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High-speed machining parametric optimization of 15CDV6 HSLA steel under minimum quantity and flood lubrication

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ABSTRACT

High-speed machining (HSM) maintains a high interest in the preparation of metal parts for optimum results, but with the application of HSM, the sustainability issue becomes important. To overcome the problem, minimum quantity lubrication (MQL) during HSM is one of the innovative and challenging tasks during conventional cutting (milling) to improve quality, productivity, and strength under the umbrella of sustainability. The objective of this research is to achieve sustainable machining by simultaneously optimizing sustainable machining drivers during the HSM of 15CDV6 HSLA steel under MQL and flood lubrication. The response surface methodology has been applied for the development of mathematical models and selecting the best combination of process parameters to optimized responses, i.e. surface roughness, material removal rate, and strength. Optimization associated with sustainability produced compromising optimal results (Min. *Ra* 0.131 µm, Max. *MRR* 0.64 cm^3/min, and Max. *ST* 1132 MPa) at the highest cutting speed 270 m/min and the lowest feed rate 0.09 mm/rev and depth of cut 0.15 mm under MQL. The comparative investigation exposed that significant improvement in *Ra* (1.1-16.6 %) and *ST* (1.3-2.3 %) of the material using MQL has been witnessed and gives a strong indication that MQL is the best substitute than the flood lubrication. The scientific contribution of the approach is to develop mathematical models under MQL and flood lubrication that will aid practitioners to choose input parameters for desired responses without experimentations. The work would be beneficial in the field of aviation, defense, and aeronautical applications due to the excellent mechanical properties of 15CDV6 HSLA steel.

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1. Introduction

The minimization of surface roughness and maximization of material removal rate may not be possible through non-conventional techniques, due to these limitations conventional machining (HSM) is preferred and has been used to improve the quality and productivity. High-speed machining is known in the advanced and emerging machining process increasingly used for innovative materials such as high strength low alloys to produce complex parts with improved quality (minimum surface roughness), high productivity (maximum material removal rate), sustainability, and economy [1]. High-speed machining (HSM) is defined as machining at higher cutting speed than conventional machining to enhance productivity without compromising quality. The range of HSM depends on the properties of material, i.e. thermal conductivity, material strength, alloying composition, microstructure, and cutting conditions [2, 3].

The influence of cutting conditions during high-speed machining has a great impact on heat generation that causes surface variation and early failure of the tool. Cutting fluids in the form of MQL and flood are used to reduce the generated heat and friction between the tool and chip through lubricating effect. The cutting fluid has a significant influence on material surface roughness, productivity, strength, tool life, and dimensional accuracies. The use of cutting fluid can be ineffective in reducing generated heat during HSM because of high spatial stress and high temperatures, it is difficult to obtain cutting fluid from the secondary contact zone. Furthermore, dry machining may not always be economically feasible due to its limited ability to withstand tools at high temperatures and perform effectively. As such, bridging technology is essential so that the cutting fluid requirements can be partially met without negotiating the environment. The most reliable and promising bridging technology between flood and dry is minimum quantity lubrication that minimizes the use of cutting fluid and improves sustainability.

The objective of this research is to achieve sustainable machining by simultaneously optimizing sustainable machining drivers during high-speed machining of 15CDV6 HSLA steel under MQL and flood lubrication.

2. Literature review

Sustainability achievement during high-speed machining is a key interest nowadays. Industrial trends are moving from conventional to sustainable manufacturing paradigms. Such reforms are a result of sicknesses found in laborers at the shop floor, a prerequisite of manufacturing cost reduction, and government policies for ecological safety [4]. Cutting fluids are dangerous to health and the environment. The environmental effects of cutting fluid contain waste disposal, the release of hazardous ingredients into the atmosphere and harmful working circumstances for the workers usually causes inhalation and skin disease. To overcome these problems scholars, have annoyed machining without using cutting fluid (dry machining). Wherever the whole exclusion of cutting fluid is not likely, a very minute quantity of lubrication is used, called minimum quantity lubrication (sustainable approach) [5].

