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Research article

Performance investigations for sustainability assessment of Hastelloy C-276 under different machining environments

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ABSTRACT

Hastelloy is categorized as difficult to cut superalloy widely used in aerospace, nuclear reactor components and chemical industry because of its magnificent strength and higher heat efficiency. Since, the machining of this material is quite difficult and hence suitable cooling systems are required to achieve sustainable manufacturing goals. The present investigation has been focused on the machining performance and sustainability assessment of turning Hastelloy C-276 in dry, flood and minimum quantity lubrication (MQL) environments. Taguchi L-9 has been utilized to conduct and record the experimental output along with TOPSIS approach to evaluate the sustainability. The output responses viz. cutting forces, surface roughness, cutting temperature, energy consumption and carbon emission have been recorded at various levels of input variables. The experimental results revealed that MQL has minimized the cutting forces, surface roughness and temperature by margin of 20–38%. Likewise, energy expenditure and carbon emission was declined by 9–27% respectively compared to other conditions. Sustainability analysis explored best performance index during equal weightage criteria at 125 m/min, 0.246 and 0.8 mm doc under MQL. However, implementing assigned weightage system evaluated best condition for dry machining as 88 m/min and 0.246 mm/rev having same doc. SEM analysis of insert reported mainly abrasion and adhesion type of tool wear at all parametric range and machining conditions.

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1. Introduction

Presently in era of industry 4.0, sustainable machining is of greater interest among the researchers to attain the objectives of united nation sustainable development goal (UNSDG) 12–13. It is possible through implementation of latest cooling techniques for processing advance and smart materials. Despite of favourable heat resisting properties of Ni based super alloy, it is quoted as difficult-to-cut material and limited data is available on its machining performance. The metal cutting of such material creates numerous challenges like larger heat formation and hence there is a requirement of suitable heat absorption system [1,2]. The cooling and lubrication feature of metal working fluids impacts the machining performance directly [3]. However, excessive usage causes several demerits like environmental degradation, health hazards, chemical decomposition and respiratory disorder. In addition to this, pollution to water, soil as well as challenges during wastages disposal [4–7].

The utilization of conventional flood lubrication adversely affects the economy of firm due to expenditure on handling, storage, wastage disposal and production cycle along with this it degrades the ecology [8]. The costs of flood cooling (30%) which include elemental cost of equipment (26%), maintenance cost (12%), scrap cost (3–5%), coolant cost (15%) and energy cost (4%). However, the cost of energy and equipment are comparatively less in MQL indicate the use of MQL for sustainable machining [9]. Numerous investigations have been conducted to reduce the amount of cutting oil and thus, MQL was one of the best alternatives to conventional cooling system [10–12]. During MQL system low quantity of fluid is discharged at 10–100 ml/h along with pressurized air jet supplied through suitable nozzle [13]. Implementation of MQL leads to formation of dry chips, absence of respiratory malfunction, and eliminate the pollution of soil, water and air. Along with this, reduction of production cost is the added benefits due to evaporation of used lubricant. Further, lower cost associated with maintenance, inspection and wastage disposal are the features of this system [14, 15].

1.1. Utility of nano-MQL for sustainable machining

The cooling action of different oil based techniques were enhanced by mixing nano dimension particles resulting into improvement of tool life, tribological attributes, heat absorption capacity and productivity of machining [16]. MQL has numerous advantages than conventional flood lubrication, but, sometimes their cooling effect is lower at higher range of process parameter. So, to enhance this, various types of nano-fluids were mixed with coolant to improve the heat transfer capacity resulting into better machining performance [17,18]. Researchers have used MQL of vegetables oil mixed with different types of nanofluids so as to enhance the thermal conductivity of amalgamation and thus the machining performance improved [19,20].

The investigation on the machining performance of AISI 1050, AISI 4340 and $60Si_2Mn$ reported that implementation of nano-MQL has reduced the forces, surface irregularities, heat generation, tool erosion and thickness of chip by favourable amount [21–23].

Performance study of machining cobalt based Haynes 25 under different cooling conditions of nano-MQL (BF, hBN, MoS_2 and Gr) revealed the enhancement of thermal conductivity coefficient by 11.90%, 16.29% and 14.12% compared to base fluid (BF). Moreover, highest surface finish was reported in Gr-NMQL and lowest notch wear was found in hBN-NMQL. The reduction in temperature was maximum during MoS_2-NMQL (34.95%), followed by Gr-NMQL (29.32%) and lastly hBN-MQL (27.18%) compared to dry machining [24].

Experimental investigation during drilling of Hastelloy-X under different NMQL situations considering hole quality, cutting forces, tool wear and tool life revealed best performance during SDS mixed hBN/GNP cutting, Whereas, minimum temperature was recorded during absence of SDS hBN/GNP condition. There was fifty one percentage increases in tool life for said condition compared to dry cutting [25]. Owing to significant impact of nanoparticles on the machining quality, it leads to several health complications if inhaled during the course of application, mixing and production process. Additionally, it negatively impacts the productivity as a consequence of higher cost and health issues. Therefore, other alternatives have been tried to cool the arduous materials were applied as liquefied N_2, carbon dioxide and ionic liquid [26].

1.2. Use of cryogenic cooling as sustainable technique

The processing of Ni–Cr superalloys was conducted under cryogenic cooling (CO_2) to enhance the tool life, product quality and lower cutting temperature due to economy, easily availability, nontoxic, odourless and bulk production features [27,28]. In manufacturing sector the usage of MWF over 600 million-gallons has been consumed in a year having 54% share of machining process [29]. Also, more than 75% of occupational skin diseases caused by the exposure of MWF having additives like Cl and S [30]. Further, to minimize the health problems caused by cutting fluid, several countries have implemented strict regulation and imposed ban on their usage and other alternative like MQL and cryogenic cooling were adopted [31–34].

An initiative to develop the sustainable cutting fluids for machining strenuous materials was made at IITRAM laboratory in collaboration with other institutes [35,36]. The machining performance of 15-5PHSS was investigated during dry and cryogenic conditions revealed that depth of cut was supreme factor for impacting forces and surface finish. Along with this, lower tool wear was reported during low temperature cooling [37,38]. The investigation on the tool wear, surface roughness, power consumption and micro-hardness during dry, flood, MQL and cryogenic treatment of 15-5 PHSS revealed better performance during LCO_2 having good surface quality in comparison to flood conditions [39].

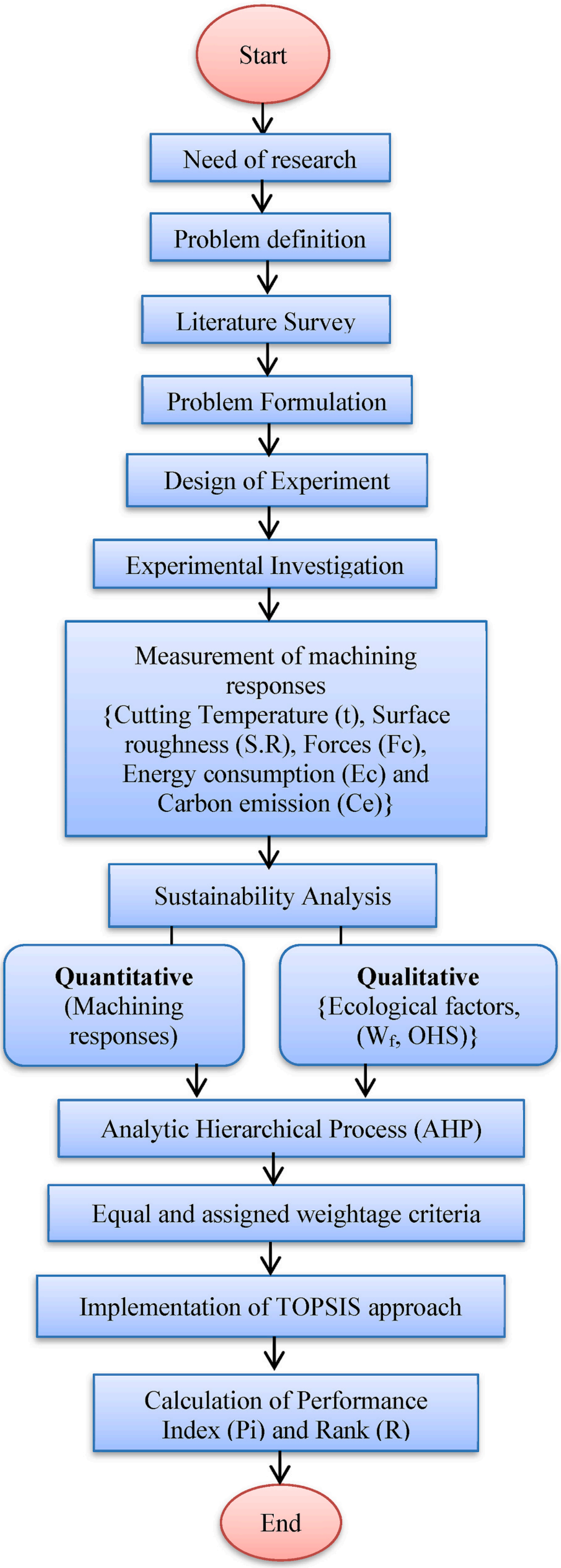

Fig. 1. Schematic diagram of work methodology.

1.3. Sustainability assessment

Despite of handsome research on the utility of MQL, nano-MQL, cryogenic cooling, ionic liquid, flood cooling, HPC and dry machining, there is huge demand of sustainability assessment to achieve the goal of sustainable manufacturing [40,41]. Hence, in this regard researchers have tried LCA, ANN and artificial intelligence techniques to evaluate the sustainability of tough workpiece. Various indicators selected by the researcher were metal cutting conditions and environmental aspects of cooling conditions. The decision making capability have been improved through implementation of MCDM techniques like TOPSIS, AHP and ANOVA analysis [42–44].

Sustainable milling of titanium alloys using MQL, CO_2 and LN_2 considering Tool damage, surface waviness, temperature, Specific energy, carbon emission and energy efficiency revealed the performance rating as CO_2 cooling, LN_2, MQL and dry machining [45]. Sustainability assessment of turning titanium alloys using in house developed hybrid cooling system has reduced the energy consumption by 1.8–3.6% compared to cryogenic cooling without degrading the quality of product [46]. MQL milling of Ni based Waspaloy alloys observed more tool life and less cutting forces during vegetable based oil discharged at 100 ml/h placed at 25 mm stand-off distance [47].

Investigations on machining performance of Ti alloys reported that utilization of MQL and cryogenic cooling benefited insert wear, tool expectancy and surface characteristics minimizing the ecological, economical and health hazards [48]. Further, the sustainability index of magnetic assisted SPDT was 2.39 times more than normal [49].

Research on the economic and environmental burden of processing Inconel-800 under numerous cooling conditions revealed substantial cut in energy consumption, insert wear, surface roughness and carbon emission during LN_2 cooling than other conditions like dry, VOMQL and GNMQL [50]. Investigation into the turning of turning AISI D3 Steel conducted through Taguchi L-9 arrangement in dry, flood and MQL condition examined that MQL assisted machining has favourable impact on surface irregularities, tool damage and temperature [51].

From literature survey, it has been revealed that the researcher worked on the enhancement of machining performance through utilization of different cooling techniques, but sustainability assessment is still very limited during machining of Hastelloy C-276. Hence, in present experimentation, the major focus has been deviated toward the sustainability assessment considering the factors having significant impacts on the machining performance. The output responses like surface finish, temperature and cutting forces have been considered as critical parameters. Along with these, the sustainability indicators like energy consumption, carbon emission, waste management and occupational health & safety have been explored. Further, to assess sustainable machining conditions, dry, flood and vegetable oil MQL environments have been compared. Moreover, to comprehend time and cost saving, the Taguchi L-9, ANOVA, AHP and TOPSIS techniques have been implemented for the analysis, optimization and sustainability assessment.

