.887	34.8	0.690	0.261	2459.87
9	435	0.18	0.7	JSO	LAMCS	1.790	64.7	0.260	0.692	2459.87
10	620	0.08	0.5	JSO	LALCS	1.430	46.2	0.330	0.242	1266.06
11	620	0.08	0.5	JSO	LAHCS	2.363	91.0	0.209	0.383	3019.07
12	620	0.08	0.5	JSO	LAMCS	1.777	68.9	0.198	0.404	1947.79
13	620	0.12	0.7	RSO	LALCS	1.320	67.8	0.775	0.155	4674.69
14	620	0.12	0.7	RSO	LAHCS	5.327	52.1	0.210	0.571	3213.85
15	620	0.12	0.7	RSO	LAMCS	2.172	50.6	0.130	0.923	1460.84
16	620	0.18	0.3	NSO	LALCS	3.520	66.1	0.700	0.257	3286.89
17	620	0.18	0.3	NSO	LAHCS	3.190	51.0	0.500	0.360	1095.63
18	620	0.18	0.3	NSO	LAMCS	1.947	64.1	0.240	0.750	3725.14
19	870	0.08	0.7	NSO	LALCS	1.453	70.3	0.550	0.146	2733.19
20	870	0.08	0.7	NSO	LAHCS	4.400	55.6	0.190	0.421	2323.21
21	870	0.08	0.7	NSO	LAMCS	1.485	104.3	0.163	0.491	2186.55
22	870	0.12	0.3	JSO	LALCS	3.667	64.0	0.590	0.203	4509.76
23	870	0.12	0.3	JSO	LAHCS	2.240	75.0	0.250	0.480	2869.85
24	870	0.12	0.3	JSO	LAMCS	1.150	57.5	0.130	0.923	1639.91
25	870	0.18	0.5	RSO	LALCS	3.883	78.0	0.763	0.236	6764.77
26	870	0.18	0.5	RSO	LAHCS	3.533	48.7	0.200	0.900	4304.77
27	870	0.18	0.5	RSO	LAMCS	1.415	73.0	0.190	1.200	4612.25

N spindle speed
CF cutting feed
DC depth of cut
FT fluid type
WP workpiece type
SR surface roughness
CT cutting temperature
ChT chip thickness
CTR chip thickness ratio
MRR metal removal rate

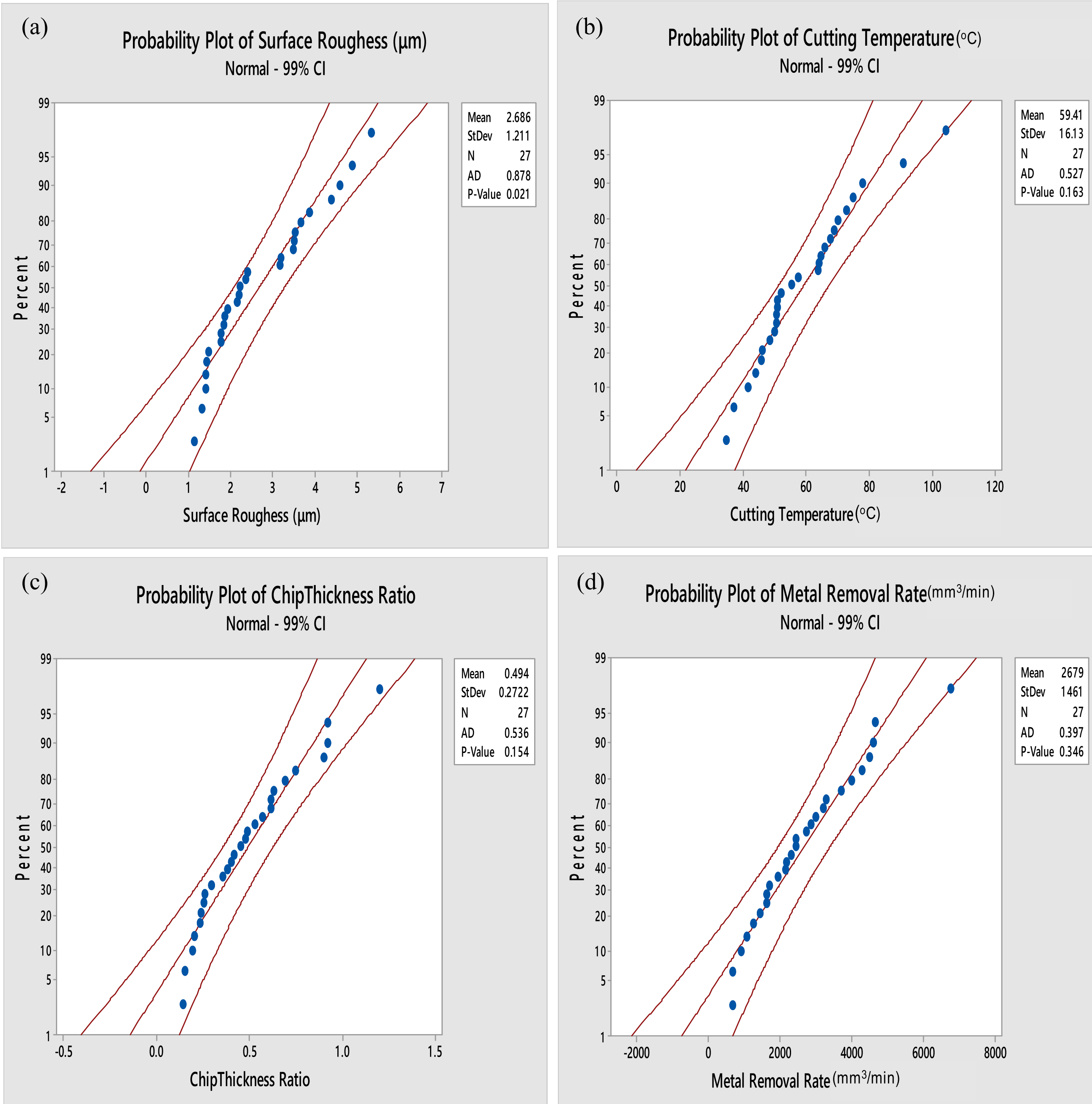


Fig. 1 Normal probability plots of **a** surface roughness, **b** cutting temperature, **c** chip thickness ratio, **d** metal removal rate

are presented in Fig. 1a–d, for checking distribution of the data generated from response parameters at confidence level of 99%. Data shown on the plotted probability distribution show means of each response parameter, standard deviations (StDev), Anderson–Darling values (AD) and *p* values. The StDev indicates departure of response data from their mean values and these data points are approximately aligned with the individual mean value lines of normal distribution plot (middle lines). The *p* values of 0.021, 0.163, 0.154 and 0.346 for SR, CT, CTR and MRR respectively are greater than 0.01 significance while AD values are small, all these are indications that response data obtained are reliable and useful for optimization of the turning process assisted by three vegetable oil based MQL system.

3.3 Analysis of variance for response parameter data

The analysis of variance conducted at significance level of 5% (0.05) on data obtained from machining operation under MQL condition are as given in Tables 7, 8, 9 and 10 for

Table 7 ANOVA for surface roughness

Source	DF	Adj SS	Adj MS	F-value	*P* value	% contribution
Spindle speed	2	0.7173	0.3587	0.77	0.522	1.88
Cutting feed	2	1.4125	0.7062	1.51	0.324	3.70
Depth of cut	2	0.3006	0.1503	0.32	0.742	0.79
Fluid type	2	1.1846	0.5923	1.27	0.374	3.11
Workpiece type	2	18.5927	9.2963	19.94	0.008	48.77
Spindle speed*Workpiece	4	2.2827	0.5707	1.22	0.425	5.99
Cutting feed*Workpiece	4	2.6797	0.6699	1.44	0.367	7.03
Depth of cut*Workpiece	4	9.0903	2.2726	4.87	0.077	23.84
Error	4	1.8649	0.4662	–	–	4.89
Total	26					100.00
$R^2 = 95.11\%$						

* interaction between

Table 8 ANOVA for cutting temperature

Source	DF	Adj SS	Adj MS	F-value	*P* value	% contribution
Spindle speed	2	2455.0	1227.70	10.65	0.079	36.32
Cutting feed	2	290.62	145.31	1.26	0.590	4.30
Depth of cut	2	60.47	30.23	0.26	0.885	0.89
Fluid type	2	116.45	58.23	0.51	0.796	1.72
Workpiece type	2	429.32	214.66	1.86	0.479	6.35
Cutting feed*Workpiece	4	1304.21	326.05	2.83	0.169	19.29
Depth of cut* Workpiece	4	679.76	169.84	1.47	0.358	10.05
Fluid type* Workpiece	4	963.41	240.85	2.09	0.246	14.25
Error	4	460.97	115.24	–	–	6.82
Total	26					100.00
$R^2 = 93.18\%$						

* interaction between

Table 9 ANOVA for chip thickness ratio

Source	DF	Adj SS	Adj MS	F-value	*P* value	% contribution
Spindle speed	2	0.05457	0.027285	5.40	0.073	2.83
Cutting feed	2	0.17204	0.086021	17.03	0.011	8.93
Depth of cut	2	0.07102	0.035510	7.03	0.049	3.69
Fluid type	2	0.13285	0.066427	13.15	0.017	6.89
Workpiece type	2	0.98093	0.490467	97.13	0.000	50.91
Spindle speed*Workpiece	4	0.15126	0.037815	7.49	0.038	7.85
Cutting feed*Workpiece	4	0.14457	0.036143	7.16	0.041	7.50
Fluid type*Workpiece	4	0.19945	0.049863	9.87	0.024	10.35
Error	4	0.02020	0.005060	–	–	1.05
Total	26	–	–	–	–	100.00
$R^2 = 98.95\%$						

* interaction between

Table 10 ANOVA for metal removal rate

Source	DF	Adj SS	Adj MS	F-value	*P* value	% contribution
Spindle speed	2	12,821,940	6,410,970	15.35	0.013	23.11
Cutting feed	2	14,720,575	7,360,288	17.62	0.010	26.53
Depth of cut	2	2,504,654	1,252,327	3.00	0.160	4.51
Fluid type	2	3,658,400	1,829,200	4.38	0.098	6.59
Workpiece type	2	5,703,529	2,851,765	6.83	0.051	10.28
Spindle speed*Workpiece	4	2,237,449	559,362	1.34	0.392	4.03
Cutting feed*Workpiece	4	9,841,213	2,460,303	5.89	0.057	17.74
Fluid type *Workpiece	4	2,329,137	582,284	1.39	0.378	4.20
Error	4	1,671,124	417,781	–	–	3.01
Total	26	–	–	–	–	100.00
$R^2 = 96.99\%$						

* interaction between

surface roughness, cutting temperature, chip thickness ratio and metal removal rate respectively. Resulting *p* values of machining parameters and their interactions showed that workpiece type characterized by hardness and composition is significant ($p < 0.05$) in effect on the surface roughness generated under MQL condition (Table 7). The other machining input parameters have their p-values higher than 5% significance level, which render these parameters of no statistical significant effect on surface roughness. That is, the change in value of surface roughness obtained as a result of change in these parameters value whose effects are non-significant statistically, only happened by chances. Most especially, the effect of cutting fluid type was not felt in the result of surface roughness value because p-value associated is greater than 5% significance level. Hence, the type of vegetable oil adopted in this work does not have a significant effect on surface roughness of machined pieces which is in accordance with the assertion made in the work of Tuan et al. [69] who compared pure soybean oil and emulsion oil as against three pure vegetable oil considered herein. Similarly, the percentage contribution and F-value of workpiece type is the highest with values 48.77% and 19.94 respectively, followed by interaction effect of depth-of-cut and workpiece type having 23.84% contribution at $R^2 = 95.11\%$. This shows that workpiece type has the dominant effect on surface roughness values obtained and it is statistically significant. Results obtained in the work of Jeevan and Jayaram [70] which did not consider workpiece type, affirms the order of factors' contribution in this current work based on spindle speed, cutting feed, depth of cut and fluid type. However, is unlikely that level of fatty acid unsaturation in the respective oils employed affected change in surface roughness of the machined pieces as evident from *p* value ($p > 0.05$) obtained; the lubricating effect caused by thin film formation [34] is not a function of oils' unsaturation level. Similar to this is the work of Elewa et al. [71] who engaged in rough turning with application of five vegetable oils types as cutting and was found that four among the five produced surface roughness with no significant difference in value (3.0–3.1 μm) and this supports assertion in Kazeem et al. [72] that fluid type has lesser influence than feed rate in lowering surface roughness. Having determined that workpiece type (classified based on hardness and composition) to be the most contributing/significant factor in MQL turning for this case, it imperative to know that this was not the case for dry hard turning by Khan et al. [73]. Khan et al. [73] in their case observed that workpiece hardness has lesser significance and percentage contribution to surface roughness than insert type and feed rate, the assertion by the authors is also in contrast with work of Tuan et al. [69].