Various researchers studied the effect of lubrication modes and process parameters like cutting speed (C_S), feed rate (F_R), depth of cut (D_C) on surface roughness (*Ra*), material removal rate (*MRR*), and strength (*ST*) of the material during high-speed machining using minimum quantity lubrication. Gunda *et al.* [6] studied the sustainability aspects during machining of stainless steel using MQL, dry, and flood lubrication modes and found that MQL gives a better surface finish as compared to dry and flood. Yildirim *et al.* [7, 8] investigated the effect of machining factors and cooling methods (dry, wet, and MQL) on *Ra*, tool life, and wear during HSM of nickel-based alloys. The results showed that MQL machining provided improvement in *Ra* and tool wear when compared to dry and wet machining. The MQL system is recommended during the milling of nickel-based alloys by considering economics, environment, and worker health. Mia *et al.* [9] studied the milling process of AISI 4140 hardened steel to optimize the parameters and fluid flow rate for minimum Ra and cutting force. Response surface methodology has been applied for experimental design and ANOVA was utilized for analysis of results. It was concluded that *Ra* was significantly affected by fluid flow rate and 150ml/h is the optimum value for minimum *Ra*. Khan *et al.* [10] examined the influence of process parameters and MQL on *Ra*, *MRR*, and energy consumption during milling of AISI 1045 steel. It was shown that lower C_S and higher width of cut were appropriate for energy efficiency with nano MQL. Nguyen *et al.* [11] optimized the machining parameters and tool geometry for minimum *Ra*, specific cutting energy, and higher *MRR*. The archive-based micro GA was employed for the determination of optimal parameters combination. The results showed that *Ra* and cutting energy is substantially affected by D_C. Further, it recommended that higher parametric values produced lower cutting energy and improved *MRR*.

Borojevic *et al.* [12] examined the influence of process parameters during milling of Al 7075 thin-walled structures. Central composite design technique in RSM was employed for the optimization of parameters. The experimental results were verified by calculated optimal values and demonstrate a satisfactory fitting. Songmei *et al*. [13] explored the effect of nano-enhanced lubricants and machining parameters (C_S, F_R, and D_C) during the milling of titanium alloy using Taguchi method. The findings confirmed that milling force was significantly influenced by type and concentration of nanoparticles, D_C, and F_R as compared to surface roughness. Liao and Lin [14] investigated HSM of hardened steel (NAK80) under MQL and dry environment. The aim was to explore the process of MQL in HSM of hardened steel and to obtain the optimal parameters combination for optimal *Ra*, cutting force, and tool life. It was found that MQL gives better results than dry cutting during HSM. Hamdan *et al*. [15] investigated the HSM of AISI 304 steel to optimize process parameters for minimum *Ra* and cutting force as well as high *MRR* during dry, MQL, and flood lubrication modes. For experimental design, RSM was applied to optimize the parameters combination and ANOVA was used to investigate the results. It was concluded that an improvement of 41.3 % *Ra* with a 25.5 % reduction in cutting force was produced with MQL lubrication mode, also revealed that D_C is the utmost substantial factor for getting the anticipated *MRR* while reducing the value of *Ra*. Zhenchao *et al*. [16] experimentally studied the HSM of 16Co14Ni10Cr2Mo HSLA steel to establish the impact of milling parameters on surface integrity using the MQL technique. It was concluded that with the increase of C_S and F_R *Ra* value increases and residual stresses increase with C_S, D_C, and F_R. Feed was the most substantial factor that affects the stresses. Begic-Hajdarevic *et al*. [17] studied HSM of hardened X37CrMoV5-1 tool steel to govern the impact of operational parameters on *Ra* using 20mm and 40mm diameter tools. It was established that the increase of C_S, *Ra* decreases and increases by the increase of F_R, and the improved surface is achieved at a larger diameter tool. Motorcu *et al*. [18] investigated the impacts of C_S, number of inserts, milling direction and coating layer on surface layer and tool life of Inconel 718 during milling process using Taguchi method. The results showed that *Ra* significantly affected by cutting tool coating.