2. Methodology of work

2.1. Methodology of work

Experiments were conducted on cylindrical specimen of Hastelloy C-276 having diameter 0.056 m and length 0.550 m utilizing good quality lathe machine at different levels of parameters under dry, flood and vegetable oil minimum quantity lubrication(MQL) environments. The length of workpiece is uniformly distributed among all experimental conditions and every time new cutting edge was utilized to machine the specimen. First nine experiments were executed in dry machining followed by flood cooling and then after MQL environments leading to total 27 experiments run. The output responses such as cutting forces (Fc), Surface roughness (S.R),

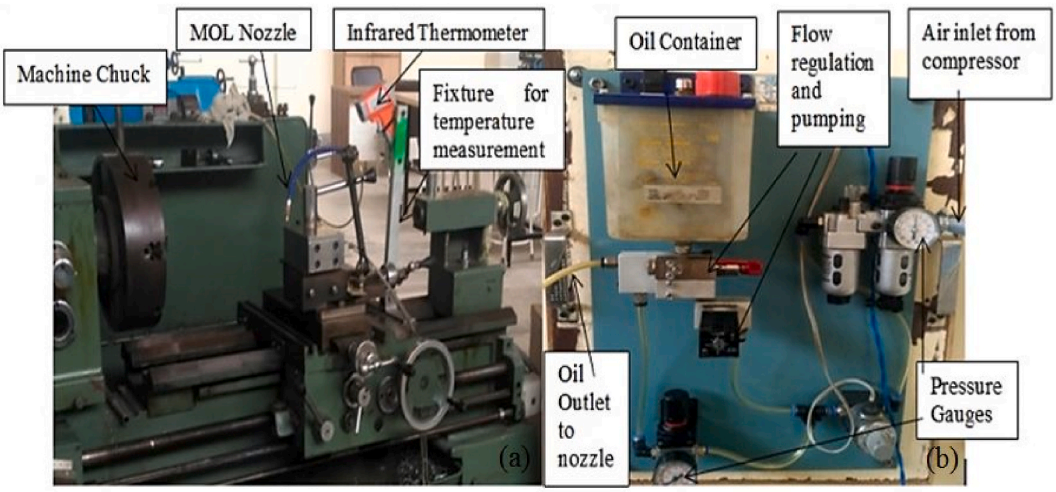

Fig. 2. (a) Picture of experimental setup; (b) MQL Set up.

temperature (t) and energy consumption (Ec) were recorded with suitable accuracy. Finally, the scanning electron microscopy (SEM) of cutting edges was performed to check the cause and mechanism of tool wear.

Post experimentation, the accuracy of observations was confirmed through various types of statistical plots. In addition, to illustrate the influence of input parameters on output responses the interaction plots were drawn. Further, the sustainability assessment was evaluated using TOPSIS approach considering output responses (Fc, S.R, t, and Ec) and sustainability indicators like carbon emission (Ce), waste management (Wf) and operational health safety (OHS) criteria. The carbon emission was calculated on the basis of cutting energy consumption formula mentioned in Eqs. (1)–(5), while the Wf and OHS were determined qualitatively based upon previous research data [52,53]. Additionally, the sustainability index was evaluated in two separate criteria like equal and assigned weightage system. The weightage of all output response has been calculated using AHP technique. Finally the performance rank (Pi) evaluated through TOPSIS approach to confirm the sustainable machining conditions. The work methodology is illustrated in Fig. 1 and the pictorial views of experimental utilities are depicted in Figs. 2 and 3.

The chemical and mechanical features of material have been expressed in Tables 1 and 2. The input parameters like depth of cut (doc), air pressure, oil flow rate and nozzle stand-off distance have been kept constant through the investigations and their values are listed in Table 3. The MQL setup has been shown in Fig. 2b along with all accessories and nozzle in Fig. 3a.

The levels of input variables have been scrutinized after preliminary tests, expert viewpoint and tool manufacturer guidelines.

2.2. Measurement of cutting temperature and surface roughness

The output parameters like temperature, surface roughness (S.R) and cutting forces remarkably impact the machining performance in metal cutting. In present investigations, the Cutting temperature was measured through digital infrared thermometer mounted on the specially fabricated fixture keeping uniform distance of instrument from the source of high temperature. The unique gap of thermometer laser was selected on the basis pilot experiments and manufacturer instructions. The device move parallel to the slide

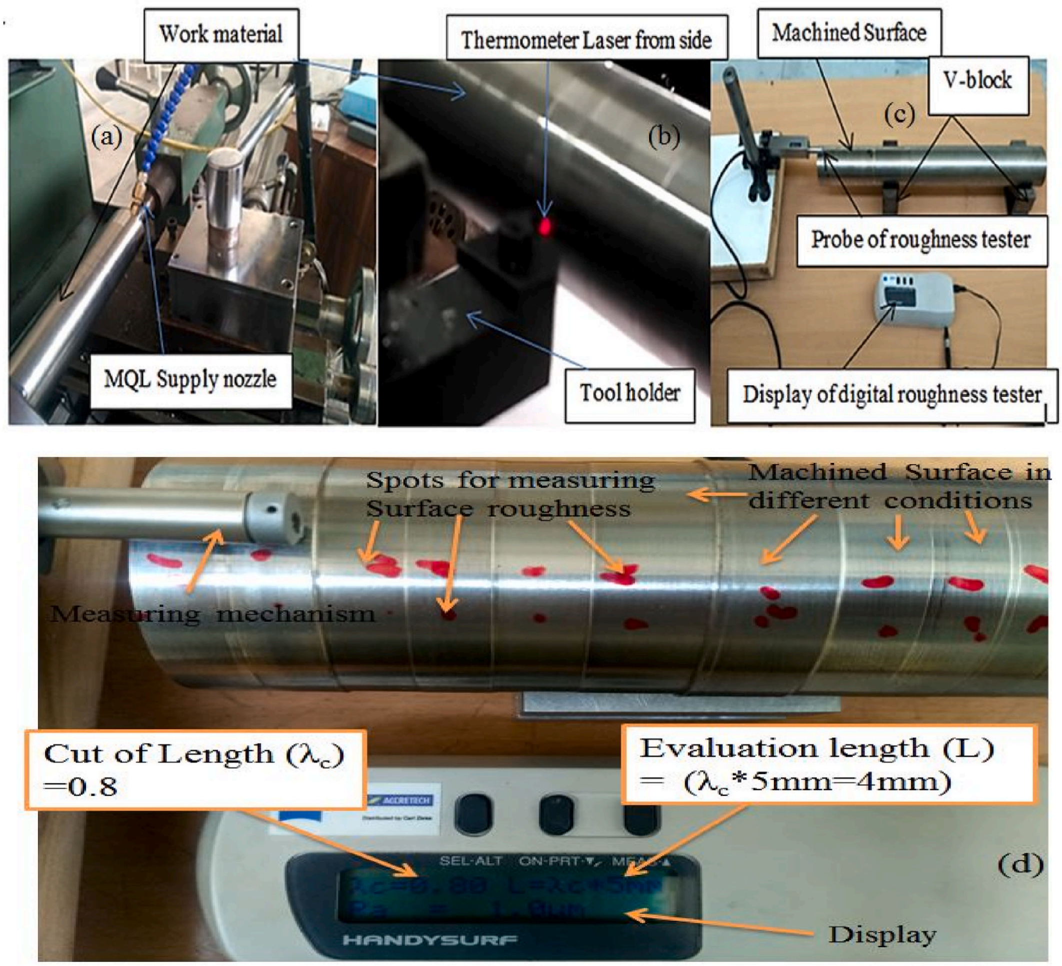

Fig. 3. (a) Picture of workpiece on Lathe with MQL nozzle; (b) Temperature measurement; (c) Evaluation of surface roughness; (d) Details of surface roughness measurement.

Table 1
Element details of work piece [55].

Element	C	Si	Mn	P	S	Ni	Cr	Mo	V	W	Co	Fe
Wt%	0.08	0.03	0.4	0.01	0.01	57.9	15.4	16	0.05	3.7	0.3	5.5

Table 2
Mechanical properties of Hastelloy C-276 [70].

Property	Hardness	Elongation	Tensile Strength	Yield Strength
Value	161HBW	68%	106 KSI	47.9 KSI

Table 3
Experimental data.

S.No	Item	Description
1	Machine details	Centre Lathe (AFM TUG-40, Poland) 5.5 kW
2	Work specimen	Hastelloy C-276, φ 0.056 m and length 0.550 m
3	Cutting tool	CNMG120408 uncoated
4	Tool holder	MCNLNR 2525M12
5	Tool designation	-6°, -6°, 6°, 6°, 95°, 95°, 0.8 mm
6	Machining speed (v)	88, 125 and 175 (m/min)
7	Feed rate (f) (mm/rev) and doc(mm)	0.06, 0.112, 0.246 mm/rev and 0.8 mm
8	Cooling environment (C.E)	Dry, flood and MQL, MQL supply: Air pressure 5 bar, 90 ml/h, Flood supply: 5 L/min
9	Compressor and spray distance	Ingersoll Rand and 35 mm
10	Roughness Tester	HANDYSURF E-35B, TOKYO SEIMITSU
11	Digital Infrared Thermometer	MTQ580 and HTC MT4 (-50 to 1200 °C)
12	Dynamometer	IEICOS, Model -MDHS, Bangalore

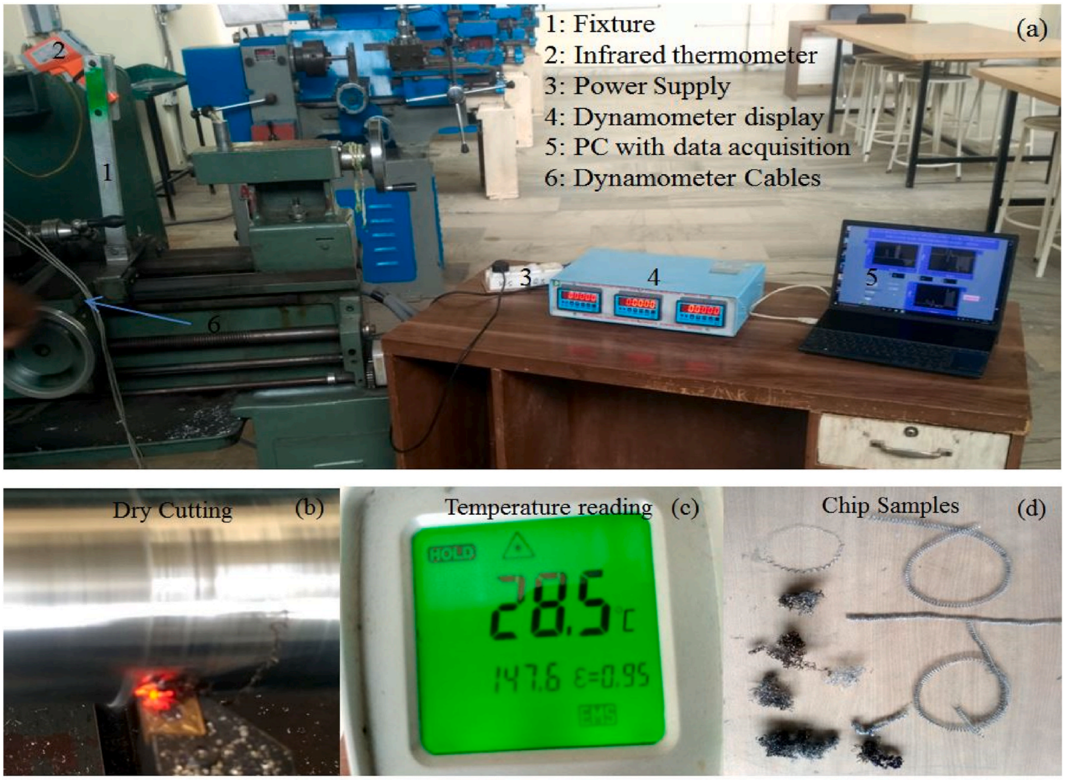

Fig. 4. (a) Measurement of cutting forces; (b) dry machining; (c) Temperature indicator; (d) Chip samples.

shown in (Fig. 2a) and provide the reading of temperature on the screen.

The instruments display the reading when dual spot converges to single point as visible in Fig. 3(b). To maintain the accuracy of reading the infrared thermometer is calibrated with thermometer at different temperature and time. The surface roughness was measured with digital surface roughness tester as shown in Fig. 3(c, d). The cut of length was set at 0.8 mm, while the evaluation length was kept 4mm as visible in Fig. 3(d).