The *p* values obtained for analysis of variance conducted for machining parameters to determine statistical significance of these parameters on cutting temperature measured at tool/chip interface indicate that they are of no statistical significance as all *p* values obtained are higher than 5% confidence as seen in Table 8. Nevertheless, spindle speed has the highest percentage contribution and F-value of 36.32% and 10.65 respectively, which is conformity with results from the work of Kazeem et al. [74]. This is followed by interaction effect of cutting feed and workpiece while the fluid-type has second least percentage contribution of 1.72% at $R^2 = 93.18\%$. The highest percentage contribution obtained from spindle is as expected as increase in spindle speed is established to result into increase in deformation at the primary shear zone which translates to increase in cutting temperature measured at tool cutting point. Since all varied machining parameters considered are of no statistical significance to the recorded tool/chip interface temperature, the variation in cutting temperature only happened by chances. Moreso, it has been stated elsewhere in Salur et al. [75] and Kazeem et al. [76] that feed rate has no significant effect on cutting temperature but on tool life and power consumption. However, the

Table 11 Surface roughness response for mean signal-to-noise ratio–smaller is better

Level	N	CF	DC	FT	WP
1	−8.686	#−6.725	−7.967	#−6.836	−11.104
2	−7.338	−7.722	#−7.516	−8.073	−7.566
3	#−7.202	−8.779	−7.742	−8.316	#−4.556
Delta	1.484	2.053	0.451	1.480	6.548
Rank	3	2	5	4	1

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, *WP* workpiece type, # optimal factor level

non-significant contributions made by all parameters considered for tool temperature measured is due to the low spindle speed employed for rough turning operation which is unlikely to generate wide tool temperature differential.

This case of machining response parameter "chip-thickness-ratio" seem quite different from the two previously presented results for surface roughness and cutting temperature. All the machining factors except spindle speed have their *p* values less than 5% significance level ($p < 0.05$), most especially "workpiece type" with least *p* value of 0.000 as shown in Table 6. This agrees with the assertion made by Khan et al. [77] that almost all parameter involved in machining have direct or indirect influence on chip thickening during deformation. It can be seen that for "chip-thickness-ratio", the effects of these factors that have $p < 0.05$ are statistically significant, including "fluid-type" with *p* value of 0.017. Factor "workpiece-type" has the highest percentage contribution and F-value of 50.91% and 97.13 respectively, which means "workpiece-type" is most influential on "chip-thickness-ratio" and this influence is also most statistically significant. The influence of "fluid-type" on "chip-thickness-ratio" is not as pronounced as that of "cutting feed" as obtained from F-value but more influential than all interaction effects of parameters considered, including "depth of cut" and "spindle speed". On the other hand, "fluid-type" percentage contribution is only higher than that obtained for "spindle speed" and "depth-of-cut". Decrease in chip-thickness-ratio ultimately leads to increase in chip thickness thereby increasing chip load on tool rake face. This increase in chip load leads to corresponding increase in the temperature at the primary and secondary shear zones [72]. Hence, change in cutting feed, depth of cut, fluid type and workpiece type either cause decrease or increase in chip load at the cutting interface, resulting to increase in cutting temperature which may be effectively dissipated by applied cutting fluid depending on fluidity. It should be noted that the influence of fluid type on chip load variation is dependent on thin film formability of fluid type employed, dictated by molecular structure [32].

Presented in Table 10 is the ANOVA results generated for Metal Removal Rate (MRR) on turning the low alloy carbon steel under MQL condition involving three varieties of vegetable oils, with other turning parameters varied accordingly. It is evident from this table that "spindle speed" and "cutting feed" are the only machining parameters which have statistically significant effects on MRR with their respective p-value less than 5% significance level ($p < 0.05$). These two machining factors have their percentage contributions as 23.11% and 26.53% respectively, which shows that cutting feed has the highest percentage contribution to MRR and most influential of all factors based on its highest F-value of 17.62. The "workpiece" and "fluid-type" in this case are of no statistical significance in differences in value of MRR. Since the relationship between machining Power Input (P), Specific Power (P_s) and MRR is defined according to Eq. 13 [78], it is affirmed that workpiece type, fluid type and depth of cut are not determinants of power inputs in this work.

$$P = P_s \times MRR \quad (13)$$

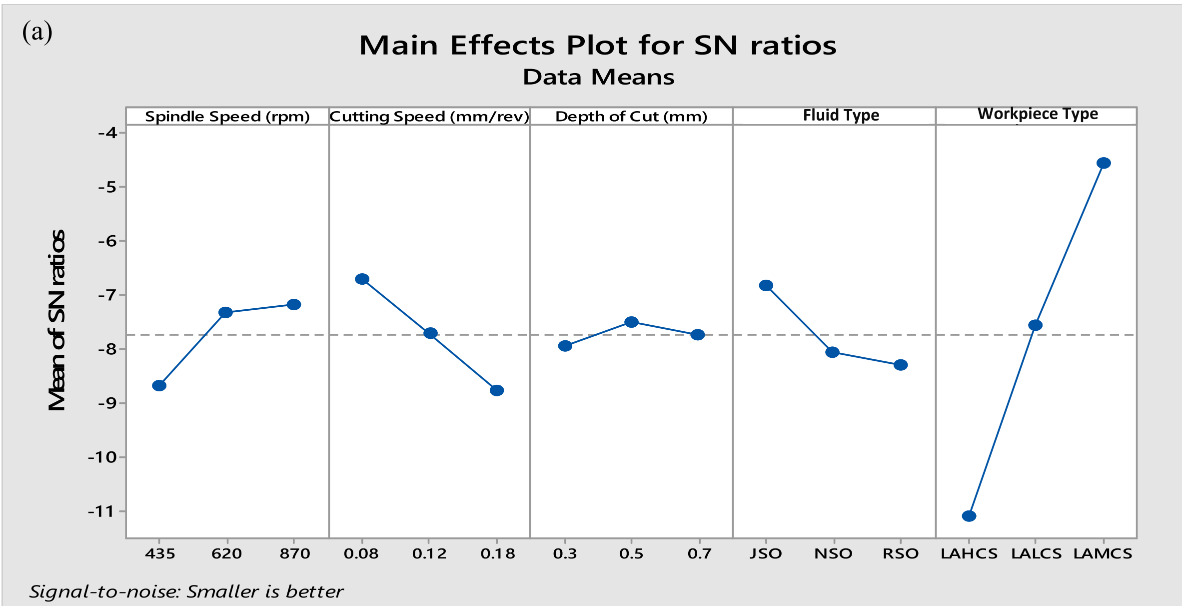
3.4 Taguchi signal-to-noise ratio analysis

The Taguchi signal-to-noise ratio employed here checks the relative importance and optimal parameter set of machining factors. In order to do this, the mean signal-to-noise ratios and mean-of-means are obtained for each of the factor's levels and differences between highest and lowest mean signal-to-noise ratios and mean-of-means respectively are obtained for each factor. These differences are denoted as Delta. The Delta value determined has been used to rank factors from highest to lowest, that is "workpiece type" with Delta values 6.548 (mean signal-to-noise ratios) and 2.027 (mean-of-means) is ranked 1st in relative importance for determination of surface roughness under "smaller-is-better" objective set as set-out in Tables 11 and 12, this follows in that order. It should be noted that "fluid-type" ranked 4th, below "spindle-speed" and "cutting-feed" in signal-to-noise ratio analysis. This indicates that vegetable oil does not importantly effect surface roughness value variation as much as workpiece type, spindle speed and cutting feed for the MQL assisted turning operation. The minimization of surface roughness is based on "smaller is better" objective and in that wise, parameter level with highest "signal-to-noise ratio" and lowest "mean"

Table 12 Surface roughness response for mean-of-means–smaller is better

Level	N	CF	DC	FT	WP
1	2.916	#2.394	2.705	#2.412	3.744
2	#2.561	2.712	#2.548	2.725	2.597
3	2.581	2.952	2.804	2.920	#1.717
Delta	0.355	0.558	0.256	0.509	2.027
Rank	4	2	5	3	1

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, *WP* workpiece type, # optimal factor level



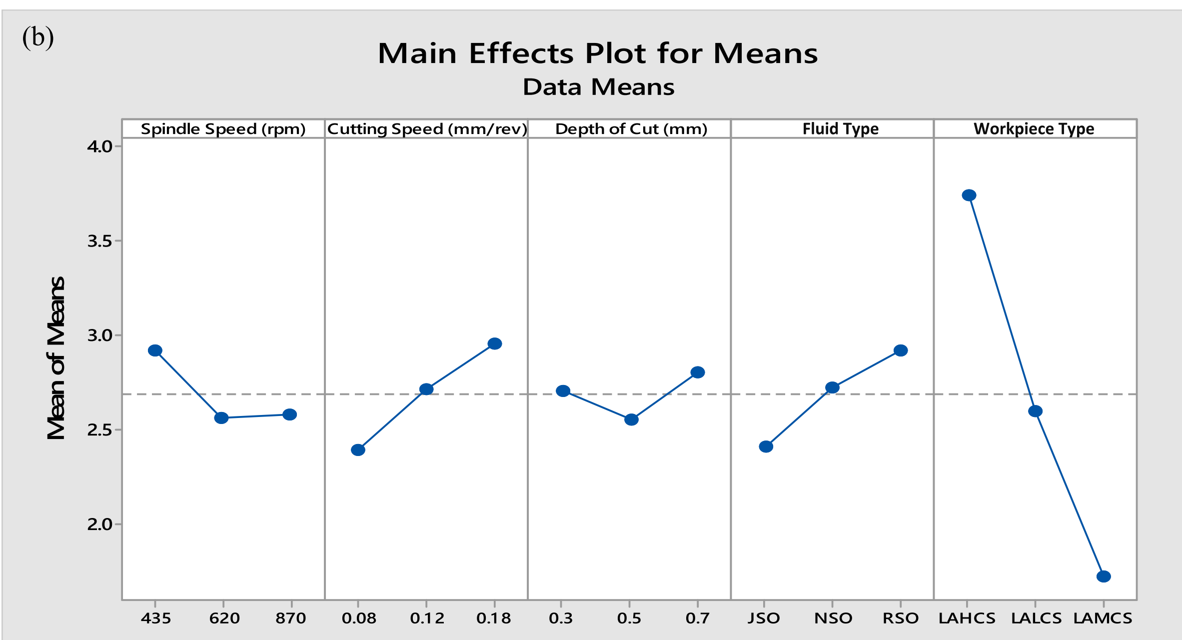


Fig. 2 Main Effect Plots for **a** Signal-to-Noise Ratio of Surface roughness, **b** Means of Surface roughness