Cutting fluids are used to reduce the generated heat during HSM, and friction between the tool and chip through lubricating effect. The cutting fluid has a significant impact on material *Ra*, productivity, strength, residual stress, tool life, and dimensional accuracies. The expense of cutting fluids and their administration framework can go up to 16-20 % of the absolute expense of the machined part [19]. Cutting fluids are applied in the machining process in many ways such as flood and minimum quantity. In the flood lubrication large volume (10-100 liters per minute) of fluid continuously applied during machining while in minimum quantity lubrication (2-15 ml/min) CF is applied in the form of mist or fog [5]. The advantages of using MQL improves surface quality, better safety characteristics, eco-friendly, and reduces machining cost [5, 20-22]. E. Benedicto *et al*. [23] analyzed the use of cutting fluids and main alternatives (dry, MQL, cryogenic, nanofluids) during machining. Especially, the examination was done concentrating on technical, economic, and environmental points. The best ecological option is dry machining since it totally expels the cutting fluid and guarantees a clean atmosphere and laborers security, however, it has numerous application impediments. To actualize this option is important to have thorough control of the cutting parameters and a reasonable tool choice. MQL framework lessens the utilization of the liquid and is a progressively feasible option considering the environmental, social, and economic effects as well as the performance.

The main pillars of sustainability are technical, environment, society, and economy [5, 20, 21, 23, 24]. The sustainable machining model of the current research is shown in Fig. 7. The key drivers that sustain these pillars are resource efficiency, a clean and green environment that incorporates effective waste reduction and management, and cost-effective production. In the domain of high-speed machining, resource efficiency can be incorporated by minimum surface roughness, a clean and green environment by reducing lubrication amounts by employing minimum quantity lubrication, and cost-effectiveness using machining productivity (material removal rate). The main limitation to achieve sustainability in machining is to simultaneously address these drivers. For instance, by increasing cost-effectiveness (*MRR*), resource efficiency (surface roughness) decreases. This problem of sustainability achievement becomes more challenging in the case of machining at higher speeds (also called high-speed machining).

The detailed review of the literature highlighted that various studies have been carried out to optimize individual performance measures including surface roughness, material removal rate, and strength. However, little or no research work has been reported to simultaneously optimize performance measures affecting key sustainable machining drivers during high-speed machining. Hence, this research aims to achieve sustainable machining by simultaneously optimizing sustainable machining drivers during high-speed machining of 15CDV6 HSLA steel under MQL and flood lubrication. 15CDV6 HSLA steel has been considered as a research candidate as it possesses excellent mechanical and heat resistant properties which make it suitable for making rocket booster, rocket motor casing, and suspension components. The response surface methodology was applied for the development of mathematical models and selecting the best combination of process parameters to optimized responses, i.e. surface roughness, material removal rate, and strength. Besides, sustainability has been achieved keeping desirability function-based multi-objective optimization.

3. Materials, methods, and experimental procedure

This section briefly explains the description of predictors, the experimental setup including CNC machining, and response measurements.

3.1 Material selection

Due to excellent mechanical properties like high strength to weight ratio, toughness, yield strength, and weldability 15CDV6 HSLA steel is selected as a research candidate mostly used in the aeronautical, defense, and aviation industry with applications in rocket motor casing, rocket booster, suspension components, pressure vessels, and many others. The 15CDV6 is a low carbon chromium-molybdenum-vanadium high strength low alloy steel containing the concentration of carbon (0.15 %), chromium (1-5 %), and the concentration of molybdenum and vanadium are less than 1.5 % each and weight proportion of all the alloying elements combined is less than 5 % [25]. The chemical composition of the material was analyzed with the XRF analyzer and wet analysis method as given in table 1.

Table 1 Chemical composition (wt %) of 15CDV6 HSLA steel

C	Si	P	S	Mn	Cr	Mo	V	Fe
0.15	0.15	0.016	0.012	0.87	1.33	0.84	0.24	96.392

3.2 Method selection

Face milling was selected as a machining process under a sustainable environment during high-speed. The experiments were performed under the framework of face milling because it gives a better surface finish as well as high productivity.

A total of 40 experimental runs were performed to collect the experimental data, twenty experiments using MQL through a controlled coolant flow of 15 ml/min, and 6 bars pressure while twenty with flood coolant flow of 100 l/min. The following four predictor variables (C_S, F_R, D_C, Lubrication mode) were controlled in the experiments:

- Process parameters: Cutting speed, feed rate, and depth of cut;
- Lubrication mode: Minimum quantity lubrication (MQL) and flood lubrication (FL).