2.3. Measurement of cutting forces

The forces were measured using IEICOS 3-components force dynamometer equipped with digital display and computerized database as illustrated Fig. 4 (a). The visualization of dry environment, observation of temperature and chip samples has been represented in Fig. 4 (b, c, d). The readings of forces were recorded in computer at intervals of 10–15 s and length of work piece for each experiment was set at 15 mm. The maximum reading is used for comparison purpose.

The details of input variable along with output measuring instruments have been mentioned in Table 3. Taguchi L-9 technique has been used as design of experiment leading to total 27 trials considering three different cooling environments (CE).

3. Results and discussion

The investigations outcomes obtained during machining Hastelloy C-276 in all trials have been illustrated in Table 4. To ensure the accuracy of results, readings have been taken three times and the mean value has been taken for analysis purposes. The experimental results have represented in two different sections like analysis of machining performance and sustainability assessment. The output observations of cutting forces, surface roughness, temperature and energy consumption has been listed in Table 4 along with carbon emission (C_e), waste management (W_f) and occupational health safety (OHS) terms.

Further, to examine the influence of input variables on output parameters the graphs have been plotted. Moreover, the ANOVA analysis has been performed to evaluate the influence and percentage contribution. In addition the scrutiny of sustainable machining combination has been performed in MS Excel implementing TOPSIS approach. Post analysis, the performance index (Pi) of each experimental set has been evaluated and trial with higher rank (R) is recommended as sustainable machining conditions [53–55].

3.1. Analysis of machining performance

In this section, the machining output responses mentioned in Table 4 have been taken into consideration and the influence of input variables have been demonstrated along with the percentage contribution evaluated by ANOVA analysis performed using MINITAB-17.

Table 4
Details of input parameter and Output responses.

Input variables				Output responses					Sustainability terms		
Exp No.	v (m/min)<	f (mm/rev)<	C.E	F_c (N)	S.R (μm)	t (°C)	E_c (W)	E_c (KJ)	C_e (Kg-CO_2)<	W_f	OHS
1	88	0.06	Dry	893	2.31	185	1309	14.55	6.15	1	1
2	88	0.112	Dry	922	2.45	195	1352	8.05	3.40	1	1
3	88	0.246	Dry	1315	2.51	209	1928	5.22	2.21	1	1
4	125	0.06	Dry	884	2.14	217	1696	13.27	5.61	1	1
5	125	0.112	Dry	1020	2.26	238	2126	8.91	3.77	1	1
6	125	0.246	Dry	1236	2.35	261	2575	4.91	2.08	1	1
7	175	0.06	Dry	870	1.59	306	2517	13.98	5.91	1	1
8	175	0.112	Dry	903	1.67	314	2632	7.83	3.31	1	1
9	175	0.246	Dry	1099	1.84	353	3205	4.34	1.84	1	1
10	88	0.06	Flood	834	1.47	136	1223	13.59	5.75	3	3
11	88	0.112	Flood	873	1.59	149	1281	7.62	3.22	3	3
12	88	0.246	Flood	1030	1.61	168	1511	4.09	1.73	3	3
13	125	0.06	Flood	785	1.63	182	1635	12.79	5.91	3	3
14	125	0.112	Flood	868	1.69	193	1717	7.20	3.04	3	3
15	125	0.246	Flood	942	1.73	234	1962	3.74	1.58	3	3
16	175	0.06	Flood	795	0.95	221	2318	12.88	5.44	3	3
17	175	0.112	Flood	834	1.24	251	2432	7.24	3.06	3	3
18	175	0.246	Flood	922	1.54	278	2690	3.64	1.54	3	3
19	88	0.06	MQL	785	1.42	132	1151	12.79	5.41	2	2
20	88	0.112	MQL	858	1.49	158	1223	7.28	3.08	2	2
21	88	0.246	MQL	1001	1.58	189	1468	3.98	1.68	2	2
22	125	0.06	MQL	736	1.35	154	1533	12.00	5.07	2	2
23	125	0.112	MQL	775	1.46	168	1615	6.77	2.86	2	2
24	125	0.246	MQL	893	1.32	193	1860	3.55	1.50	2	2
25	175	0.06	MQL	706	0.91	213	2060	11.45	4.84	2	2
26	175	0.112	MQL	765	1.18	241	2232	6.64	2.81	2	2
27	175	0.246	MQL	834	1.32	269	2432	3.30	1.39	2	2

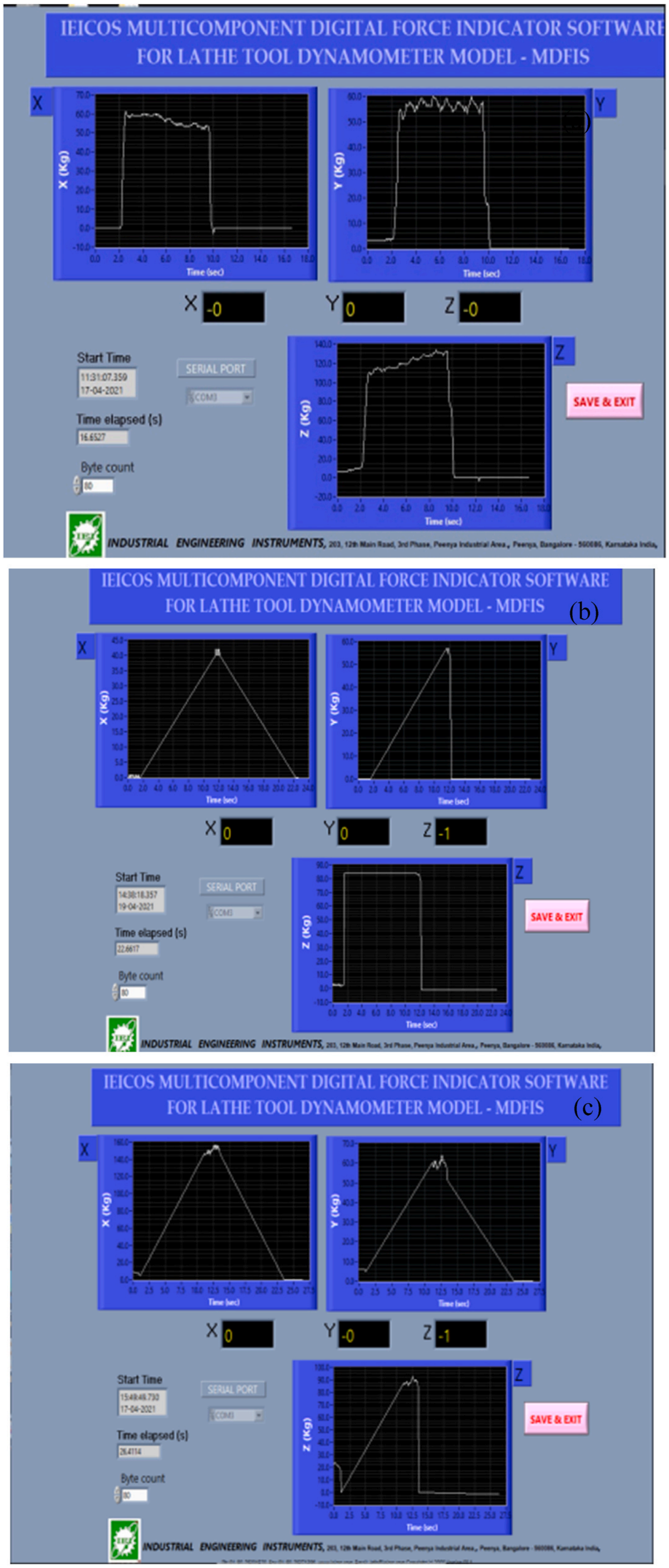

Fig. 5. Screenshots of measuring cutting forces: (a) Dry machining; (b) Flood cooling; (c) MQL.

3.1.1. Analysis of main cutting force

During metal cutting operation various types of cutting forces are generated at different sections and it is very important to measure these forces to evaluate the power consumption and machining performance [56–58]. In present investigation 3-Components force dynamometer was used to measure the forces in x, y and z, indicating feed forces, radial force and tangential force. For analysis purpose, only main cutting force (F_z) has been taken into consideration represented by z direction. The screenshots of measuring the cutting forces in different environments have been shown in Fig. 5 indicates that the cutting forces rises sharply during dry cutting shown in Fig. 5(a) due to involvement of higher friction causing interlocking of the surface and resistance to shearing in Primary deformation zone.

But on the other hand, there is some rising slope during flood cutting and MQL machining as visible in Fig. 5 (b, c). It will generate fewer loads on the cutting tool due to reduction in friction caused by cooling and lubrication action of lubricant. Thus, reduce the cutting forces and power consumption as compared to dry conditions [59–61]. As the feed rate increases, more chip load on the tool and larger area of cutting produces higher cutting forces [62–64].

From ANOVA results shown in Table 5, it has been depicted that main cutting force is significantly impacted by feed rate (44.88%), cooling environment (35.92%) and cutting speed 6.52% at designed parameters levels. The influence of input parameter on cutting force is represented in Fig. 6 (a) indicates that higher cutting force was recorded in dry cutting trailed by flood cooling and lowest in MQL system. Further, the cutting forces reduces with surge in cutting speed causing softening of work specimen ahead of tool at higher temperature and therefore, require less forces to cut the material [65–67]. The similar observations have been mentioned by researchers [53,54]. While on the other hand, increment in feed rate raises the magnitude of forces due to engagement of larger machining area on tool tip, extensive ploughing effect at nose radius, more friction and higher material removal rate. The same is also reflecting in the percentage contribution of feed rate (44.8%) evaluated from ANOVA analysis. Results confirmed that dry cutting has 12–24% higher cutting forces than MQL machining and these observations are mapping with author [54–69].

The main reason for increment in cutting force during dry cutting is due to higher friction, more temperature, rapid tool wear and absence of coolant & lubricant. The cause of heat generation at different zones of cutting is mentioned in Fig. 8. Whereas, appreciable lubrication action of MQL provide suitable cushion effect, reduced friction and lower tool wear leads to less cutting forces in MQL.

As per Statistics importance, the p value less than 0.05 is required for the term to be significant and the entities having magnitude less than 0.05 are significant to impact the machining performance. Also, the predicted and adjusted R^2 should be close to 0.8.

3.1.2. Analysis of surface roughness

The output response in the form of surface finish has significant influence on the machinability index of any material. As depicted in Fig. 6 (b), S.R reduces as the speed rises and contrary to this, it increases on enlarging the feed rate. This has happened because increment in cutting speed leads to higher friction and more heat generation that softens the material due to work hardening and causing reduction in cutting forces and surface roughness [67–69]. Further, at low speed, there are more chances of chip/material adhesion that causes low surface quality due to activation of sticking zone. However, increments of feed led to higher friction, vibration and more MRR which raises the irregularities on the work surface and hence, lower the S.R. On the other hand, lower S.R during MQL system has been attributed due to the cooling action of air jet mixed with the vegetable based lubricant supplied at tool chip interaction area as depicted in Fig. 7. The mechanism may be due to capillary action of atomized liquid droplet that travel to cutting zone and provide the cooling and lubrication action and hence improved the surface roughness by 28–36% as compared to dry cutting conditions. In addition to this, ANOVA results expressed in Table 6 signifies that S.R is majorly dominated by cutting speed (23.90%), cooling environment (64.22%) and feed rate (4%) respectively.

3.1.3. Analysis on cutting temperature

The cutting temperature measures the amount of heat generation in different sections of metal cutting and hence the computation of this response is necessary to check its influence on machining performance. From Fig. 7(a), it has been revealed that higher cutting temperature was reported during dry machining due to higher friction at tool-work, tool interaction, and deformation at various sections of metal cutting as shown in Figs. 7 and 8. The absence of cooling and lubrication media is also the main reason of elevated temperature. However, comparatively low temperature was recorded in flood and MQL conditions due to the reasons mentioned in Fig. 9. Further, the rise in cutting speed and feed rate has surged the temperature due to involvement of more friction, higher cutting area and rapid tool erosion [70–72].