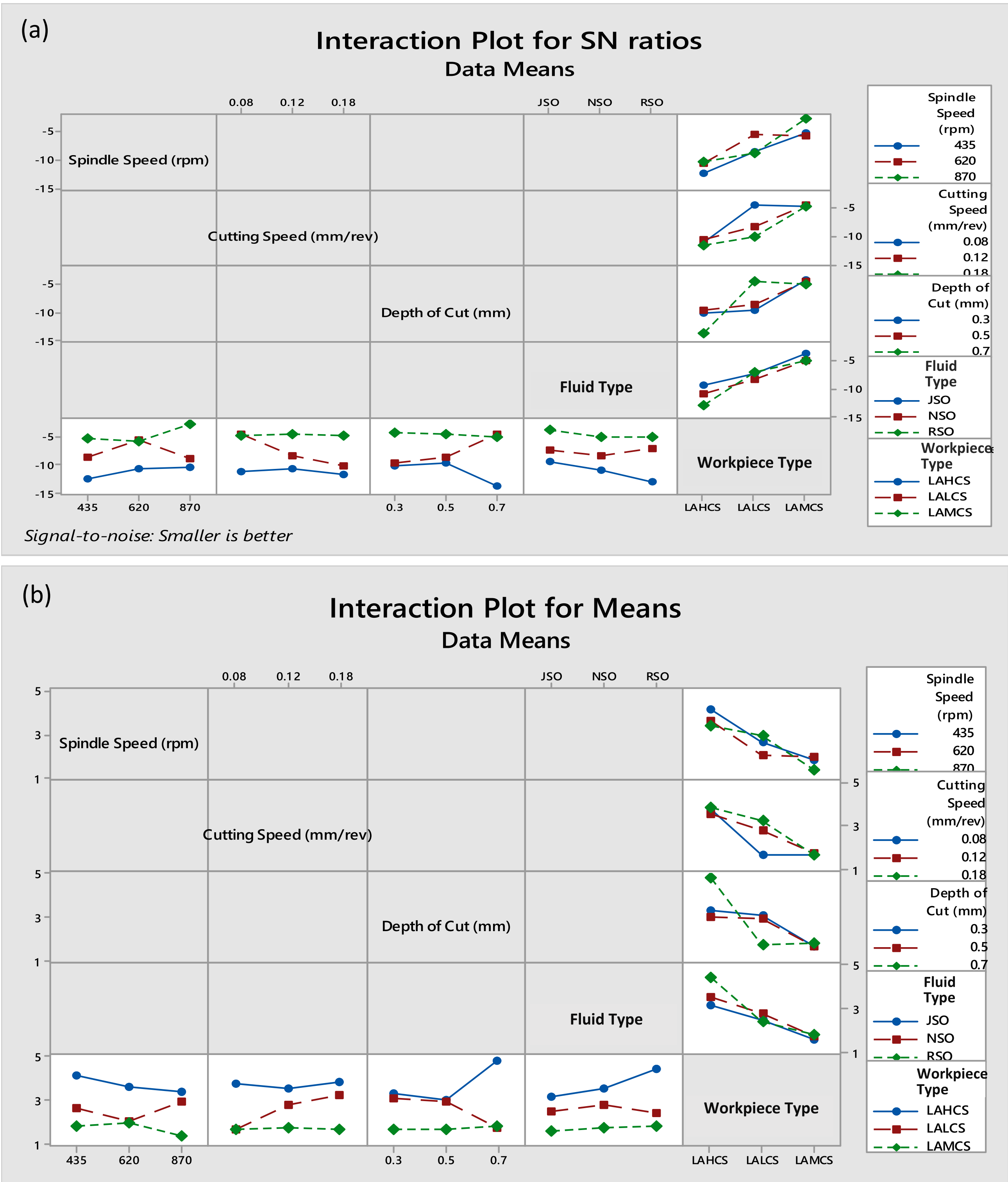


Fig. 3 Interaction Plots for **a** Signal-to-Noise Ratio of Surface roughness, **b** Means of Surface roughness

values are selected. Hence, optimal parameter set for minimization of surface roughness are highest spindle speed (level 3—870 rpm), lowest cutting feed (level 1—0.08 mm/rev.), mid depth-of-cut (level 2—0.5 mm), JSO (level 3 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 1 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as

Table 13 Cutting temperature response table for signal to noise ratio—smaller is better

Level	N	CF	DC	FT	WP
1	#−33.24	−35.66	#−35.00	−35.37	#−34.57
2	−35.66	#−34.81	−35.28	−35.37	−34.97
3	−36.65	−35.09	−35.28	#−34.00	−36.02
Delta	3.41	0.86	0.28	0.54	1.45
Rank	1	3	5	4	2

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, workpiece type, # optimal factor level

Table 14 Cutting temperature response table for means—smaller is better

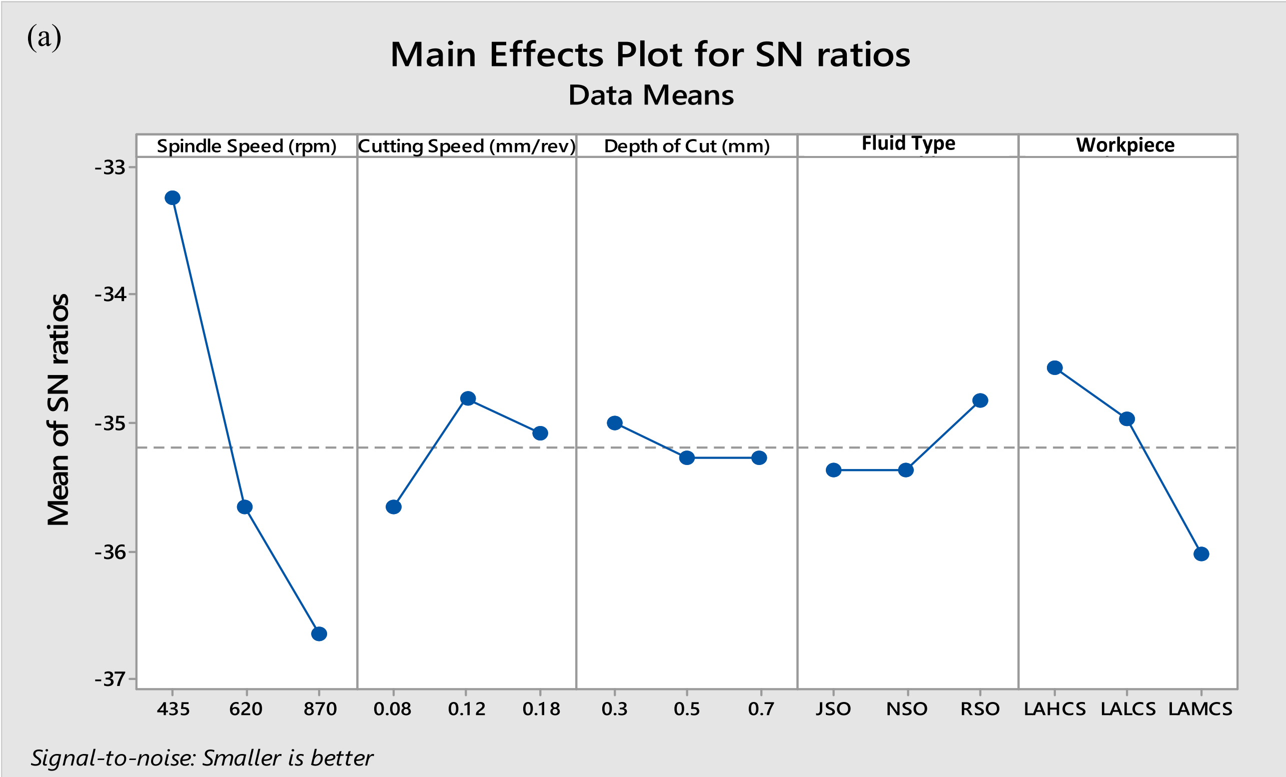
Level	N	CF	DC	FT	WP
1	#46.67	63.82	#57.31	60.88	#55.61
2	61.98	#55.96	60.27	60.89	57.71
3	69.60	58.47	60.67	#56.48	64.92
Delta	22.93	7.87	3.36	4.41	9.31
Rank	1	3	5	4	2

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, workpiece type, # optimal factor level

shown in Figs. 2 and 3), workpiece-LAMCS (level 3 in both orthogonal array table and Minitab alphabetical rearrangement. It should be noted that LAMCS has the highest Rockwell hardness of 109 HRB). Workpiece type being the only statistically significant factor in this case can be said to have caused improvement in surface quality at highest hardness value as explained in the work of Struzikiewicz and Sioma [79] that at higher material hardness, workpiece material adhesion to the cutting edge is limited. Consequently, the formation of built-up edges that contributes to poor surface finish is controlled by the hardness level of the workpiece material. Hardest material generated lesser built-up edges and resulted in lesser surface roughness. The highest hardness value of workpiece materials producing optimal surface roughness means that machinable hardness increased [69]. There exists a difference between optimal value in terms of "spindle-speed" in signal-to-noise ratio and mean-of-means where signal-to-noise ratio detected highest spindle speed (level 3—870 rpm) as optimal while mean-of-means detected mid spindle speed (level 3—620 rpm) as the optimal. The difference in optimal values detected under signal-to-noise ratio and mean has no difference in effect judging by result from main effect plot for mean in Fig. 2b where the line joining both values seemed parallel to the mean-of-means line. However, these optimal spindle speed conform with the general knowledge that increase in spindle speed lowers surface roughness in turning operation [80] as both spindle speeds are higher than the minimum considered in this work. According to Fig. 3a, b, there exist interactions between pairs of factors, effect of a particular factor depended on the factor level of the other because the plotted lines are no-parallel to one another and optimal values obtainable from the interaction plots of signal-to-noise ratio and mean correspond with that obtained in effect plots in Fig. 2a, b, most especially with effect plot of signal-to-noise ratio for spindle speed. The phenomenon of obtaining minimum surface roughness can be explained from the perspective of turning operation mechanics as indicated in Eq. 14 [73] where surface roughness is directly proportional to square of feed rate and inversely proportional to tool nose radius. As stated in Kazeem et al. [76] and Kazeem et al. [72], increase in feed rate results in greater feed load on tool of which built-up edge is promoted with consequent emergence of greater feed marks on machined piece and vice-versa. Though not significant in effect, the cutting fluid type that optimized surface roughness is that with minimum thermal resistivity (JSO—664.40 °C−cm/W) and viscosity value (JSO—140.0 cP) that is higher than RSO but lower than NSO. The position of JSO viscosity value corresponds with its linoleic acid content, making have better flowability than NSO and its oleic acid content which is highest among the fluid types contributes to its lubricating capability. This means JSO has better capability to conduct heat away from the tool cutting point and lubricated the tool/chip interface best, thereby reducing risk of tool softening and eventual wear that generates poor surface finish. This preferred feature of raw JSO in lowering surface roughness as also been demonstrated in the work of Shashidhara and Jayaram [81] for lowering cutting power during turning operation.

$$R_a = \frac{f^2}{32r} \tag{14}$$

Presented in Tables 13 and 14 are Taguchi signal-to-noise ratio and means values for cutting temperature considering



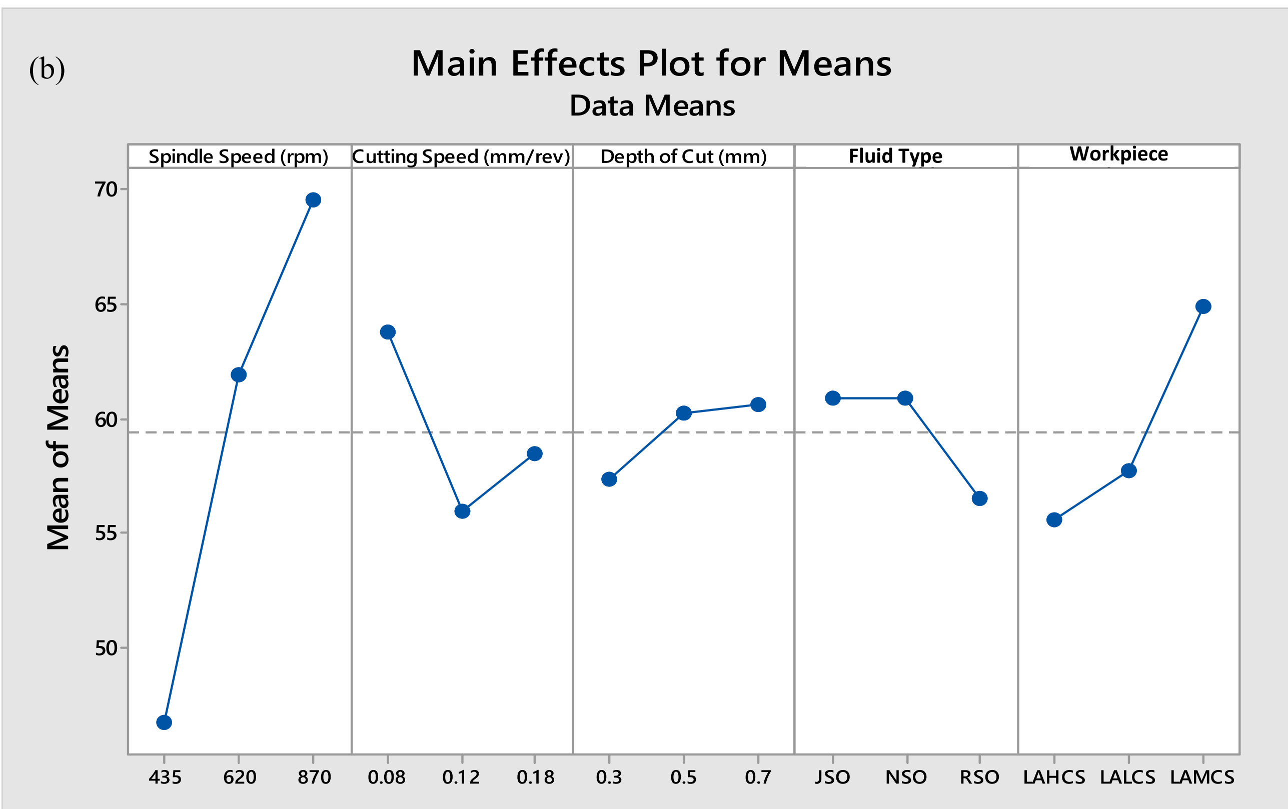


Fig. 4 Effect plots for **c** signal-to-noise ratio of cutting temperature, **d** means of cutting temperature