The 3-controlled variables with cooling mode, central composite design (CCD) technique was used for the design of experiments. The CCD in RSM is a very efficient design for fitting the second-order model. Two parameters in the design must be specified: the distance α of the axial runs from the design center and the number of center points n_c. In this study, twenty ($2^n + 2n + 2n_c$, n is the number of input parameters, including eight factorial points 2^n, six axial points $2n$ and six center points $2n_c$) design points for each MQL and flood were considered for experimentation with six-star points [26]. The complete DOE with experiment runs, input variables, and responses have been presented in table 4 for MQL and flood lubrication.

3.3 Experimental procedure

After the confirmation of composition, the material was cut from a bigger plate of 40 mm thickness to block size 150×120 mm using a bandsaw machine for heat treatment.

The material was heat treated to the required hardness value of 39 ± 2 HRC [27], the procedure given in table 2. The hardness was measured using a Universal hardness tester with a diamond indenter.

Table 2 Heat treatment parameters

Austenzing		Quenching			Tempering		Cooling
Temp (˚C)	Time (min)	Medium	Temp (˚C)	Time (min)	Temp (˚C)	Time (min)	Medium
600 700 960	45 10 60	PSO Oil No. 10	30	30	650	120	Air cool to 39HRC

The input process parameters such as C_S, F_R, and D_C are selected due to their significant impact on responses which are surface roughness, material removal rate, and strength of the material. The objective is to optimize input parameters to achieve the desired value of performance measurements. The levels of input process parameters during HSM of HSLA steel were selected after the detailed literature survey, pilot run, and expert's opinion as given in table 3. The recommended threshold values mostly dependent on C_S, F_R, D_C, and lubrication mode. The range of cutting speed during HSM (210 m/min < cutting speed < 360 m/min) [28] and for steel materials having hardness value 39HRC-48HRC (cutting speed > 150 m/min for rough cutting and cutting speed < 350 m/min for finish cutting) (Sandvik).

Table 3 Levels of input process parameters

Cutting parameters	Levels		
	Low	Middle	High
Cutting speed, C_S (m/min)	200	235	270
Feed rate, F_R (mm/rev)	0.08	0.10	0.12
Depth of cut, D_C (mm)	0.1	0.2	0.3

Before running the actual experimental runs, initially, the material was cut from a bigger plate of 40 mm thickness using a bandsaw machine in a 150×120 mm block. The block was then split into 04 parts of 10 mm thickness each on the wire-cut along with the thickness such that the final size of the blocks was 150×120×10 mm each. Now each block is further split into half from the 150mm length, so the final dimensions of each block become 120×75×10 mm (08 blocks). Now, each of the blocks was held on the CNC Milling machine vice, dialled and faced from one side and then the cavity for the tensile sample is machined out overall 75mm length as per the drawing taking the center of 120 mm length. A similar process was carried out on the other side of the block to give it a proper shape of the tensile sample. The same way all 08 blocks were machined. The sides of each block were faced to 100mm length and the block dimension becomes 75×100×10 mm with a proper sample shape. The blocks were engaged to wire cut again for slicing them into 10×100×10 mm sample sizes (05 from each block). Now, tensile sample preparation is completed in final dimensions according to ASTM E-8M-04 standard except the thickness that is 10mm which gives us a margin for experimentation.