The ANOVA analysis depicted in Table 7 indicates that the cutting speed has major contribution (59.85%) on heat formation followed by cooling environment (24.44%) and then feed rate (11.45%). Further, the predicted and adjusted values of R^2 are very close

Table 5
ANOVA details of Cutting Forces.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	34089	6.52%	34089	17044	5.15	0.016
Feed rate	2	234492	44.88%	234492	117246	35.42	0.000
C.E	2	187648	35.92%	187648	93824	28.34	0.000
Error	20	66206	12.67%	66206	3310	-	-
Total	26	522435	100%	-	-	-	-
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	57.535	87.33%	83.53%	120661	76.90%		

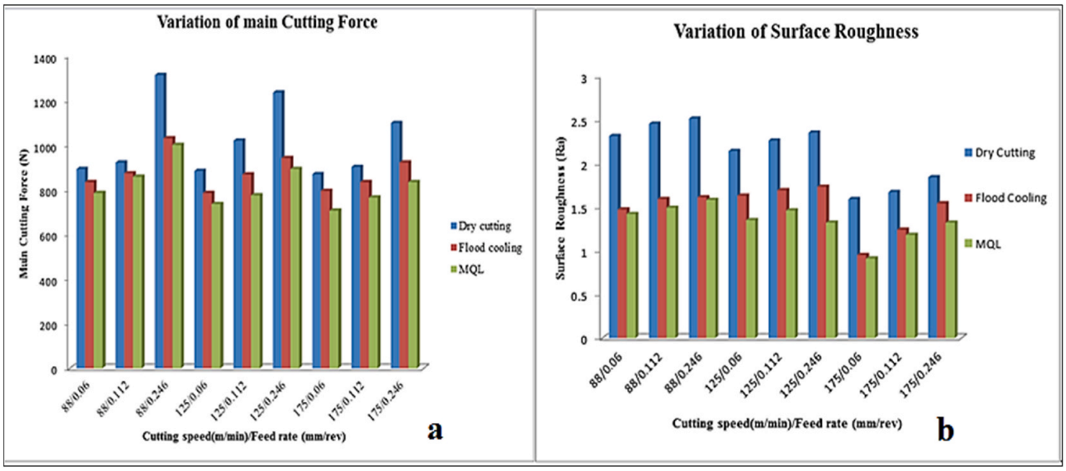

Fig. 6. (a) Influence of parameters on cutting forces; (b) Surface roughness.

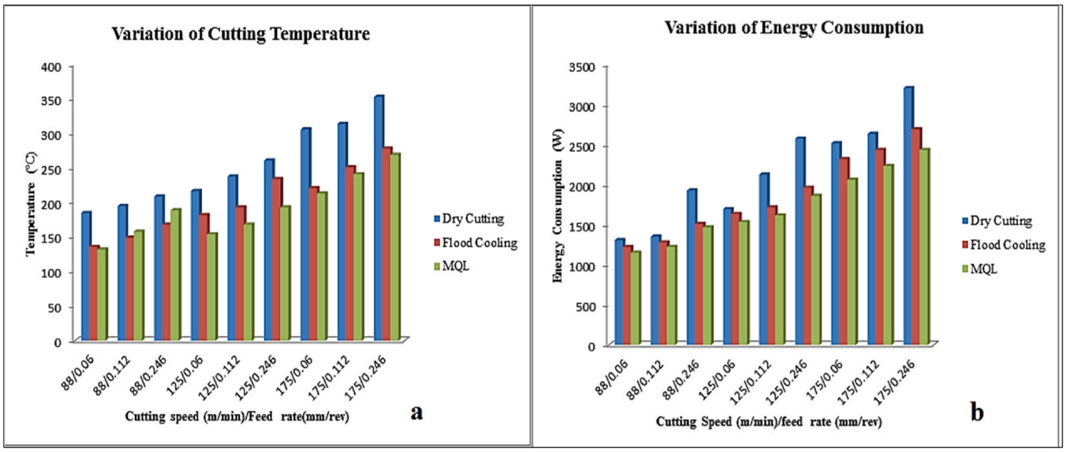

Fig. 7. (a) Influence of parameters on cutting temperature; (b) Energy consumption.

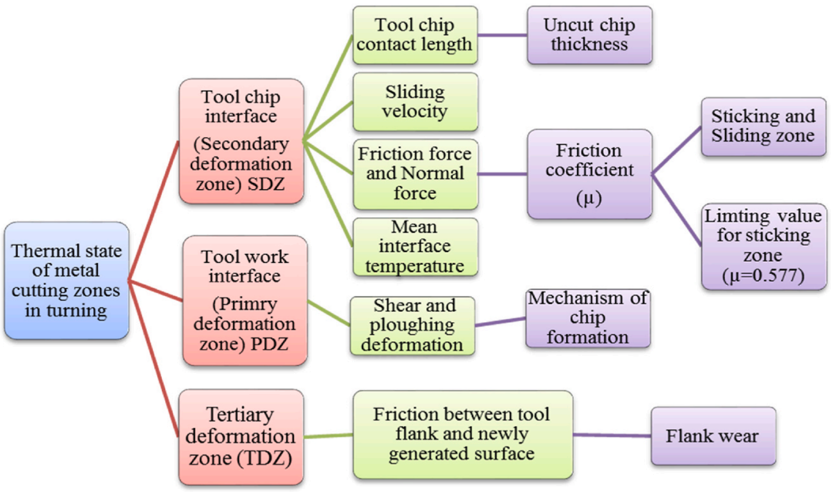

Fig. 8. Overview of heat generation in different zones of turning operation.

Table 6
ANOVA details of Surface Roughness.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	1.1638	23.90%	1.1638	0.58189	33.73	0.000
Feed rate	2	0.2334	4.79%	0.2334	0.11669	6.76	0.000
C.E	2	3.1272	64.22%	3.1272	1.56358	90.62	0.000
Error	20	0.3451	7.09%	0.3451	0.01725	–	–
Total	26	4.8694	100%	–	–	–	–
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	0.1313	92.91%	90.79%	0.6288	87.08%		

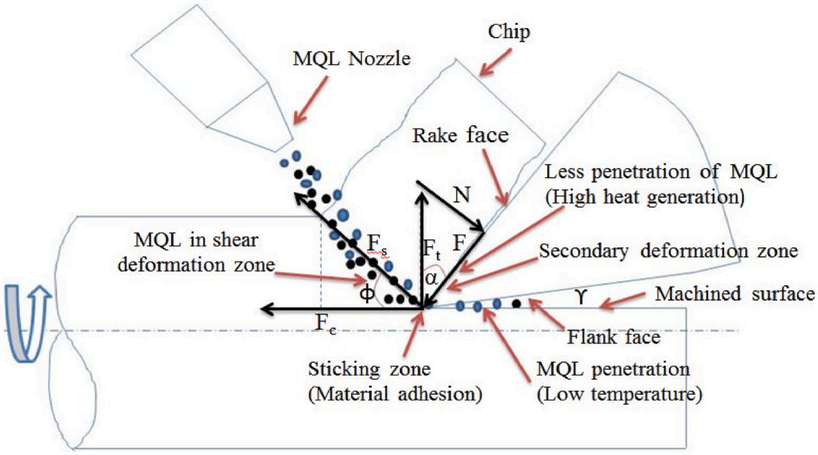

Fig. 9. Mechanics of metal cutting and mechanism of minimum quantity lubrication (MQL).

Table 7
ANOVA details of Temperature.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	49060	59.85%	49060	24530	140.28	0.000
Feed rate	2	9385	11.45%	9385	4692.5	26.83	0.000
C.E	2	20033	24.44%	20033	10016.7	57.28	0.000
Error	20	3497	4.27%	3497	174.9	-	-
Total	26	81976	100%	-	-	-	-
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	13.223	95.73%	94.45%	6374.0	92.02%		

to each other that signify the validity of experimental and predicted observations. These results indicate that MQL has significant contribution and has minimized the heat generation by margin of 9–30% compared to dry machining and the same has been depicted in Fig. 7(a).

From experimental observations (Fig. 7a), it has been revealed that less temperature difference has been observed among flood cooling and MQL machining due to noteworthy cooling and lubrication effect of tiny atomized droplet discharged from MQL nozzle. The vegetable oil provides the boundary lubrication along with this the aerosol action of fluid droplet absorb the heat significantly and hence minimize the heat generation as depicted in Fig. 10.

3.1.4. Analysis of energy consumption

As the world population is increasing and the requirement of energy consumption is also going to become many folds as compared to present scenario. In Indian context the major sources of energy are fossil fuels and if other alternatives are not investigated, then it would leads to major crisis. Further, the manufacturing sector is consuming almost sixty per cent of industrial energy which is further 30% of total energy consumption [9,52,54]. Hence, the energy burden should be minimized to meet the demands of future along with the achievement of sustainable manufacturing targets. In addition to this, energy consumption also impacts the production cost, carbon emission and natural energy resources. Thus, determination of this parameter is of upmost importance for generating the database for turning strenuous materials. Also, it impacts the degradation of natural resources, human health and environment. As per the sustainable manufacturing goal, the developing countries are focusing on the target of zero emission by 2030 [15]. So, it is important to determine the energy consumption, carbon emission and wastage disposal cost to achieve the targets of sustainable

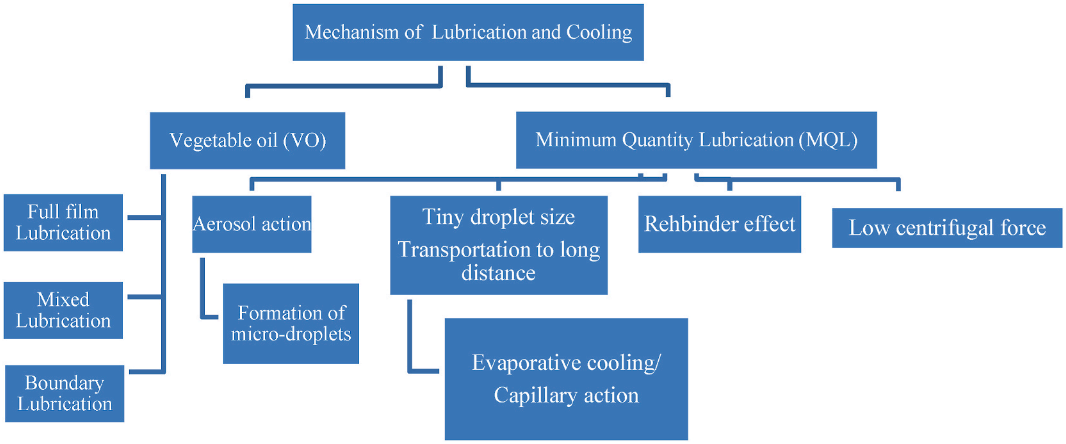

Fig. 10. Mechanism of Lubrication in Vegetable oil and MQL [15,55].

development goals. In present investigation the energy consumption was evaluated based upon computation of main cutting force. As depicted in Fig. 7(b), higher energy consumption was reported in dry cutting due to higher cutting forces and more load on the prime mover which give rise to numbers of pulses in energy meter and thus large expenditure of power. Moreover, increment in cutting speed yields to larger energy expenditure as compared to feed rate. It is because on accelerating the feed rate, less time is required to machine the work material despite of larger machining load on tool chip area [73–75]. Fig. 7(b) illustrated the role of speed and feed on power consumption which indicates that speed has more influence on power expenditure as compared to feed rate.

3.1.5. *Mechanism of heat generation and cooling action*

As represented in Fig. 8, heat is generated at different zones (PDZ, SDZ and TDZ) of metal cutting due to friction at tool-work and tool-chip interaction, which influence the cutting forces, surface quality, power consumption and tool wear. So, to minimize the impact of friction the cutting fluids are applied that reduces the rubbing at different section and decreases the forces, roughness, temperature and power consumption. The higher heat formation at secondary deformation zone is due to chip sliding on the rake face of tool and prior to sliding zone sticking zone appear that leads to generation of material adhesion and causing lower surface quality, crater wear and higher cutting forces [76–78].

The application of atomized MQL droplet as shown in Figs. 9 and 10 travel to primary and secondary deformation section by capillary action and thus produces the cooling and lubrication effect causing reduction in friction, temperature and the phenomenon of material adhesion leading to improvement in machining performance [79–81].