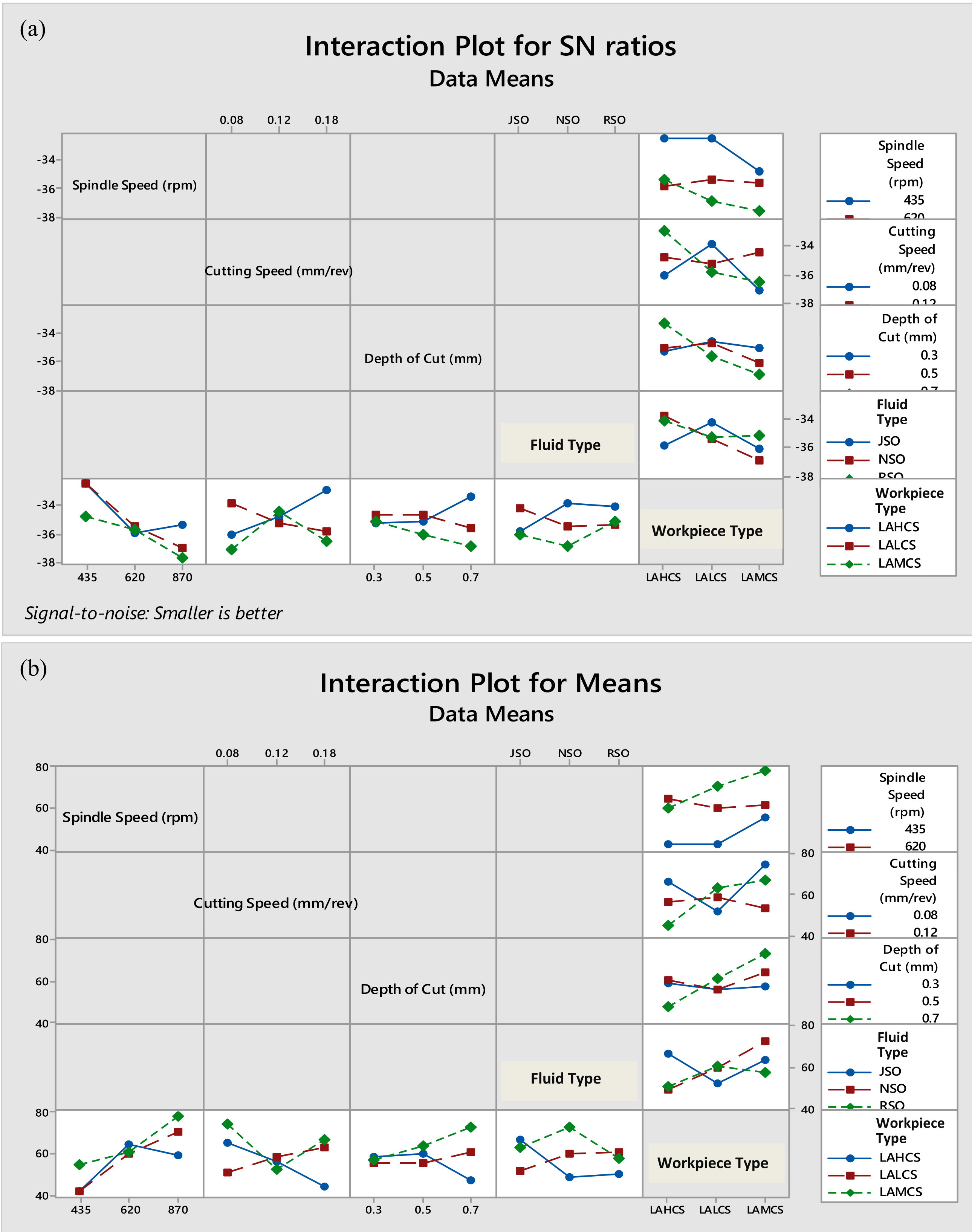


Fig. 5 Interaction plots for **a** signal-to-noise ratio of cutting temperature, **b** means of cutting temperature

Table 15 Chip thickness ratio response for signal to noise ratio—lager is better

Level	N	CF	DC	FT	WP
1	−7.154	−9.203	−7.554	−8.318	#−3.223
2	−8.163	#−6.418	#−6.166	−7.630	−12.488
3	#−7.022	−6.717	−8.619	#−6.391	−6.628
Delta	1.140	2.785	2.453	1.927	9.265
Rank	5	2	3	4	1

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, workpiece type, # optimal factor level

Table 16 Chip thickness ratio response for means—lager is better

Level	N	CF	DC	FT	WP
1	0.4770	0.3811	0.4796	0.4317	#0.7276
2	0.4494	#0.5506	#0.5628	0.4583	0.2607
3	#0.5556	0.5503	0.4397	#0.5920	0.4938
Delta	0.1061	0.1694	0.1231	0.1603	0.4669
Rank	5	2	4	3	1

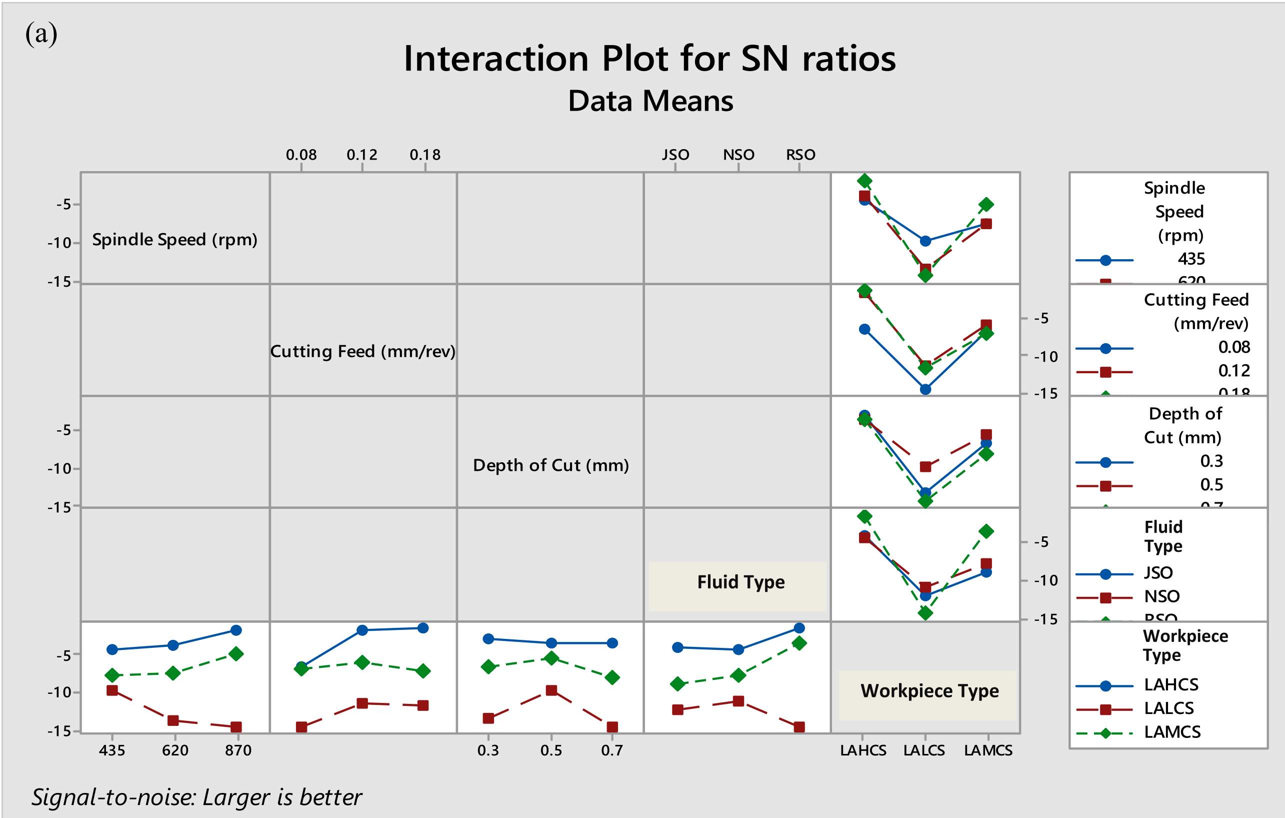
N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, workpiece type, # optimal factor level

smaller-is-better objective set. The Delta value ranking in both tables show that spindle speed ranks 1st in effect on cutting temperature, followed by workpiece. It is evident from both tables that fluid type ranks 4th behind spindle speed, workpiece and cutting feed. Since the objective is smaller-is-better, determining optimal parameters values that minimize cutting temperature will be based on highest signal-to-noise ratio and lowest means. Hence, optimal parameters values as obtainable from Tables 13 and 14 are lowest spindle speed (level 1—435 rpm), mid cutting feed (level 2—0.12 mm/rev), lowest depth of cut (level 1—0.3 mm), fluid type—RSO (level 1 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 3 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as shown in Figs. 4a, b and 5a, b) and workpiece—LAHCS (level 2 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 1 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as shown in Figs. 4a, b and 5a, b). It is evident from Fig. 5a, b that effect of a particular factor depended on the factor level of the other. As expected, low spindle speed and cutting feed leading to minimized cutting temperature is a result of lowered shear deformation taking place at the primary shear zone. Also, RSO having lowest viscosity value and highest thermal resistivity resulted in minimization of cutting temperature due to its ability to flow best into the interface between cutting tool and cut chip, initiating cooling by convective and evaporative heat transfers [82]. The flowability of RSO is made possible by the higher presence of unsaturated linoleic acid which is responsible for decrease in viscosity of the fluid as previously stated.