Now, high-speed milling of 15CDV6 HSLA steel was performed during MQL and flood lubrication using a CoroMill 290 Square Shoulder Milling Cutter (R290-040A32-12L) attached multilayer tungsten carbide inserts (TiCN+Al2O3+TiN) having 0.8 mm nose radius to achieve the high surface finish. The MQL apparatus (Model: LXL-210-2L) was attached outside the machine and the nozzle was adjusted near the tool so that mist can be thrown out on the cutting zone. The following parameters were selected for nozzle position; spray distance from the nozzle to the tool-tip 9 mm, nozzle diameter 3 mm as shown in Fig. 1b [29], fluid flow rate 15 ml/min, a compressor is attached outside the MQL setup which produces air pressure of 6 bars. The flow rate was controlled through an adjustable screw (point A) attached to the MQL pump. The range of MQL setup is 0.03-0.3 ml/s. Finally, at the mist line small quantity of fluid (15 ml/min) mixed with compressed air flow (6 bars) resulting to produce mist or fog that is delivered to the cutting zone. The experimental setup has been shown in Fig. 1. Initially, the MQL setup was calibrated, followed by special care, and after each experiment, it was ensured that proper mist was delivered to the cutting zone. Pakistan state oil (PSO) neat metal cutting oil was used for lubrication in MQL and flood machining because of good thermal stability, environmentally acceptable, rust-free and provides good surface finishes.

Now, each sample was held on a machine vice on the CNC milling machine (DAHLIH MCV-720) and dialled to keep them perpendicular to the tool axis. The sample was firstly faced to provide a good surface for experimental precise depth of cut value (final thickness 6mm). Each experiment was carried out on a separate sample as per the DOE has given in table 4. Twenty experiments were carried out using MQL through a controlled coolant flow of 15 ml/min and 6 bar pressure while twenty were carried out with flood coolant flow of 100 l/min [30, 31]. The machine tool coolant pump (TUAN LU-China) specifications are as under; (Model: YLP-900MFWD, flow rate 180 l/min (maximum).

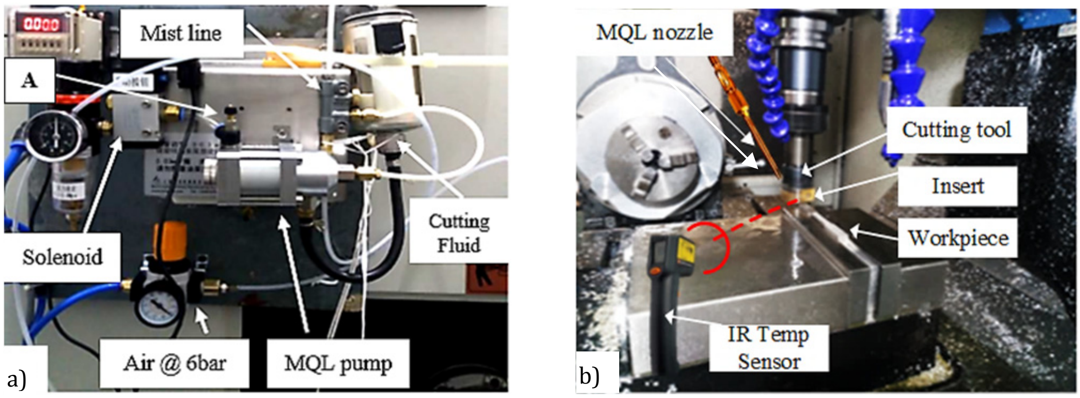

Fig. 1 Experimental setup: a) MQL setup, b) CNC machining

3.4 The responses

During each experimental run following responses were measured:

1. Surface roughness (μm): The *Ra* is a part of the surface texture and measured by the deviation in the direction of the normal surface vector, if the deviation is large, the surface rough otherwise the surface is smooth. The surface roughness of each experimental run during MQL and flood lubrication was measured using Mitutoyo SJ-410 surface roughness measuring apparatus and values recorded.

2. Material removal rate (cm^3/min): The *MRR* was calculated as the volume of material removed per unit time (cm^3/min), which is productivity. It has been measured for each sample using the weight-loss method. Each machined sample was weighed before and after the experimentation using a weight balance machine. The machining time was observed using a stopwatch. Volume removed/Unit time was then calculated using Eq. 1 [32].

$$MRR = \frac{(initial\ weight\ of\ specimen - final\ weight\ of\ specimen)}{density \cdot machining\ time} \tag{1}$$

3. Strength (MPa): Ability to bear loads without failure. The strength of the specimen has been measured after machining at different machining parameter combinations. The strength was measured using the Material Testing System (MTS) and values were recorded. The specimens have been adjusted among the two hydraulic grips of a 21 MPa, having a static force capacity of 120 KN and Dynamic 100 KN MTS load frame by MTS System Corporation with the automatic data acquisition processing.