As already illustrated in Fig. 8, that heat is primarily generated due to shear deformation, ploughing effect and tool-chip interface at primary and secondary deformation zone. The maximum amount of generated heat is carried away by the chip which slides on the tool rake face and thus erodes its surface causing crater wear, vibration, higher cutting forces, impaired surface quality and more power consumption [82,83]. Whereas, near to the nose of cutting tool, sticking zone appear that causes the material adhesion and wear of nose. In addition, the friction between newly generated surface and flank part of tool causes the wear of flank portion and influence the surface quality. Therefore, it is necessary to apply the efficient cooling and lubrication medium to reduce the friction at various zones for improvement in machining performance possible due to mechanism of lubrication mentioned in Fig. 10.

3.2. *Influence of input parameter on output responses*

In order to verify the results expressed in Figs. 6 and 7, the interaction plots between output responses and input variables like cutting speed, feed rate and cooling environments (CE) have been expressed in Figs. 11 and 12**.** The influence of all factors can be clearly visible on these types of plots. The interaction plot 11 (a) demonstrates that cutting force rises on increasing the feed rate, while it reduces with change in speed and cooling conditions. The reason for the same is already mentioned that elevating the feed rate increases the chip load on the tool area, larger area of cutting and more MRR causes increment in main cutting force w.r.t feed rate.

Higher cutting force has been observed at 0.246 mm/rev represented by green colour with steeping down line. On the other hand cutting force reduces with rise initially from 88 m/min to 125 m/min and then reduces till 175 m/min. It is due to work hardening of material because post this phenomenon the material reaches to plastic flow and hence reduction in cutting forces. In addition the higher cutting in dry cutting is due to non-availability of cooling and lubrication. Similarly, Fig. 11(b) reported that S.R has declining trend with rise in speed and increasing slope with higher feed rate. Also, S.R is huge in dry condition and minimum during MQL environment. The cause of higher surface roughness with rise in feed rate is due to higher intensity of feed marks on machined surface, vibration and more area of cutting [84,85]. Whereas, S.R reduces with rise in speed because lofty velocity of cutting produce higher temperature because of higher friction that tends to cause work hardening and plastic flow of material. Thus, lower the cutting forces and consequently enhance the surface roughness. On the other side, with application of flood cooling and MQL, the SR improved due to lubrication action of vegetable oil as mentioned in Fig. 10.

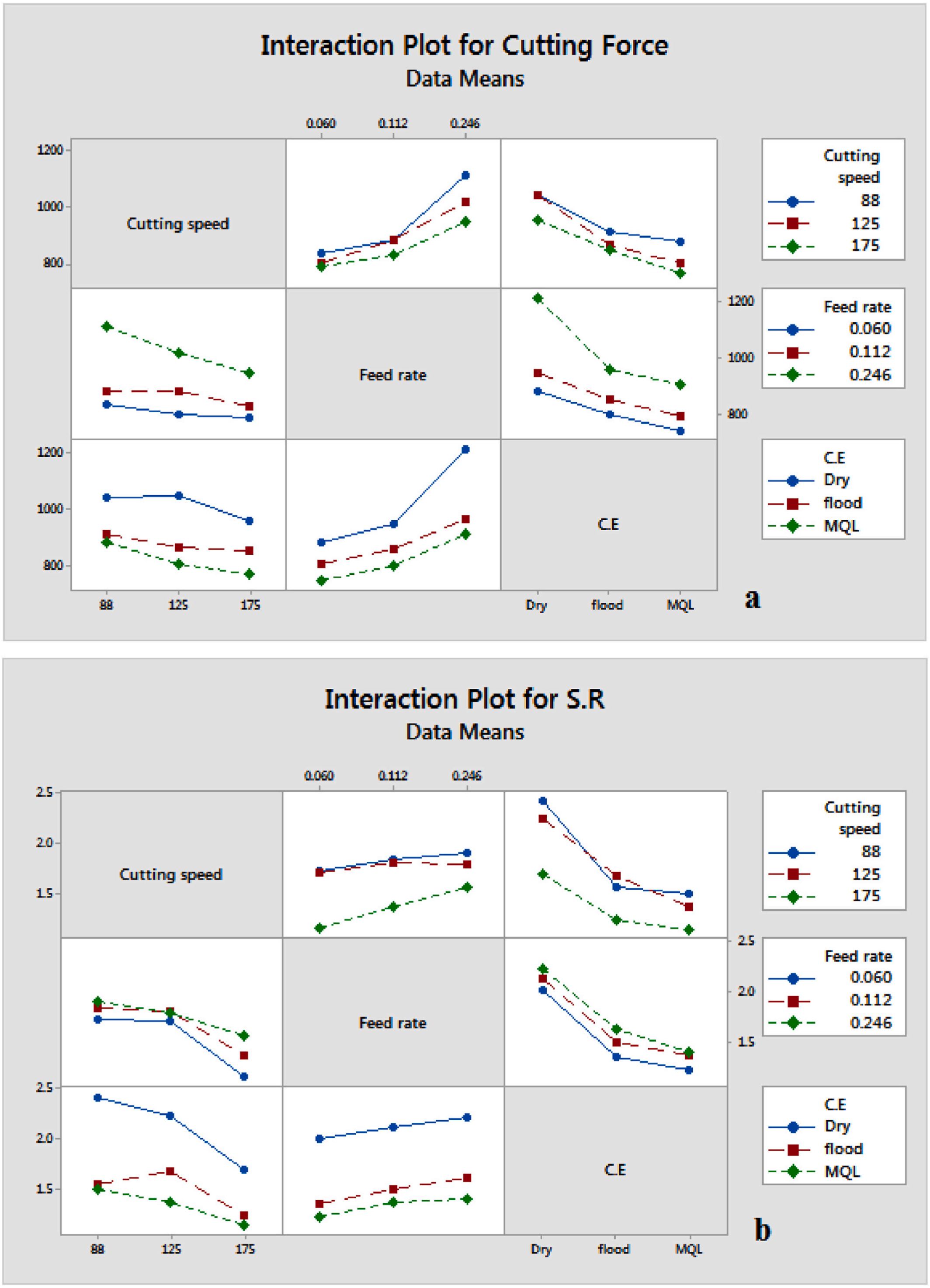

Fig. 11. (a) Interaction plot between input variable and cutting force; (b) Interaction plot for SR.

In addition to this, temperature becomes higher on inflation of cutting speed and feed rate, while it is little in MQL as compared to dry and flood cooling as visible in Fig. 12(a). Moreover, Fig. 12(b) illustrates that the energy consumption (W) becomes higher with increment in speed as well feed rate. Contrary to this, it reduces during change in cooling condition from dry to MQL. As explained earlier that temperature rises with speed and feed rate due to increment in friction, higher area of machining and more loads on the tool tip. Also, the reason for temperature generation in different zones of metal cutting and its impact on different element is explained in

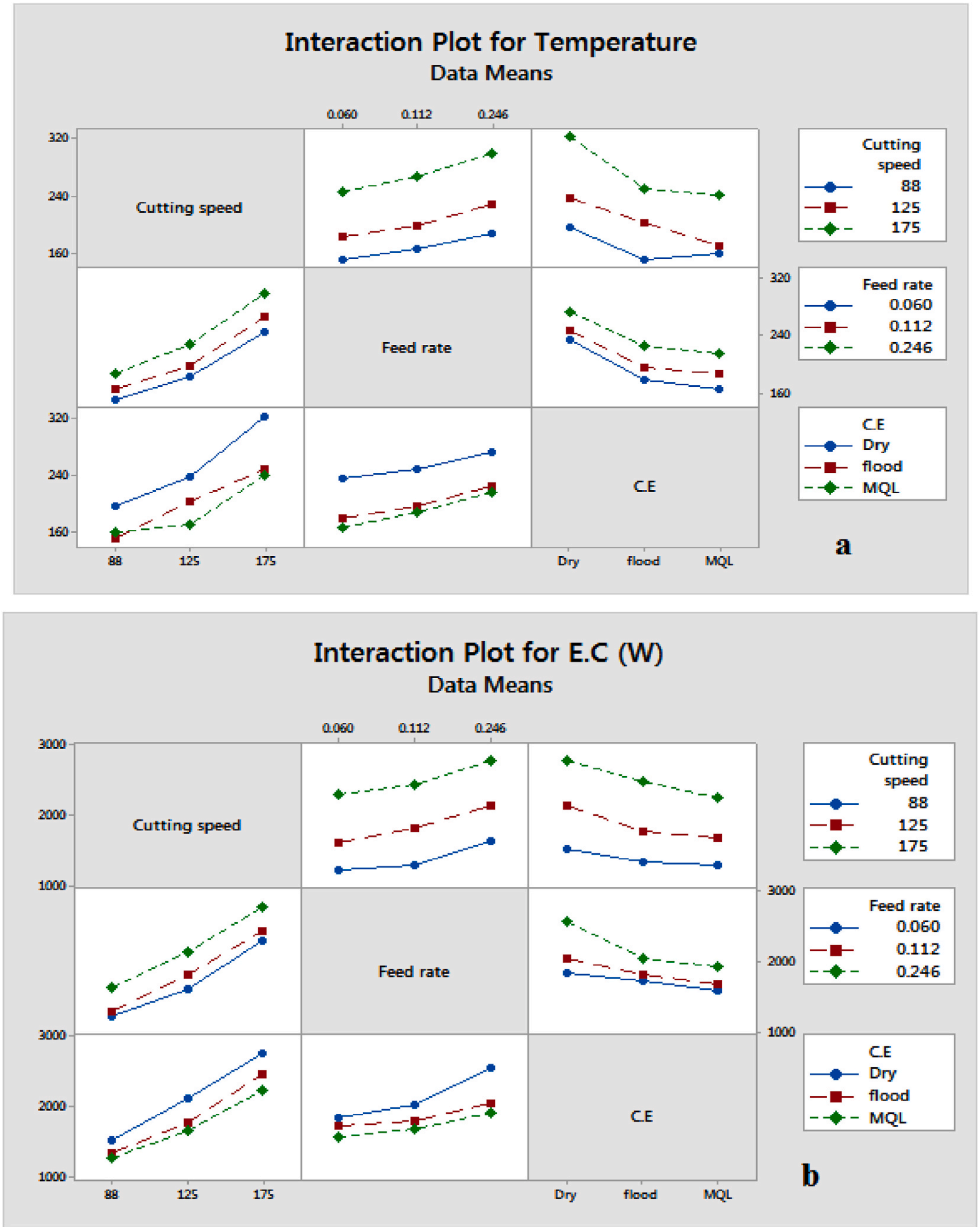

Fig. 12. (a) Interaction plot between input variable and temperature; (b) Interaction plot for energy consumption.

Fig. 8. Further, the energy consumption is directly proportion to cutting speed, so it rises with speed and feed rate accordingly [81–83]. However, these responses declined with the use of MQL significantly because of efficient cooling and lubrication as per the reason explained in Fig. 9 and 10.