Contained in Tables 15 and 16 are Taguchi signal-to-noise ratio and means values for Chip-Thickness-Ratio considering Larger-is-better objective set. The Delta value ranking in Tables 15 and 13 show that workpiece type ranks 1st in effect on Chip-Thickness-Ratio, followed by Cutting-Feed. Least ranked of the input parameters is spindle speed in 5th position while fluid-type ranks 4th behind depth-of-cut. The objective set being larger-is-better, optimal parameters values that maximize Chip-Thickness-Ratio is based on highest signal-to-noise ratio and highest means. Therefore, optimal parameters values as obtainable from Tables 15 and 16 are highest spindle speed (level 3—870 rpm), mid cutting feed (level 2—0.12 mm/rev), mid depth of cut (level 2—0.5 mm), fluid type—RSO (level 1 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 3 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as shown in Figs. 6a, b and 7a, b) and workpiece—LAHCS (level 2 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 1 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as shown in Figs. 6a, b and 7a, b). It is revealing in Fig. 7a, b that effect of a particular factor depended on the factor level of the other. Optimal parameter values obtained in Figs. 7a, b differ from that obtained in Fig. 6a, b and Tables 15 and 16 in terms of cutting feed and depth of cut which gave highest cutting feed (level 3—0.18 mm/rev) and lowest depth of cut (level 2—0.3 mm) as optimal values respectively. The

Fig. 6 Main effect plots of **a** signal-to-noise ratio of chip thickness ratio, **b** means of chip thickness ratio

ability of RSO to spread more effectively than other types of oil as MQL oil chiefly gives it edge to be ranked as the optimal, owing to its lowest viscosity value obtained [66]. It is this lowest viscosity value that enhances easier spreadability through the MQL nozzle and penetration into interface between cutting tool and chip formed leading to better lubrication performance [83]. It has been stated previously that all machining parameters considered for this work did not have statistical significant contribution towards cutting temperature variation. Hence, it can be affirmed that the lubricating action of RSO occasioned by its ability to easily spread and



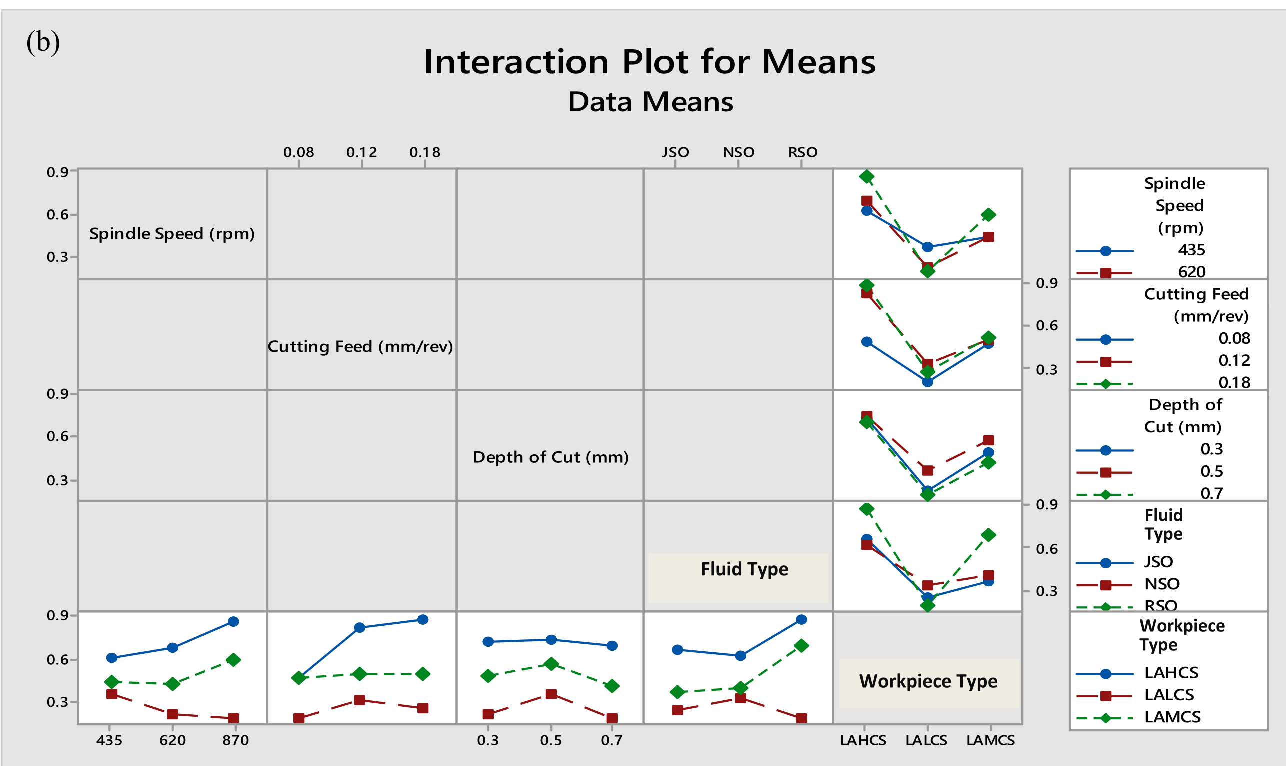


Fig. 7 Interaction plots of **a** signal-to-noise ratio of chip thickness ratio, **b** means of chip thickness ratio

Table 17 Metal removal rate response for signal to noise ratio—larger is better

Level	N	CF	DC	FT	WP
1	64.04	64.25	65.28	#67.91	67.69
2	67.37	67.07	67.76	66.18	#68.58
3	#70.22	#70.31	#68.59	67.53	65.36
Delta	6.18	6.06	3.32	1.73	3.22
Rank	1	2	3	5	4

N spindle speed, *CF* cutting feed, *DC* depth of cut, *FT* fluid type, workpiece type, # optimal factor level

Table 18 Metal removal rate response table for means—larger is better

Level	N	CF	DC	FT	WP
1	1864	1836	2252	2674	2580
2	2621	2565	#2948	2229	#3284
3	#3549	#3634	2834	#3131	2171
Delta	1685	1798	695	902	1113
Rank	2	1	5	4	3

N spindle speed, *CF* cutting feed, DC depth of cut, *FT* fluid type, workpiece type, # optimal factor level

penetrate cutting zone must have significantly resulted in reducing shear at the cutting zone. This that could have led to decrease in temperature through which chip thickness produced became comparatively lesser.

Presented in Tables 17 and 18 are Taguchi signal-to-noise ratio and means values for metal-removal-rate considering Larger-is-better objective set. The Delta value ranking as contained in Table 17 show that spindle speed ranks 1st in effect on metal-removal-rate, followed by cutting-feed and depth-of-cut respectively. Least ranked of the input parameters is fluid-type in 5th position. Optimal values are highest spindle speed (level 3—870 rpm), highest cutting feed (level 3—0.18 mm/rev), highest depth of cut (level 3—0.7 mm), fluid type—JSO (level 3 according to L_{27} orthogonal array but level 1 based on Minitab software alphabetical arrangement) and workpiece—LALCS (level 1 according to L_{27} orthogonal array but level 2 according to Minitab software alphabetical arrangement). Contrarily, Delta values obtained in Table 18 shows that cutting feed ranks 1st followed by spindle speed which ranks 2nd, then workpiece, fluid type and depth of cut rank 3rd, 4th and 5th respectively. Optimal values obtained in this case of mean in Table 18 has highest spindle speed (level 3—870 rpm), highest cutting feed (level 3—0.18 mm/rev), mid depth of cut (level 2—0.5 mm), fluid type—RSO (level 1 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 3 while conducting Signal-to-Noise Ratio analysis and Mean-of-Means, which is also evident in the interaction and main effect plots as shown in Figs. 8a, b and 9a, b) and workpiece—LALCS (level 1 according to L_{27} orthogonal array table but rearranged alphabetically by the Minitab software to become level 2). Optimal values obtained in Fig. 8a, b correspond with that obtained in Tables 17 and 18 respectively. According to Fig. 9a, b, effect of a particular factor depended on the factor level of the other and optimal parameter values obtained in these respective figures tally with that obtained in Tables 17 and 18, same as Fig. 8a, b.

3.5 Multiple response optimization using technique for order preference by similarity to ideal solution (TOPSIS)

The multiple response parameter values obtained previously in Table 6 are converted to a single equivalent response at each experimental level using TOPSIS as contained in Table 19 which show previously obtained raw response parameters, normalized and weighted normalized values. Equal priorities have been applied to all responses because it is assumed that all these parameters contribute to features possessed by components after machining equally and as such the weight criterion of 0.25 was evaluated using Analytic Hierarchy Process (AHP) with a consistency ratio 0.00 < 0.10. Desirability for surface roughness and cutting temperature are their minimum values while that of chip thickness ratio and metal removal rate are their maximum values. Hence, Positive Ideal Solution (PIS) for surface roughness and cutting temperature are their Minimum Weighted Normalized Values (MiWNV) as denoted symbolically with superscript ǂ while chip thickness ratio and metal removal rate had their Maximum Weighted Normalized Values (MaWNV) as denoted symbolically with superscript ˥. The Negative Ideal Solution (NIS) on the other hand, for surface roughness and cutting temperature are their MaWNV denoted symbolically with superscript ˥ and chip thickness ratio with metal removal

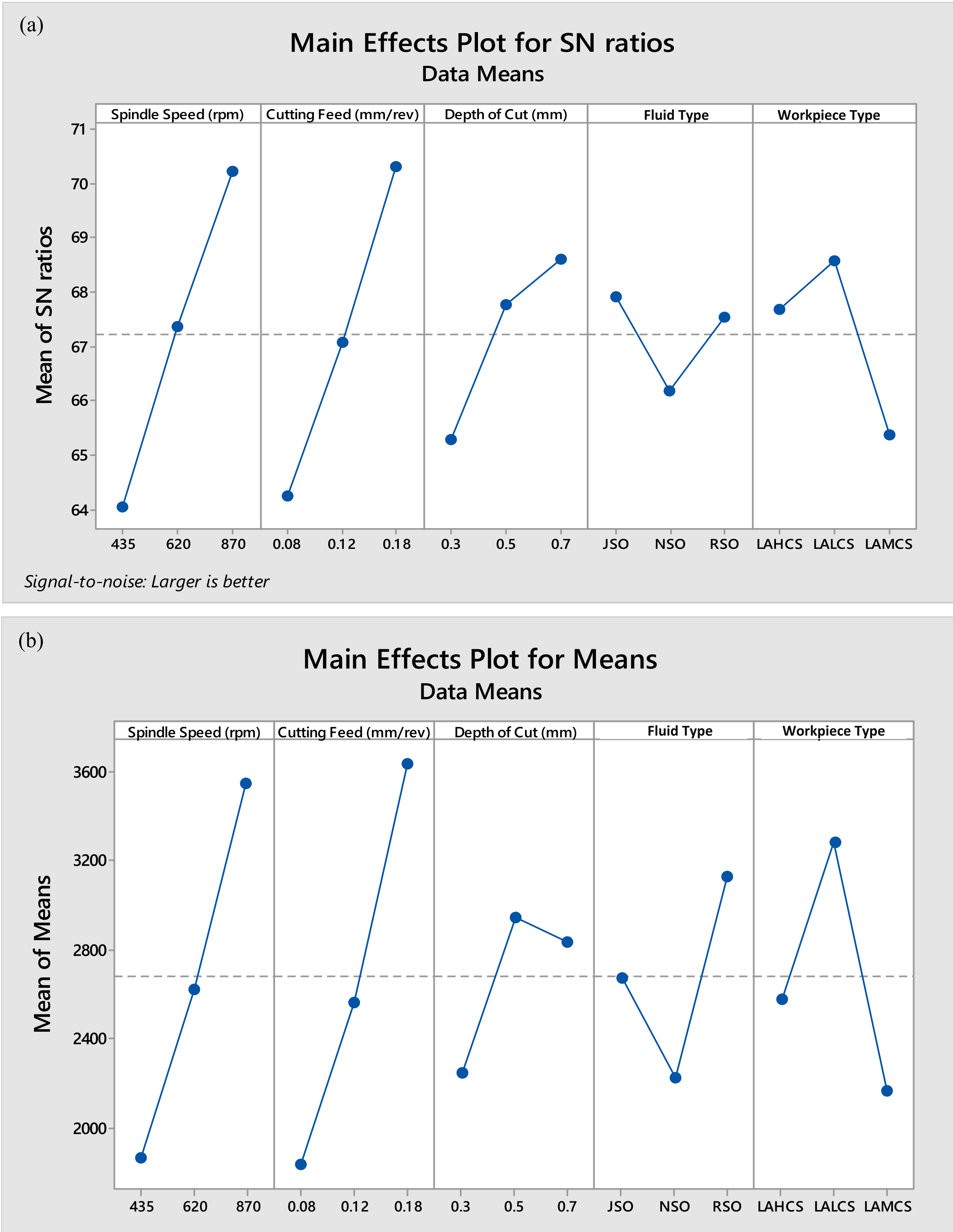


Fig. 8 Means and main effect plots of **c** signal-to-noise ratio of metal removal rate, **d** means of metal removal rate