3.3. Statistical analysis of experimental results

To review the accuracy of obtained result, statistical analysis has been carried out using MINITAB software. The residual plots have been drawn for all output responses as shown in Fig. 13 (a-d). The normal probability plots for all output responses indicate that the spread of residual is lying near to straight which ensure the valid outcomes considering 95% confidence limit. Further, the residual vs. fitted values are scattered within uniform distance from the zero line. Also, the frequency of observation vs. residual plot indicates the

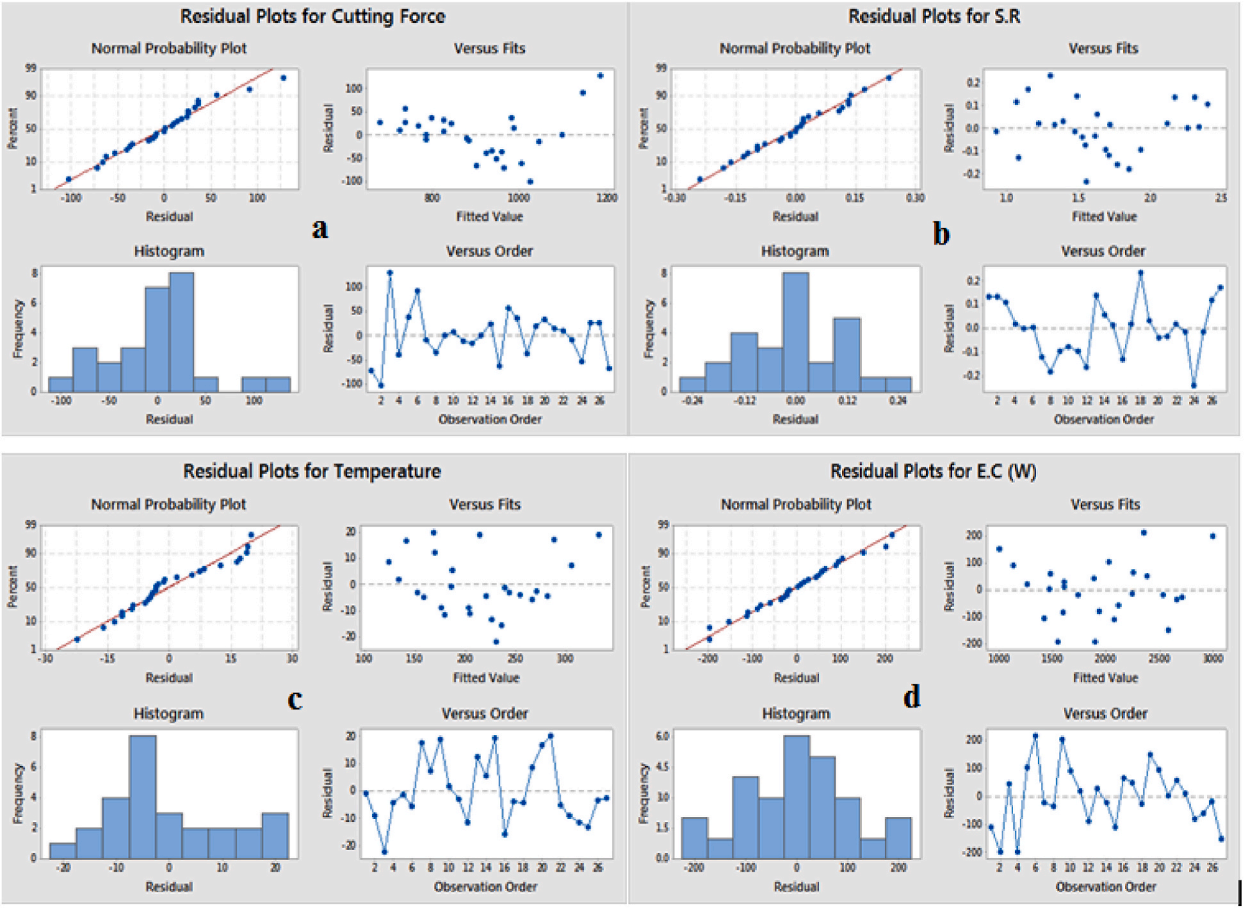

Fig. 13. Residual plot for output responses.

precision of reading obtained from experimental results. As out of nine observations in each condition there is at least repeatability of two observations shown by rectangular bar graphs. In addition to this, the observation order vs. frequency also falls within uniform range signifies the validity of results obtained. Moreover, the ANOVA analysis shown in Table 8 confirmed that power consumption (W) is dominant by speed (72.46%), feed rate (13.25%) and cooling environment (10.50%) respectively.

The implementation of vegetable oil MQL has reduced the energy expenditure by a margin of 9–27% than dry condition owing to lower intensity of cutting forces, temperature and tool damage. Which further leads to reduction in carbon emission and hence adhere to implement the sustainable development goal (SDG-12). From all the results depicted in Fig. 13 (a-d) illustrates that the experimental observation are significant and valid.

3.4. Sustainability analysis of machining parameters

As the developed nations has imposed strict regulation regarding the use of non-biodegradable fluids due to plenty of negative effects during flood cooling. Therefore, alternative lies on MQL and other cooling techniques as an approach to sustainable machining. Also, sustainability assessment of difficult to cut materials under dry, flood and MQL conditions considering different indicators

Table 8
ANOVA details of Energy Consumption (W).

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	5678967	72.46%	5678967	2839484	191.27	0.000
Feed rate	2	1038459	13.25%	1038459	519229	34.98	0.000
C.E	2	822993	10.50%	822993	411497	27.72	0.000
Error	20	296905	3.79%	296905	14845	-	-
Total	26	7837324	100%	-	-	-	-
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	121.84	96.21%	95.08%	541109	93.10%		

(economic, environmental and social) provides an information to select the process for sustainable machining approach. Hence, in present investigation the different pillars of sustainability have been undertaken. The economic indicator comprises of cutting forces, surface roughness, temperature and energy consumption, whereas, carbon emission, wastage disposal (W_f) and occupational health & safety (OHS) have been opted as ecological cum environmental factors [53]. The impact of mentioned indicators has been evaluated in three conditions like dry, flood and MQL.

Sustainability analysis of economic factors have been determined quantitatively, while the terms W_f and OHS have been evaluated qualitatively with low, medium and high impact on sustainability. Further, the energy consumption has been evaluated in two different units like Watt and kJ using fundamental of metal cutting utilizing Eqs. (1) and (2). Computation of energy consumption in two different form has been done to explore the impact of machining time (t_m) on the energy consumption (E_c) and carbon emission (C_e), because increasing feed rate reduces machining time and vice versa. However, practically energy consumption increases on raising the feed rate due to increases in prime mover load, friction, ploughing effect and cutting temperature. So, to nullify this concept the constant machining time should be assumed in future study. However, in present investigation the energy consumption in (KJ) has been considered for analysis of carbon emission (C_e) using Excel computation with value of Eq. (5). Further, machining time and MRR has been evaluated with the help of Eqs. (3) and (4).

$$E_c(W) = F_c * v \tag{1}$$

$$E_c(kJ) = F_c * v * t_m \tag{2}$$

$$t_m = {}^{l}\!/_{f * N} \tag{3}$$

$$MRR\left(\frac{mm^3}{sec}\right) = \frac{v * f * d * 1000}{60} \tag{4}$$

$$C_e = E_c * 0.4288 \tag{5}$$

Fig. 14(a) depicts that energy consumption (KJ) reduces on increasing the feed rate because of reduction in machining time at particular level of cutting speed. The higher power expenditure has been reported in dry machining, followed by flood cooling and then after MQL system [84,85]. It is because of change in cutting forces during different machining condition as represented in Fig. 5(a). The same has happened due to reduction in cutting forces, hot softening of material ahead of tool and consequently energy consumption has reduced. As far as the evaluation of carbon emission has been concerned, it is reminded that it is directly proportional to energy consumption and hence, the trends similar to energy consumption have been observed and demonstrated in Fig. 14(b).

The Carbon emission has been determined using Eq. (5) as per literature guidelines [52–54]. The maximum carbon emission has been discharged during first set of experiment as represented in dry machining and shown in Fig. 14(b). It is caused due to higher magnitude of cutting forces and energy consumption. Further, ANOVA analysis shown in Tables 9 and 10 indicated that energy consumption (kJ) and carbon emission have been mainly influenced by feed rate (96%) followed by minor contribution of speed and cooling environment.

In addition to this, similar trends have also been reported in carbon emission because it is directly proportional to energy consumption and feed rate has influenced it by 96.13%, whereas cooling environment 2.52% only.

3.4.1. *Impact of MRR on energy consumption and carbon emission*

The MRR is the amount of material removed during machining operation at set parameter levels and based upon this the performance of process can be investigated. In present research, the energy consumption and carbon emission have evaluated. As

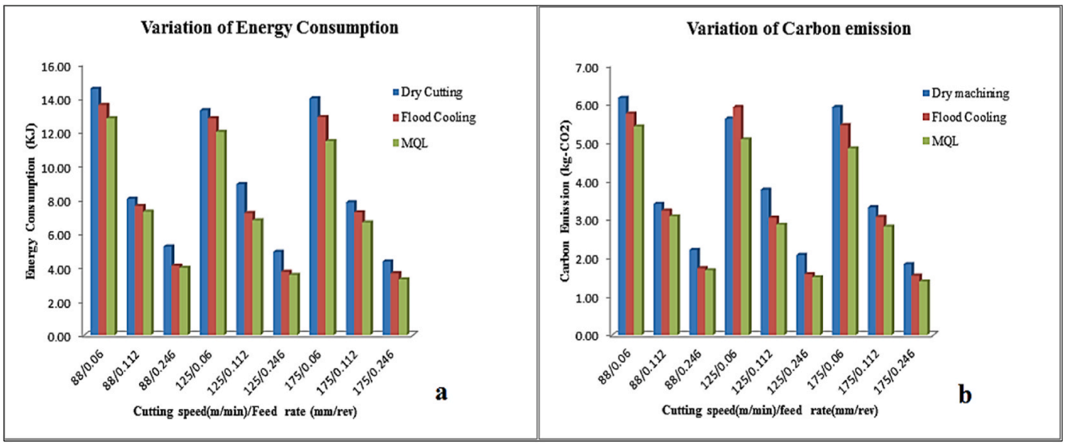

Fig. 14. (a) Influence of parameters on energy consumption; (b) Carbon emission.

Table 9
ANOVA details of Energy Consumption (kJ).

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	2.003	0.53%	2.003	1.002	8.31	0.000
Feed rate	2	366.960	96.22%	366.960	183.480	1522.0	0.000
C.E	2	10.022	2.63%	10.022	5.011	41.57	0.000
Error	20	2.411	0.63%	2.411	0.121	-	-
Total	26	381.396	100%	-	-	-	-
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	0.3471	99.37%	99.18%	4.39393	98.85%		

Table 10
ANOVA details of Carbon Emission.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	0.3445	0.49%	0.3445	0.1723	5.70	0.011
Feed rate	2	67.6290	96.13%	67.6290	33.8145	1118.36	0.000
C.E	2	1.7699	2.52%	1.7699	0.8849	29.27	0.000
Error	20	0.6047	0.86%	0.6047	0.0302	-	-
Total	26	70.3481	100%	-	-	-	-
Model Summary	**S**	**R^2**	**R^2(adj)**	**PRESS**	**R^2(pred)**		
	0.1738	99.14%	98.88%	1.10210	98.43%		

described in Fig. 15 (a, b), it has been revealed that the energy consumption reduces on increment in MRR, similarly the carbon emission changes according to variation in expenditure of energy.

The same results have been reported by author [53] and mentioned the effects of feed rate on the decrement of power consumption. From graphical expression Fig. 15 (a, b) it has been found that the maximum energy consumption at MRR of 70.4 mm^3/s having least speed-feed combination along with minimum expenditure of energy at 574 mm^3/s. Likewise, the maximum and least carbon emission have been reported at MRR of 70.4 mm^3/s and 574 mm^3/s. As far as different machining environments have been concerned, maximum power consumption and carbon emission have been reported during dry machining [85–87]. However, for calculation of energy consumption, the expenditure of recycling equipment along with other accessories of flood cooling and MQL system have not been included that will increases the overall cost in flood cooling. Hence, from experimental results it is worth to say that MQL machining has reduced the carbon emission by a margin of 9–24% compared to dry machining.

3.4.2. Evaluation of Overall Sustainability Index (Pi)

In this section, sustainability index of machining Hastelloy C-276 during different machining conditions has been discussed. The ranking of each machining environments has been calculated on the basis of output responses and sustainability indicators as mentioned in Table 5. For evaluation of Pi two different approaches have been applied i.e. equal weighted criteria and assigned weighted system. These two approaches have been adopted to extract out the sustainable machining condition with or without assigned value to quantitative terms (Cutting Force, Surface Roughness, Temperature, energy consumption, carbon emission) and qualitative parameters (W_f and OHS) of sustainability. During equal weightage system uniform importance has been given to all quantitative parameters. On the other hand, during assigned weightage system, the higher importance have been granted to

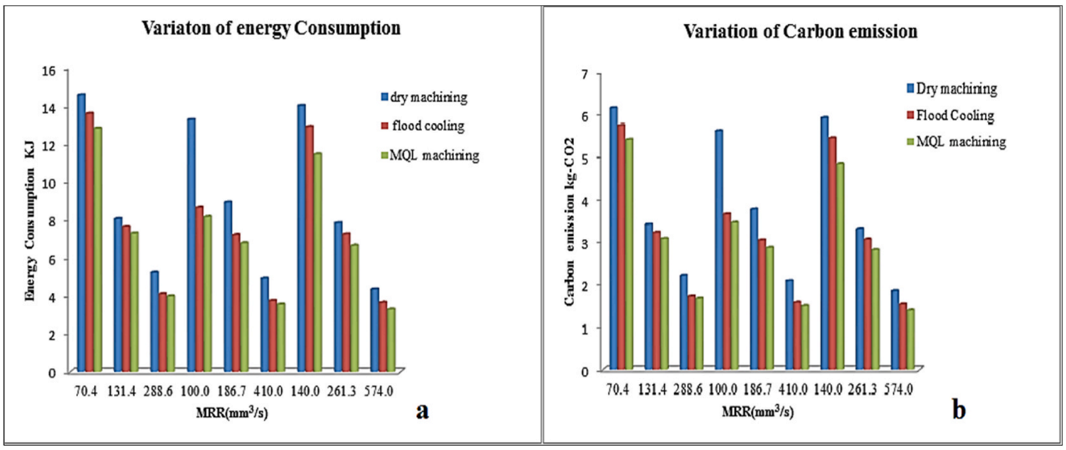

Fig. 15. (a) Influence of MRR on energy consumption; (b) Carbon emission.

sustainability indicators like energy consumption, carbon emission, W_f and OHS factors as mentioned in Table 11.

The weightage have been evaluated using standard procedure of Analytic Hierarchical process (AHP). The Pairwise matrix to calculate the weightage using AHP is mentioned in Table 11. The score of 1 has been assigned to equal importance, 3 for moderate, 5 for strong and 9 for extreme importance indicators. Further utilizing standard procedure of AHP, the weightage (W_j) for quantitative responses [F_c, S.R, Temp, E_c (W), E_c (kJ), C_e] and qualitative parameters [W_f and OHS] have been calculated as 0.0266, 0.0302, 0.0302, 0.1461, 0.1461, 0.2069, 0.2069 and 0.2069. These weightage indicates 2.66%, 3.02%, 3.02%, 14.61%, 14.61%, 20.69% and 20.69% importance of mentioned indicators to evaluate the sustainability. After calculation of weightage, the standard TOPSIS approach has been implemented to determine the sustainability index among different cooling conditions amid 27 experiments. The Solved pairwise matrix for the evaluation of weightage is given in Table 12. The formula to calculate the normalize matrix and other entities have been expressed below.Where, Sum for $F_c = (1 \times 1 \times 1 \times 0.20 \times 0.20 \times 0.11 \times 0.11 \times 0.11)^{1/8} = 0.293370579$ and so on for other parameters.

Further, the weightage of F_c is calculated as $(0.293370579) \div (11.01559332) = 0.0266$ and so on.

The step by step procedure of TOPSIS approach is mentioned below.

i. Formation of matrix (n × m) for input variables, output responses and sustainability indicators as given in Table 4.
ii. Creation of normalized matrix X_{ij}
iii. Weightage assignment to output response on the basis of its critical impact on sustainability, $V_{ij} = X_{ij} \times W_j$. The value of W_j is 1 during equal weightage criteria and the values evaluated by AHP are applicable during assigned weightage system.
iv. Evaluation of positive ideal (S+) and worst solution (S−).
v. Determination of 'Euclidean distance' based upon S+ and S− data for each set of machining.
vi. Calculation of Performance index (Pi) with reference to relative closeness to ideal positive solution.
vii. Computation of Rank (R) for all machining conditions based upon highest value of (Pi).

The formulas to calculate the different entities have been mentioned in Eqs. (6)–(9).

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=0}^{n} X_{ij}^2}} \tag{6}$$

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{7}$$

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \tag{8}$$

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5} \tag{9}$$

The rank near to unity has been preferred for best machining environments [55]. From these results, it has been revealed that highest rank has been evaluated in MQL machining condition performed at 24 trial followed by 23 and 21. The sustainable conditions during dry conditions have been found during 2nd and 3rd trials.

However, despite of highest score awarded to dry machining during qualitative weightage, the ranking is still below the MQL machining due to the impact of poor machining performance in terms of temperature, surface roughness and cutting forces. On the other side, flood cooling has been ranked lowered due to higher risk of occupational health & safety (OHS) as well as more cost involved to wastage disposal, recycling and coolant purchasing [15]. In addition to this, water usage, power consumed for running the recycling equipment, bad odour, fumes and wet chips leads to lower the rank during flood cooling. Among all these situations, flood cooling has achieved the 10th rank of sustainability amid 27 set of experiments. The best ranked 1st -3rd has been highlighted in Table 13.

However, during weighted analysis of sustainability, the maximum rank has been achieved by dry machining in 3rd trial and represented in Table 14. On the other hand MQL has secured 5th and 6th rank shown in yellow colour. Moreover, flood cooling has gained rank of 13 out of 27 trials.

The results expressed in Fig. 16(b) illustrated that highest sustainability rank has been achieved at speed of 88 m/min along with feed rate of 0.246 mm/rev followed by speed rate of 125 m/min at same feed rate. This is happened due to better performance of highly important criterion OHS and W_f despite the fact of product quality and machining cost attributes. The results evaluated from Table 13 has been represented in Fig. 16 (a), which signifies that the best machining performance at speed of 125 m/min and feed 0.246 during equal weightage criteria. However, when different weightage has been assigned using AHP process, then dry machining has been ranked at 1st position compared to MQL in previous criterion.

Table 11
Pairwise matrix for assigned weightage criteria.

Parameters	F_c	S.R	Temp	E_c (W)	E_c (KJ)	C_e	W_f	OHS
F_c	1	1	1	1/5′	1/5′	1/9′	1/9′	1/9′
S.R	1	1	1	1/3′	1/3′	1/9;	1/9′	1/9′
Temp	1	1	1	1/3′	1/3′	1/9′	1/9′	1/9′
E_c (W)	5	3	3.00	1	1	1	1	1
E_c (kJ)	5	3	3	1	1	1	1	1
C_e	9	9	9	1	1	1	1	1
W_f	9	9	9	1	1	1	1	1
OHS	9	9	9	1	1	1	1	1

Table 12
Solved Pairwise matrix and evaluation of weightage.

Parameter	F_c	S.R	Temp	E_c (W)	E_c (kJ)	C_e	W_f	OHS	Sum	Weightage (W_j)
F_c	1.00	1.00	1.00	0.20	0.20	0.11	0.11	0.11	**0.293370579**	**0.0266**
S.R	1.00	1.00	1.00	0.33	0.33	0.11	0.11	0.11	0.332496857	0.0302
Temp	1.00	1.00	1.00	0.33	0.33	0.11	0.11	0.11	0.332496857	0.0302
E_c (W)	5.00	3.00	3.00	1.00	1.00	1.00	1.00	1.00	1.609353928	0.1461
E_c (KJ)	5.00	3.00	3.00	1.00	1.00	1.00	1.00	1.00	1.609353928	0.1461
C_e	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	2.279507057	0.2069
W_f	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	2.279507057	0.2069
OHS	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	2.279507057	0.2069
	Total								**11.01559332**	1

Table 13
Sustainability analysis using TOPSIS approach with equal weightage.

Experiment No.	Cutting speed	Feed rate	Machining environment	S+	S-	Pi	Rank
1	88	0.06	Dry	0.378312	0.356025	0.484825	21
2	88	0.112	Dry	0.23671	0.399205	0.627765	6
3	88	0.246	Dry	0.249969	0.415675	0.624471	7
4	125	0.06	Dry	0.389322	0.316244	0.448213	23
5	125	0.112	Dry	0.270857	0.343027	0.558782	14
6	125	0.246	Dry	0.269673	0.397391	0.595731	9
7	175	0.06	Dry	0.387702	0.299062	0.435465	24
8	175	0.112	Dry	0.270367	0.353413	0.566566	12
9	175	0.246	Dry	0.308277	0.406546	0.568736	11
10	88	0.06	Flood	0.404836	0.311482	0.434838	25
11	88	0.112	Flood	0.296453	0.358696	0.547503	15
12	88	0.246	Flood	0.277749	0.406358	0.593998	10
13	125	0.06	Flood	0.408133	0.262486	0.391408	26
14	125	0.112	Flood	0.303193	0.325822	0.517987	19
15	125	0.246	Flood	0.29778	0.379946	0.560618	13
16	175	0.06	Flood	0.406685	0.256845	0.387089	27
17	175	0.112	Flood	0.325027	0.304012	0.483296	22
18	175	0.246	Flood	0.330017	0.364453	0.524793	17
19	88	0.06	MQL	0.317503	0.349924	0.524288	18
20	88	0.112	MQL	0.189888	0.389118	0.672045	4
21	88	0.246	MQL	0.195929	0.404685	0.673785	3
22	125	0.06	MQL	0.297353	0.331167	0.5269	16
23	125	0.112	MQL	0.183856	0.383221	0.675783	2
24	125	0.246	MQL	0.164666	0.432613	0.724306	1
25	175	0.06	MQL	0.297466	0.317134	0.516001	20
26	175	0.112	MQL	0.216636	0.355655	0.621458	8
27	175	0.246	MQL	0.219565	0.411496	0.65207	5

3.5. Qualitative analysis of tool wear

The qualitative analysis of tool wear has been carried out ensure the sustainable machining of selected material during distinct cooling conditions. The scanning electron microscopy (SEM) images of insert after machining has been taken for evaluating the impact of input variables on cutting forces, temperature, surface roughness and energy consumption. The SEM micrographs of CNMG120408 uncoated carbide insert have been shown in Figs. 17 and 18.

As shown in Fig. 17(a) representing majorly adhesion and abrasion on the rake surface along with nose wear during machining at 88 m/min, 0.246 mm/rev and 0.8 mm doc. This has occurred due to material softening and clinging to the tool rake area. Further, the

Table 14
Sustainability analysis using TOPSIS approach with assigned weightage.

Experiment No.	Cutting speed	Feed rate	Machining environment	S+	S-	Pi	Rank
1	88	0.06	Dry	0.060732	0.058842359	0.492098	16
2	88	0.112	Dry	0.026324	0.068163109	0.721403	3
3	88	0.246	Dry	0.016542	0.074630496	0.818565	1
4	125	0.06	Dry	0.059982	0.055872911	0.482266	17
5	125	0.112	Dry	0.03365	0.062309464	0.649333	9
6	125	0.246	Dry	0.022923	0.074061734	0.763642	2
7	175	0.06	Dry	0.060803	0.053294438	0.467095	18
8	175	0.112	Dry	0.032626	0.064038128	0.662484	8
9	175	0.246	Dry	0.030383	0.075724996	0.713662	4
10	88	0.06	Flood	0.076057	0.029389346	0.278714	25
11	88	0.112	Flood	0.057179	0.046585178	0.448953	19
12	88	0.246	Flood	0.052659	0.061366476	0.53818	13
13	125	0.06	Flood	0.076409	0.023800789	0.23751	26
14	125	0.112	Flood	0.056858	0.04511574	0.442425	20
15	125	0.246	Flood	0.053599	0.060839317	0.531635	14
16	175	0.06	Flood	0.075152	0.016933566	0.183889	27
17	175	0.112	Flood	0.059224	0.041181171	0.41015	23
18	175	0.246	Flood	0.056712	0.05921946	0.510813	15
19	88	0.06	MQL	0.057329	0.04084403	0.41604	22
20	88	0.112	MQL	0.033829	0.055094981	0.619573	11
21	88	0.246	MQL	0.028016	0.065450101	0.700254	6
22	125	0.06	MQL	0.053832	0.038468799	0.416776	21
23	125	0.112	MQL	0.032795	0.05458063	0.624663	10
24	125	0.246	MQL	0.028064	0.067640591	0.706762	5
25	175	0.06	MQL	0.052612	0.035699909	0.40425	24
26	175	0.112	MQL	0.035297	0.05208643	0.596068	12
27	175	0.246	MQL	0.031986	0.066971584	0.676769	7