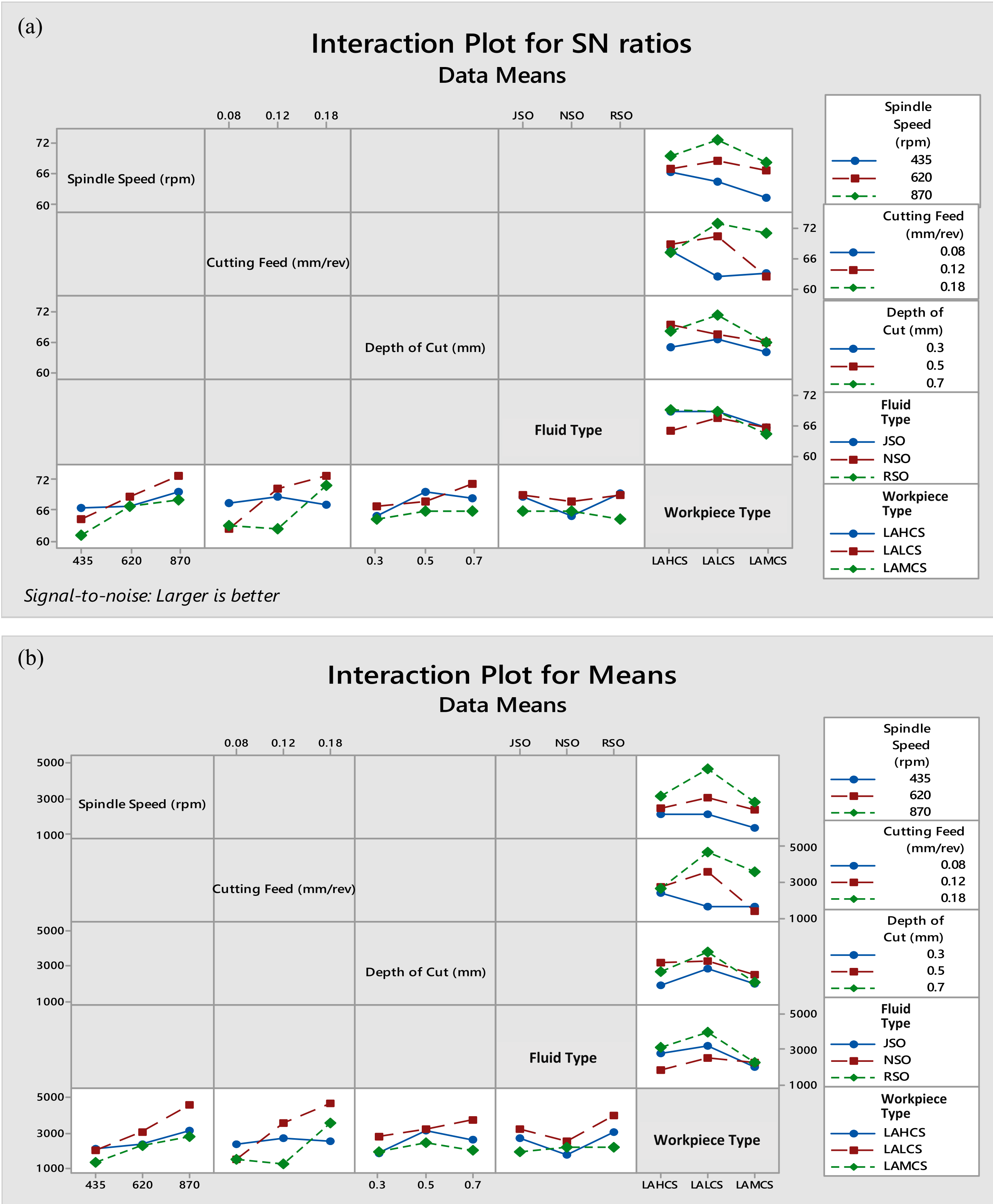


Fig. 9 Interaction plots of **a** signal-to-noise ratio of metal removal rate, **b** means of metal removal rate

Table 19 Raw and normalized values of machining response parameters

S/N	Raw Values SR (μm)	CT (°C)	CTR	MRR (mm^3)	Normalized Values SR	CT	CTR	MRR
1	2.200	37.2	0.195	683.30	0.144162	0.116436	0.069061	0.043255
2	4.587	50.7	0.615	1780.24	0.300577	0.158690	0.217807	0.112696
3	1.847	50.2	0.533	683.30	0.121030	0.157125	0.188766	0.043255
4	3.493	44.0	0.615	1639.91	0.228889	0.137719	0.217807	0.103812
5	3.167	41.6	0.453	2152.38	0.207527	0.130208	0.160434	0.136253
6	1.870	51.0	0.632	922.45	0.122537	0.159629	0.223828	0.058394
7	2.403	45.8	0.297	3997.28	0.157464	0.143353	0.105185	0.253042
8	4.887	34.8	0.261	2459.87	0.320236	0.108924	0.092435	0.155719
9	1.790	64.7	0.692	2459.87	0.117295	0.20251	0.245078	0.155719
10	1.430	46.2	0.242	1266.06	0.093705	0.144605	0.085706	0.080146
11	2.363	91.0	0.383	3019.07	0.154843	0.284829	0.135643	0.191118
12	1.777	68.9	0.404	1947.79	0.116443	0.215656	0.14308	0.123302
13	1.320	67.8	0.155	4674.69	0.086497	0.212213	0.054895	0.295925
14	5.327	52.1	0.571	3213.85	0.349068	0.163072	0.202225	0.203448
15	2.172	50.6	0.923	1460.84	0.142327	0.158377	0.326888	0.092476
16	3.520	66.1	0.257	3286.89	0.230659	0.206892	0.091019	0.208072
17	3.190	51.0	0.360	1095.63	0.209034	0.159629	0.127497	0.069357
18	1.947	64.1	0.750	3725.14	0.127583	0.200632	0.265619	0.235815
19	1.453	70.3	0.146	2733.19	0.095212	0.220038	0.051707	0.173021
20	4.400	55.6	0.421	2323.21	0.288323	0.174027	0.149101	0.147067
21	1.485	104.3	0.491	2186.55	0.097309	0.326458	0.173892	0.138416
22	3.667	64.0	0.203	4509.76	0.240291	0.200319	0.071894	0.285484
23	2.240	75.0	0.480	2869.85	0.146783	0.234749	0.169996	0.181672
24	1.150	57.5	0.923	1639.91	0.075357	0.179974	0.326888	0.103812
25	3.883	78.0	0.236	6764.77	0.254445	0.244139	0.083581	0.428234
26	3.533	48.7	0.900	4304.77	0.231511	0.15243	0.318743	0.272507
27	1.415	73.0	0.947	4612.25	0.092722	0.228489	0.335388	0.291972

S/N	Weighted normalized values SR	CT	CTR	MRR
1	0.03604	0.02911	0.01727	0.01081
2	0.07514	0.03967	0.05445	0.02817
3	0.03026	0.03928	0.04719	ǂ0.01081
4	0.05722	0.03443	0.05445	0.02595
5	0.05188	0.03255	0.04011	0.03406
6	0.03063	0.03991	0.05596	0.01460
7	0.03937	0.03584	0.02630	0.06326
8	0.08006	ǂ0.02723	0.02311	0.03893
9	0.02932	0.05063	0.06127	0.03893
10	0.02343	0.03615	0.02143	0.02004
11	0.03871	0.07121	0.03391	0.04778
12	0.02911	0.05391	0.03577	0.03083
13	0.02162	0.05305	0.01372	0.07398
14	ī0.08727	0.04077	0.05056	0.05086
15	0.03558	0.03959	0.08172	0.02312

Table 19 (continued)

	Weighted normalized values			
S/N	SR	CT	CTR	MRR
16	0.05766	0.05172	0.02275	0.05202
17	0.05226	0.03991	0.03187	0.01734
18	0.03190	0.05016	0.06640	0.05895
19	0.02380	0.05501	ǂ0.01293	0.04326
20	0.07208	0.04351	0.03728	0.03677
21	0.02433	Ī0.08161	0.04347	0.03460
22	0.06007	0.05008	0.01797	0.07137
23	0.03670	0.05869	0.04250	0.04542
24	ǂ0.01884	0.04499	0.08172	0.02595
25	0.06361	0.06103	0.02090	Ī0.10706
26	0.05788	0.03811	0.07969	0.06813
27	0.02318	0.05712	Ī0.08385	0.07299

ǂ = MiWNV; Ī = MaWNV

rate having their NIS obtained as MiWNV values as denoted symbolically with superscript ǂ. Separation measures (D^+ and D^-) of the alternatives are given in Table 20 which is a measure of closeness to the PIS and NIS respectively. Closeness Coefficients (CC_i) of the alternatives are graphed in Fig. 10 where the value 0.719233 immerged as the closest to unity, corresponding to parameter sets in experiment No. 27 having spindle speed-870 rpm, cutting feed-0.18 mm/rev, depth of cut-0.5 mm, RSO and LAMCS. These are optimum conditions for machining as the global solution for MQL assisted turning process conducted.

Table 20 Separation measures of alternatives

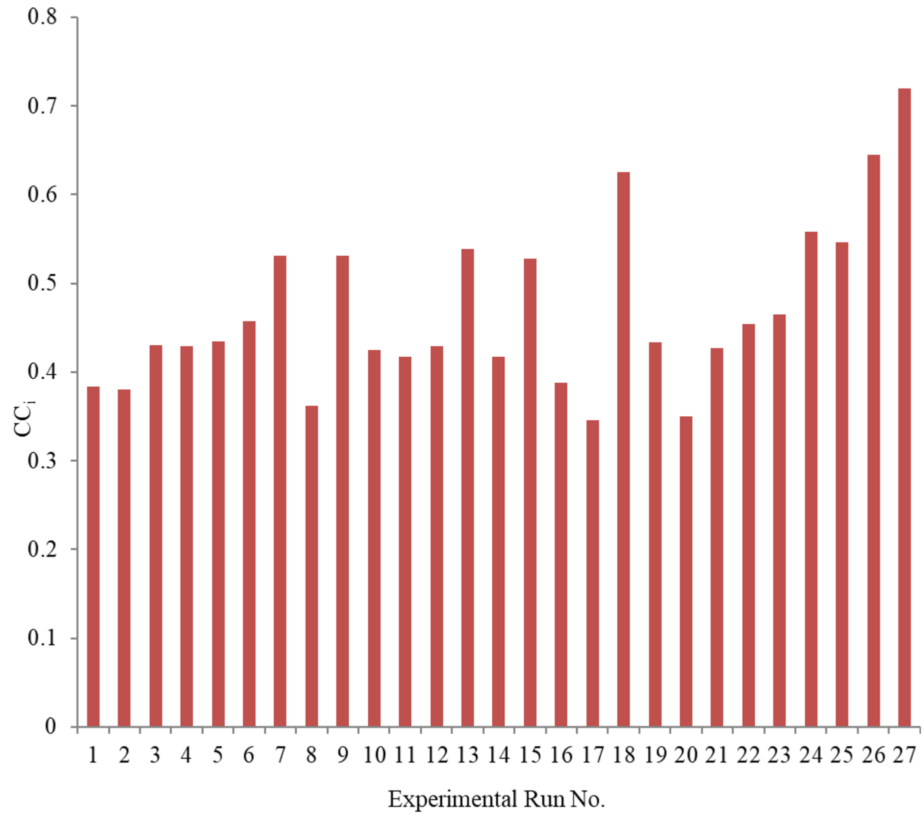
S/N	D^+	D^-
1	0.118306	0.073482
2	0.102040	0.062700
3	0.104320	0.078842
4	0.094698	0.071290
5	0.091444	0.070274
6	0.098117	0.082537
7	0.075672	0.085554
8	0.109904	0.062477
9	0.076217	0.086285
10	0.107566	0.079371
11	0.091307	0.065369
12	0.094556	0.071217
13	0.081771	0.095478
14	0.095563	0.068469
15	0.086509	0.096545
16	0.094178	0.059702
17	0.109676	0.058021
18	0.057573	0.096088
19	0.099486	0.076081
20	0.101044	0.054305
21	0.099338	0.073897
22	0.088519	0.073668
23	0.082571	0.0718
24	0.083057	0.10481
25	0.084324	0.10154
26	0.056351	0.102459
27	0.04553	0.116632

4 Conclusion

The optimization of low-alloyed steel in turning operation while applying vegetable oil-based cutting fluids via minimum quantity lubrication technique has been conducted and the following are conclusions drawn based on values obtained from TAGUCHI, ANOVA and TOPSIS optimization techniques:

- Workpiece type, classified based on hardness has dominant effect on surface roughness value while the fluid type employed as cutting fluid in minimum quantity lubrication assisted turning has no significant effect.
- Workpiece type which happened to be the only statistically significant factor influencing surface roughness showed that hardest material of low-alloy medium carbon steel gave the optimal surface roughness value.

Fig. 10 Closeness coefficients of alternatives



- Jatropha seed oil having highest value of oleic acid which contributed to lubricity of oil, gave optimum value of surface roughness despite the none significant effect cutting fluid type has on surface roughness.
- Most statistically influential factor on chip thickness ratio is the workpiece type while being followed by cutting feed and cutting fluid type respectively.
- Flowability of rubber seed oil occasioned by its highest value linoleic acid with resulting lowest viscosity value gave optimum value of chip thickness ratio.
- Three parameters that are statistically significant on chip thickness ratio and optimized its value are low alloyed high carbon steel, 0.12 mm/rev cutting feed and rubber seed oil.
- Spindle speed and cutting feed are the only influencing factors on metal removal rate while fluid type and workpiece type are of no statistical significance.
- Highest values 870 rpm and 0.18 mm/rev spindle speed and cutting feed respectively, gave optimal value of metal removal rate.
- Global optimization conducted using TOPSIS approach showed that irrespective of statistical significance, 870 rpm, 0.18 mm/rev, 0.5 mm, rubber seed oil and low-alloy low carbon steel gave optimum values of response parameters.
- Rubber seed oil which is an inclusive parameter in the global optimization TOPSIS scheme is basically due to its low viscosity value as a result of its relatively higher linoleic acid content, making flow easily into cutting zone.

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Declarations

Conflict of interest Authors have no known competing interest to declare. All authors have read and approved content of the manuscript for publication.

References

1. Kumar, S., Kumar, R., Singh, S., Singh, H., Kumar, A., Goyal, R., Singh, S.: A comprehensive study on minimum quantity lubrication. Mater. Today Proc. **56**(5), 3078–3085 (2022)
2. Revankar, G.D., Shetty, R., Rao, S.S., Gaitonde, V.N.: Analysis of surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes. Mater. Res. **17**(4), 1010–1022 (2014)
3. Kedare, S.B., Borse, D.R., Shahane, P.T.: Effect of minimum quantity lubrication (MQL) on surface roughness of mild steel of 15HRC on universal milling machine. Proc. Mater. Sci. **6**, 150–153 (2014)
4. Darsin, M., Pratama, N.K., Qoryah, R.D.H., Hermawan, Y., Asrofi, M., Basuki, H.A., Syuhri, A., Djumhariyanto, D., Sidartawan, R., Dwilaksana, D.: Study of chip formation in turning of AISI 4340

under minimum quantity lubrication (MQL. Adv. Eng. Sci. **54**(2), 1007–1020 (2022)
5. Bhosetty, K., Gurram, V.K., Kumba, A.B.: Effect of minimum quantity lubrication on surface roughness and temperature in milling of en31 steel for die making. J. Mech. Eng. **69**(1), 61–68 (2019)
6. Lisowicz, J., Habrat, W., Krupa, K.: Influence of minimum quantity lubrication using vegetable-based cutting fluids on surface topography and cutting forces in finish turning of Ti–6Al–4V. Adv. Sci. Technol. Res. J. **16**(1), 95–103 (2022)
7. Yuan, J., Liu, N., Zou, X., Wu, L., Zhang, Y., He, T., Xia, H., Wang, Y., Chen, Y.: Processing characteristics and lubrication performance of castor oil-ethanol blended coolant based minimal quantity lubrication. CIRP J. Manuf. Sci. Tech. **36**(1–4), 78–89 (2022)
8. Sen, B., Gupta, M.K., Mia, M., Pimenov, D.Y., Mikołajczyk, T.: Performance assessment of minimum quantity castor-palm oil mixtures in hard-milling operation. Materials **14**(1), 198 (2021). https://doi.org/10.3390/ma14010198
9. Liu, N., Zou, X., Yuan, J., Wu, S., Chen, Y.: Performance evaluation of castor oil-ethanol blended coolant under minimum quantity lubrication of difficult-to-machine materials. J. Manuf. Process. **58**, 1–10 (2020)
10. Sadeghifar, M., Javidikia, M., Songmene, V., Jahazi, M.: A comparative analysis of chip shape, residual stress, and surface roughness in minimum-quantity-lubrication turning with various flow rates. Int. J. Adv. Manuf. Technol. **121**, 3977–3987 (2022)
11. Pervaiz, S., Ahmad, N., Ishfaq, K., Khan, S., Deiab, I., Kannan, S.: Implementation of sustainable vegetable-oil-based minimum quantity cooling lubrication (MQCL) machining of titanium alloy with coated tools. Lubricants **10**(10), 235 (2022). https://doi.org/10.3390/lubricants10100235
12. Gurbuz, H., Gonulacar, Y.E., Baday, S.: Effect of MQL flow rate on machinability of AISI 4140 steel. Mach. Sci. Technol. **24**(5), 663–687 (2020)
13. Ghuge, N.C., Palande, D., Mahalle, A.M., Belkhode, P.: Minimum quantity lubrication alternative to flood cutting and dry cutting. Int. J. Sci. Res. Sci. Technol. **8**(2), 345–351 (2021)
14. Hossain, S., Abedin, M.Z.: Effect of minimum quantity lubrication system for improving surface roughness in turning operation. Int. J. Eng. Mater. Manuf. **6**(1), 50–59 (2021)
15. Yildirim, C.V., Kivak, T., Sarikaya, M., Sirin, S.: Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL. J. Mater. Res. Technol. **9**(2), 2079–2092 (2020)
16. Urmi, W.T., Rahman, M.M., Safiei, W., Kadirgama, K., Maleque, M.A.: Effect of minimum quantity lubrication technique in different machining processes: a comprehensive review. J. Adv. Res. Fluid Mech. Therm. Sci. **90**(2), 135–159 (2022)
17. Kumar, U., Jamal, A., Ahmed, A.A.: Performance evaluation of neat vegetable oils as cutting fluid during CNC turning of aluminium (AA1050). J. Mater. Sci. Mech. Eng. **2**(7), 70–75 (2015)
18. Nguyen, V.C., Nguyen, T.D., Tien, T.H.: Cutting parameter optimization in finishing milling of Ti–6Al–4V titanium alloy under MQL condition using TOPSIS and ANOVA analysis. Eng. Technol. Appl. Sci. Res. **11**(1), 6775–6780 (2021)
19. Mumtaz, J., Li, Z., Imran, M., Yue, L., Jahanzaib, M., Sarfraz, S., Shehab, E., Ismail, S.O., Afzal, K.: Multi-objective optimisation for minimum quantity lubrication assisted milling process based on hybrid response surface methodology and multi-objective genetic algorithm. Adv. Mech. Eng. **11**(4), 1–13 (2019)
20. Nguyen, T.C., Pham, T.T.T., Dung, H.T.: Research of multi-response optimization of milling process of hardened S50C steel using minimum quantity lubrication of Vietnamese peanut oil. EUREKA Phy. Eng. **6**, 74–88 (2021)
21. Wagri, N.K., Jain, N.K., Petare, A., Das, S.R., Tharwan, M.Y., Alansari, A., Alqahtani, B., Fattouh, M., Elsheikh, A.: Investigation on the performance of coated carbide tool during dry turning of AISI 4340 alloy steel. Materials **16**, 668 (2023). https://doi.org/10.3390/ma16020668
22. Mia, M., Gupta, M.K., Singh, G., Krolczyk, G., Pimenov, D.Y.: An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. J. Clean. Prod. **187**, 1069–1081 (2018)
23. Mondal, K., Das, S., Mondal, B.: An investigation on machining of hard AISI 4340 steel under varying environmental conditions. Manuf. Technol. Today **20**(7–8), 26–44 (2021)
24. Mia, M., Dey, P.R., Hossain, M.S., Arafat, M.T., Asaduzzaman, M., Ullah, M.S., Zobaer, S.M.T.: Taguchi S/N based optimization of machining parameters for surface roughness, tool wear and material removal rate in hard turning under MQL cutting condition. Measurement **122**, 380–391 (2018)
25. Martowibowo, S.Y., Ariza, I.J., Damanik, B.K.: Comparison of metal removal rate and surface roughness optimization for AISI 316L using sunflower oil minimum quantity lubrication and dry turning processes. J. Mech. Eng. Sci. **16**(3), 8976–8986 (2022)
26. Singh, G., Aggarwal, V., Singh, S., Kumar, A.: Influence of nozzle distance on tool–chip interface temperature using minimum quantity lubrication. Adv. Prod. Ind. Eng. (2021). https://doi.org/10.1007/978-981-15-5519-0_13
27. Masoudi, S., Vafadar, A., Hadad, M., Jafarian, F.: Experimental investigation into the effects of nozzle positon, workpiece hardness, and tool type in mql turning of aisi 1045 steel. Mater. Manuf. Process. **33**(9), 1011–1019 (2017)
28. Benkai, L., Changhe, L., Yanbin, Z., Yaogang, W., Dongzhou, J., Min, Y.: Grinding temperature and energy ratio coefficient in MQL grinding of high-temperature nickel-base alloy by using different vegetable oils as base oil. Chin. J. Aeronaut. **29**, 1084–1094 (2016)
29. Kaynak, Y., Gharibi, A., Yılmaz, U., Köklü, U., Aslantaş, K.: A comparison of flood cooling, minimum quantity lubrication and high pressure coolant on machining and surface integrity of titanium Ti-5553 alloy. J. Manuf. Process. **34**, 503–512 (2018)
30. Abdul Sani, A.S., Abd Rahim, E., Sharif, S., Sasahara, H.: The influence of modified vegetable oils on tool failure mode and wear mechanisms when turning AISI 1045. Tribol. Int. **129**, 347–362 (2019)
31. Zhang, X., Li, C., Zhou, Z., Liu, B., Zhang, Y., Yang, M., Gao, T., Liu, M., Zhang, N., Said, Z., Sharma, S., Ali, H.M.: Vegetable oil-based nanolubricants in machining: from physicochemical properties to application. Chin. J. Mech. Eng. (2023). https://doi.org/10.1007/s00170-022-10767-2
32. Wang, Y., Li, C., Zhang, Y., Yang, M., Li, B., Jia, D., Hou, Y., Mao, C.: Experimental evaluation of the lubrication properties of the wheel/workpiece interface in minimum quantity lubrication (MQL) grinding using different types of vegetable oils. J. Clean. Prod. **127**, 487–499 (2016)
33. Cui, X., Li, C., Zhang, Y., Ding, W., An, Q., Liu, B., Li, H.N., Said, Z., Sharma, S., Li, R., Debnath, S.: Comparative assessment of force, temperature, and wheel wear in sustainable aerospace alloy using biolubricant. Front. Mech. Eng. **18**(1), 3 (2023). https://doi.org/10.1007/s11465-022-0719-x
34. Joshy, J., Mahipal, D.N.: The effect of free fatty acids on the tribological properties of karanja oil. IOP Conf. Ser.: Mat. Sci. Eng. **1114**, 012053 (2021). https://doi.org/10.1088/1757-899X/1114/1/012053
35. Xu, W., Li, C., Zhang, Y., Ali, H.M., Sharma, S., Li, R., Yang, M., Gao, T., Liu, M., Wang, X., Said, Z., Liu, X., Zhou, Z.: Electrostatic atomization minimum quantity lubrication machining: from mechanism to application. Int. J. Extrem. Manuf. **4**, 042003 (2022). https://doi.org/10.1088/2631-7990/ac9652
36. Wang, Y., Li, C., Zhang, Y., Li, B., Yang, M., Zhang, X., Guo, S., Liu, G., Zhai, M.: Comparative evaluation of the lubricating