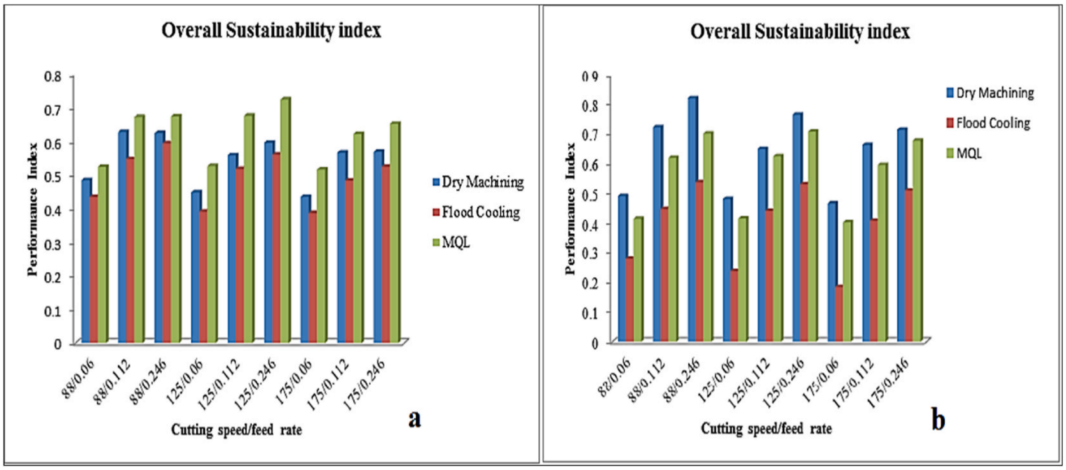

Fig. 16. (a) Performance index during equal weightage; (b) Performance index with assigned weightage.

sliding friction of chip produced the abrasion marks leading to loss of material on side of tool surface. Accumulation of material on tool tip forces the chip to slide laterally causing abrasion. As visible in Fig. 17 (b), there is an improvement in adhesion and abrasion as compared to dry condition due to application of flood coolant enabling reduction in temperature and friction. Moreover, minor abrasion and adhesion have been found on the rake face in comparison to dry and flood condition as illustrated in Fig. 17 (c) because of sufficient lubrication of vegetable oil and cooling action of air jet. However, increment in cutting speed causes higher friction at primary, secondary and tertiary deformation zone producing the higher magnitude of abrasion in dry machining. Similar results abrasion, adhesion and Nose wear was reported during machining of Hastelloy C-276 using MQL machining of different oil [9,56].

Fig. 18(a) represents that higher amount of tool wear on the rake as well as flank portion of cutting tool. The nose wear of 317 μm has been evaluated along with flank wear of 376 μm. This has been caused due to higher friction, absence of cutting fluid, intense cutting temperature and larger cutting forces leading to impact surface roughness, energy consumption and carbon emission [87–89]. During these machining conditions force of 1231 N, 261 °C temperature, 2.35 μm S.R, 2575 W of energy consumption and 2.08 kg-CO_2 has attributed to larger tool wear on various section of insert as illustrated in Fig. 18(a). On the other side, Fig. 18(b) represents the tool wear during flood cooling at same levels of input parameters causing adhesion, abrasion, minor flank and nose wear. There is 173.2 μm

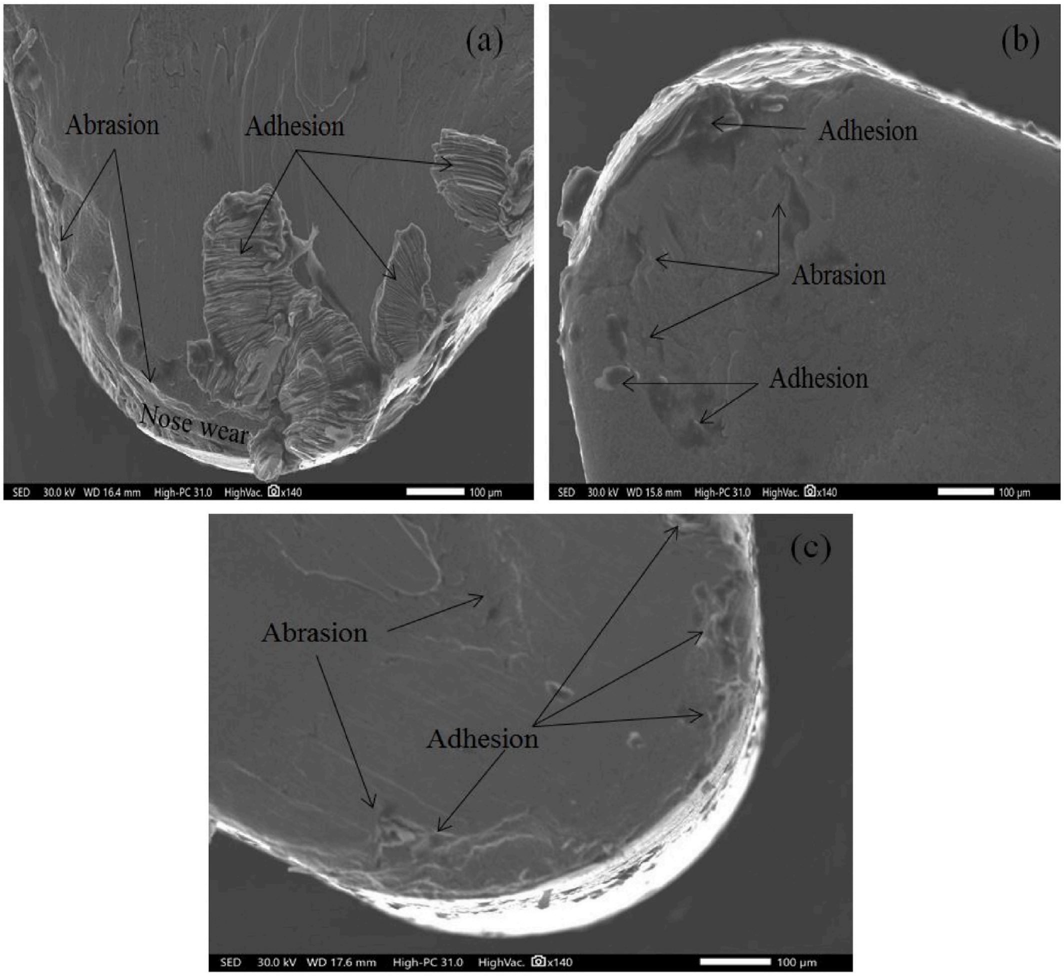

Fig. 17. Analysis of tool wear in different conditions: (a) Dry condition; (b) Flood cooling; (c) MQL condition at 88 m/min, 0.246 mm/rev and 0.8 mm doc.

of flank wear appeared on the left portion of image and pile up of material adhesion on the right section. In addition to this, minute abrasion marks have been noticed on the rake face of inset just near to nose radius. As far as MQL condition has been concerned, wear trends similar to flood conditions have been observed in Fig. 18(c). The nose wear of 115.2 μm has been found along with abrasion marks on the left and right portion of cutting edge. However, minor adhesion has been reported during MQL condition because of suitable cooling action of air jet assisted by significant lubrication effect of soybean oil. Whereas, Fig. 18(d) indicates the SEM micrograph of broken insert during dry condition conducted at 175 m/min, 0.06 mm/rev and 0.8 mm depth of cut. It has happened because of turning work piece beyond the machining time resulting into complete failure of cutting insert. For machining conditions mentioned earlier, MQL has reduced the cutting forces by 38.40% and 5.48 % compared to dry and flood conditions. Whereas, cutting temperature, S.R and carbon emission have been declined by 35.23%, 78.03% and 38.66% than dry condition. Further, the same responses have been minimized by 21.24%, 31.06% and 5.33% than flood cooling [90]. Hence, from all these observations, it can be stated that MQL machining has performed better than other and secured sustainability machining condition as evaluated in Table 5 and Fig. 16(a).

4. Conclusions

On the basis of experimental observation and Sustainability analysis the following conclusion have been drawn.

i. The machining of Hastelloy without aid of coolant and lubrication is tedious task because lower thermal conductivity of material tends to raise the temperature of specimen leading to material adhesion.
ii. Results indicate that the cutting speed was dominant to influence heat formation and power expenditure. Whereas feed rate was significant parameter to impact cutting forces. On the other side, surface roughness was remarkably affected by cooling environment.

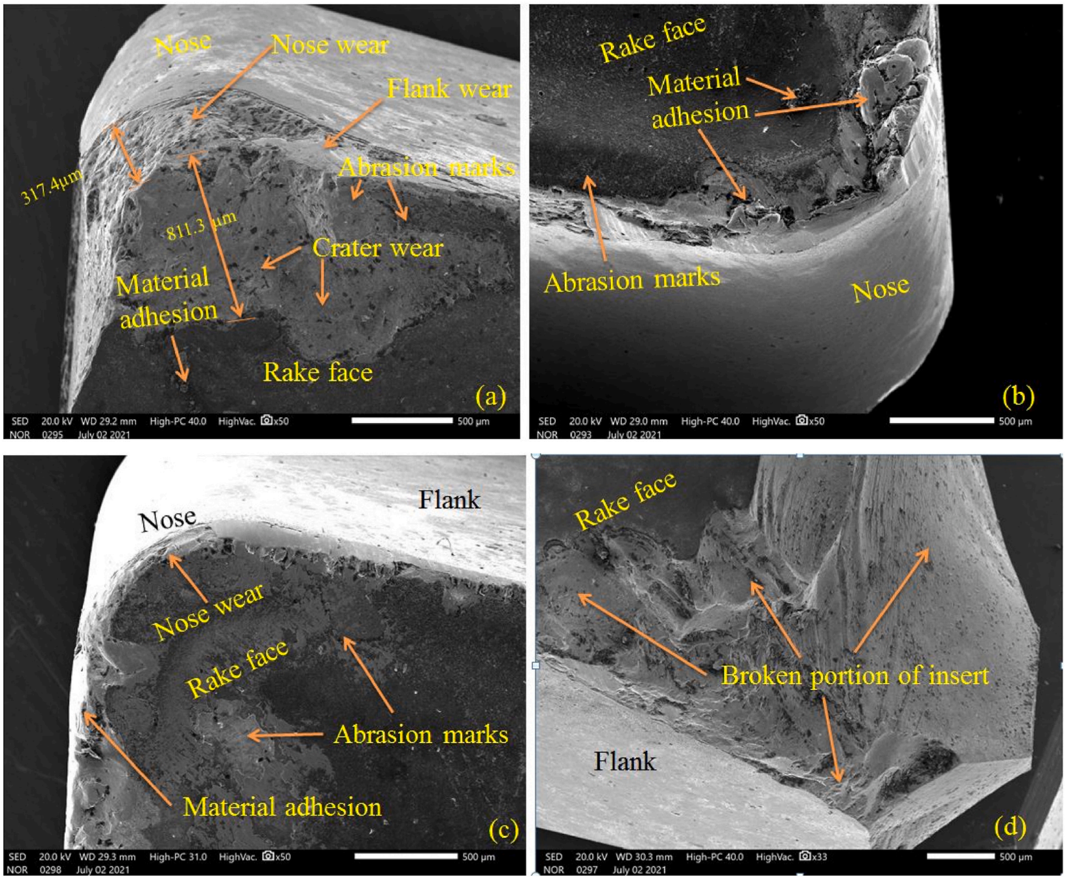

Fig. 18. Analysis of tool wear in different conditions: (a) Dry condition; (b) Flood cooling; (c) MQL condition; (d) Dry cutting at 175 m/min, 0.06 mm/rev and 0.8 mm doc.

iii. The maximum carbon emission has been discharged during dry machining because of the larger cutting forces and energy consumption.
iv. MQL has reduced the energy expenditure and carbon emission significantly by margin of 9–27% and 9–24% than dry machining.
v. Highest performance rank was evaluated in MQL machining during equal weightage criteria. However, during assigned weighted system best rank was assessed in dry condition.
vi. Best setting of parameters has been evaluated at 125 m/min, 0.246 and 0.8 mm doc during MQL condition using TOPSIS approach.
vii. SEM analysis of cutting tool reported adhesion and abrasion at 88 m/min and 125 m/min under dry, flood and MQL condition. However, catastrophic mechanism of tool wear occurred at 175 m/min during dry condition.

Author contribution statement

Gurpreet Singh: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Vivek Aggarwal, Jujhar Singh, Changhe Li, Grzegorz Królczyk, Abhinav Kumar, Sayed M. Eldin: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sehijpal Singh, Balkar Singh: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Shubham Sharma: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

No data was used for the research described in the article.

Declaration of interest's statement

The authors declare no conflict of interest.

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