properties of vegetable-oil-based nanofluids between frictional test and grinding experiment. J. Manuf. Proc. **26**, 94–104 (2017)
37. Yin, Q., Li, C., Dong, L., Bai, X., Zhang, Y., Yang, M., Jia, D., Li, R., Liu, Z.: Effects of physicochemical properties of different base oils on friction coefficient and surface roughness in MQL milling AISI 1045. Int. J. Prec. Eng. Manuf.-Green Technol. **8**, 1629–1647 (2021)
38. Yalcin, H., Toker, O.S., Dogan, M.: Effect of oil type and fatty acid composition on dynamic and steady shear rheology of vegetable oils. J. Oleo Sci. **61**(4), 181–187 (2012)
39. Awogbemi, O., Onuh, E.I., Inambao, F.L.: Comparative study of properties and fatty acid composition of some neat vegetable oils and waste cooking oils. Int. J. Low-Carbon Technol. **14**, 417–425 (2019)
40. Liu, J., Zhao, L., Cai, H., Zhao, Z., Wu, Y., Wen, Z., Yang, P.: Antioxidant and anti-inflammatory properties of rubber seed oil in lipopolysaccharide-induced RAW 2674 macrophages. Nutrients **14**, 1349 (2022)
41. Annissa, N., Suprayudi, M.A., Satiawati, M., Fauzi, I.A.: Evaluation of processed rubber seed oil *Hevea brasiliensis* utilization as lipid source in clarias gariepinus feed. J. Akuakultur Indonesia **19**(2), 131–141 (2020)
42. Yousif, E., Abdullah, B., Ibraheem, H., Salimon, J., Salih, N.: Rubber seed oil properties, authetication and quality assessment using (chloroform: methanol) as solvent. J. Al-Nahrain Univ. **16**(3), 1–6 (2013)
43. Koffi, E.N., Niamketchi, L.G., Koffi, U.K., Guei, J.F., Konon, M.K., Anin, L.: Chemical analysis and antifungal activity of rubber seed oil (hevea brasiliensis) from the southern region of Cote d'Ivore. J. Mater. Environ. Sci. **13**(4), 382–390 (2022)
44. Agboola, J.B., Abubakre, O.K., Mudiare, E., Adeyemi, M., Hassan, S.B.: Physico-chemical characteristics and fatty acids composition of some selected Nigerian vegetable oils for quenching medium. Br. J. Appl. Sci. Technol. **8**(3), 246–253 (2015)
45. Usman, J.G., Okonkwo, P.C., Mukhtar, B.: Design and construction of pilot scale process solvent extraction plant for neem seed oil. Niger. J. Technol. **32**(3), 528–537 (2013)
46. Adigwe, O.P., Ibrahim, J.A., Adamu, A., Okhala, S.E., Elias, A., Egharevba, H.O.: Chemometric analysis of volatile compounds of NIPRINEEM oil and other brands of neem seed oils sold in Nigeria. J. Biophy. Chem. **13**, 1–12 (2022)
47. de Paulo Barbosa, L.M., Samos, J.O., de Sousa, R.C.M., Furtado, J.L.B., Vindiha, P., Garcia, M.A.S., Vitorino, H.A., Dall'oglio, D.F.: Bioherbicide from Azadirachta indica seed waste: exploitation, efficient extraction of neem oil and allelopathic effect on senna occidentalis. Recycling **8**, 50 (2023). https://doi.org/10.3390/recycling8030050
48. Tchinda, J.S., Tchebe, T.M.F., Abdou, T., Yona, A.M.C., Fauconnier, M.L., Ndikontar, M.K., Richel, A.: Fatty acid profiles, antioxidant and phenolic contents of oils extracted from Acacia polycautha and Azadiratcha indica (Neem) seeds using green solvent. J. Food Process. Preserv. (2020). https://doi.org/10.1111/jfpp.15155
49. Ugbogu, A.E., Akubugwo, E.I., Uhegbu, F.O., Chinyere, C.G., Ugbogu, O.C., Oduse, K.A.: Quality assessment profile of Jatropha curcas (L) seed oil from Nigeria. Int. Food Res. J. **21**(2), 735–741 (2014)
50. Nayak, B.S., Patel, K.N.: Physicochemical characterization of seed and seed oil of Jatropha curcas L. collected from Bardoli (south Gujarat). Sains Malaysiana **39**(6), 951–955 (2010)
51. Callistus, U.N., Dominic, O.O., Justina, O.I., Lovet, E.N.: Preparation of biodiesel from non-edible Nigerian Jatropha curcas oil: effect of process parameters and kinetics of reacton. Sigma J. Eng. Nat. Sci. **34**(3), 415–437 (2016)
52. Azeez, A.M., Fasakin, A.O., Orege, J.I.: Production, characterization and fatty acid composition of Jatropha curcas biodiesel as a viable alternative to conventional diesel fuel in Nigeria. Green Sust. Chem. **9**, 1–10 (2019)
53. ASTM D1217: Standard Test Methods for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pychometer. ASTM International. West Conshohoden, United State (2016)
54. KD2 Pro: Thermal Properties Analyzer: Operator's Manual. Decagon Devises, Inc., Washinton, United State (2016)
55. ASTM D2983: Standard Test Methods for Low-Temperature Viscosity of Lubricants Measured by Brookfield Viscometer. ASTM International. West Conshohoden, United State (2009)
56. ASTM E415: Standard Test Methods for Analysis of Carbon and Low-Alloy Steel by Spark Atomic Emmission Spectrometry. ASTM International. West Conshohoden, United State (2014)
57. ASTM E18: Standard Test Methods for Rockwell Hardness of Metallic Materials. ASTM International. West Conshohoden, United State (2015)
58. Krishman, P.G., Saravanan, P., Raj, D.S., Hussain, S., Shankar, V.R., Raj, N.: Optimization of jet position and investigation of the effects of multijet MQCL during end milling of Ti-6Al-4V. J. Manuf. Process. **64**, 392–408 (2021)
59. Ogedengbe, T.S., Abdulkareem, S., Aweda, J.O.: Effect of coolant temperature on machining characteristics of high carbon steel. Covenant J. Eng. Technol. **1**(1), 73–86 (2018)
60. Ogundimu, O., Lawal, S.A., Okokpujie, I.P.: Experimental study and analysis of variance of material removal rate in high speed turning of AISI 304L alloy steel. IOP Conf. Ser.: Mater. Sci. Eng. **413**, 1–9 (2018)
61. Yildirim, Ç.V., Kıvak, T., Sarıkaya, M., Erzincanl, F.: Determination of MQL parameters contributing to sustainable machining in the milling of nickel-base superalloy waspaloy. Arab. J. Sci. Eng. **42**, 4667–4681 (2017)
62. Parida, A.K., Routara, B.C.: Multiresponse optimization of process parameters in turning of GFRP using TOPSIS method. Int. Schol. Res. Not. (2014). https://doi.org/10.1155/2014/905828
63. Vafaei, N., Ribeiro, R.A., Camarinha-Matos, L.M.: Data nornalization techniques in decision making case study with TOPSIS Method. Int. J. Info. Decis. Sci. **10**(1), 19–38 (2018)
64. Wahydi, Wardana, I.N.G., Widolo, A., Wijayanti, W.: Improving vegetable oil properties by transforming fatty acid chain length in jatropha oil and coconut oil blends. Energies **11**(394), 1–12 (2018)
65. Abdukareem, B., Dan-asabe, B., Abdullahi, A.: Development of cutting fluid and optimization of its cutting speed from *thevetia peruviana* seed oil. J. Mekanikal **42**, 51–60 (2019)
66. Zamiruddin, N.E.H., Sani, A.S.A., Rosli, N.: Oil viscosity effects on lubricant oil film behaviour under minimum quantity lubrication. IOP Conf. Ser.: Mater. Sci. Eng. (2021). https://doi.org/10.1088/1757-899X/1092/1/012029
67. Adesusi, O.M., Adetunji, O.R., Erinle, T.J., Okediran, I.K., Akinpelu, O.O., Ipadeola, S.O.: Free fatty acid influenced corrosion inhibition mechanism of some inedible plants seeds oils on low alloyed medium-carbon steel in H2SO4. World J. Eng. **19**(4), 467–479 (2022)
68. Adesusi, O.M., Adetunji, O.R., Ismaila, S.O., Dare, E.O., Erinle, T.J., Akinpelu, O.O.: Electrochemical inhibitory effects of non-edible vegetable oils on low-alloyed low carbon steel in H_2SO_4. J. Fail. Anal. Prev. **20**(1), 159–172 (2020)
69. Tuan, N.M., Duc, T.M., Long, T.T., Hoang, V.L., Ngoc, T.B.: Investigation of machining performance of MQL and MQCL hard turning using nano cutting fluids. Fluids **7**(5), 143 (2022). https://doi.org/10.3390/fluids/7050143
70. Jeevan, T.P., Jayaram, S.R.: Performance evaluation of Jatropha and Pongamia oil based environmentally friendly cutting fluids for turning AA 6061. Adv. Tribol. (2018). https://doi.org/10.1155/2018/2425619
71. Elewa, I., Galal, A., Saker, N., Abd El Tawab, A.: Comparative study on the effect of vegetable based cutting fluid and mineral oil

on cutting forces and surface roughness during turning operation. Mansoura Eng. J. **40**(4), 121–131 (2015)
72. Kazeem, R.A., Fadare, D.A., Ikumapayi, O.M., Adediran, A.A., Aliyu, S.J., Akinlabi, S.A., Jen, T.-C., Akinlabi, E.T.: Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations—a review. Lubricant **10**, 69 (2022). https://doi.org/10.3390/lubricants10040069
73. Khan, S.A., Umar, M., Saleem, M.Q., Mufti, N.A., Raza, S.F.: Experimental investigation on wiper inserts' edge preparation, workpiece hardness and operating parameters in hard turning of AISI D2 steel. J. Manuf. Process. **34**, 187–196 (2018)
74. Kazeem, A.R., Fadare, D.A., Ikumapayi, O.M., Azeez, T.M., Adediran, A.A.: Development of bio-cutting fluid (Cirtullus lanatus) and its performance assessment on the machining of AISI 1525 steel using Taguchi technique and grey relational analysis. Biointerface Res. Appl. Chem. **12**(4), 5324–5346 (2022)
75. Salur, E., Kuntoglu, M., Aslam, A., Pimenov, D.Y.: The effects of MQL and dry environments on tool wear, cutting temperature, and power consumption during end milling of AISI 1040 steel. Metals **11**(11), 1674 (2021). https://doi.org/10.3390/met11111674
76. Kazeem, R.A., Aregbesola, D.S., Jen, T.C., Akande, I.G., Akinlabi, S.A., Akinlabi, E.T.: Multi-response optimization of process parameters for sustainable machining of AISI 1018 steel with palm kernel oil-assisted minimum quantity lubrication technique. Int. J. Interac. Des. Manuf. (2023). https://doi.org/10.1007/s12008-023-01696-9
77. Khan, M.M.A., Mithu, M.A.H., Dhar, N.R.: Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. J. Mater. Process. Technol. **209**, 5573–5583 (2009)
78. Ali, S.: Performance evaluation of quantity lubrication (MQL)) when machining high-performance materials. Unpublished Master Degree Thesis. Rochester Institute of Technology, United Arab Emirate (2022)
79. Struzikiewicz, G., Sioma, A.: Evaluation of surface roughness and defect formation after the machining of sintered aluminium alloy AlSi10Mg. MaterIALS **13**, 1662 (2020). https://doi.org/10.3390/ma13071662
80. Kazeem, R., Jen, T., Akande, G., Akinlabi, S., Akinlabi, E.: Performance valuation of hybrid biodegradable oils as a lubricant during cylindrical turning of AISI 304 austenitic stainless steel. AIMS Mater. Sci. **11**(2), 256–294 (2024)
81. Shashidhara, Y.M., Jayaram, R.S.: Experimental determination of cutting power for turning and material removal rate for drilling of AA 6061–T6 using vegetable oils as cutting fluid. Adv. Tribol. (2013). https://doi.org/10.1155/2013/362931
82. Lohar, D.V., Nanavaty, C.R.: Performance evaluation of minimum quantity lubrication (MQL) using CBN tool during hard turning of AISI 4340 and its comparison with dry and wet turning. Bonfring Int. J. Ind. Eng. Manag. Sci. **3**(3), 102–106 (2013)
83. Agarwal, V., Agarwal, S.: Performance profiling of solid lubricant for eco-friendly sustainable manufacturing. J. Manuf. Process. **64**, 294–305 (2021)