Table 4 Design matrix with responses for flood and MQL

Exp. No.	Input process parameters			Responses				
	C_S m/min	F_R mm/rev	D_C mm	*Ra* µm		*MRR* cm³/min	Strength (*ST*) MPa	
				Flood	MQL		Flood	MQL
1	200	0.08	0.1	0.145	0.121	0.228	1088	1106
2	270	0.08	0.1	0.112	0.098	0.392	1124	1142
3	200	0.12	0.1	0.168	0.153	0.392	1066	1084
4	270	0.12	0.1	0.148	0.134	0.627	1102	1120
5	200	0.08	0.3	0.205	0.185	0.794	1058	1076
6	270	0.08	0.3	0.185	0.175	1.032	1094	1112
7	200	0.12	0.3	0.219	0.196	1.276	1036	1054
8	270	0.12	0.3	0.208	0.181	1.648	1076	1090
9	176.12	0.1	0.2	0.189	0.173	0.591	1050	1068
10	293.86	0.1	0.2	0.145	0.135	0.932	1110	1128
11	235	0.07	0.2	0.181	0.162	0.542	1096	1114
12	235	0.13	0.2	0.219	0.187	0.973	1062	1082
13	235	0.1	0.032	0.109	0.1	0.157	1110	1128
14	235	0.1	0.37	0.187	0.185	1.476	1054	1072
15	235	0.1	0.2	0.197	0.167	0.847	1083	1108
16	235	0.1	0.2	0.197	0.167	0.748	1083	1105
17	235	0.1	0.2	0.189	0.167	0.821	1086	1107
18	235	0.1	0.2	0.197	0.172	0.785	1087	1108
19	235	0.1	0.2	0.191	0.171	0.832	1085	1108
20	235	0.1	0.2	0.194	0.167	0.769	1084	1103

4. Results and discussion

4.1 Analysis of surface roughness

The integrity of machining surface was systematically characterized by surface roughness, microhardness, and microstructure changes [33]. In this investigation, experimentally the influence of process parameters and lubrication mode during high-speed machining of 15CDV6 HSLA steel on surface roughness has been presented as shown in Fig. 2. A concise vision of the plot indicates the following observations: a) The surface roughness decreases with higher cutting speed, and lower feed rate and depth of cut; b) The trend lines showed that surface roughness has been improved using MQL than flood lubrication and the percentage improvement in *Ra* is ranging from 1.1-16.6 %.

The effects of cutting speed, feed rate, and depth of cut on surface roughness are illustrated in response surface plots shown in Fig. 3a and 3b. The trends highlight that *Ra* is more influenced by D_C followed by F_R and C_S. Further, observed that *Ra* decreased with the increase of cutting speed because C_S increases heat generation and reduces the friction coefficient of tool-chip and cutting force [34]. The *Ra* increases with the increase of F_R due to the reason the contact area between the cutting tool and the workpiece increases, which leads to higher thrust force and vibration and therefore increases the *Ra*. Moreover, *Ra* increases with the increase of D_C because when D_C increases tool-chip contact length also increases which leads to an increase in cutting forces and temperature which in turn affects *Ra* [35]. During HSM minimum value of *Ra* (0.098

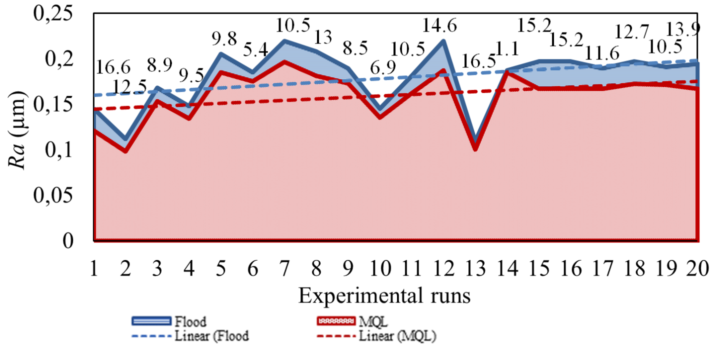

Fig. 2 Experimental results with percentage (%) improvement in surface roughness

µm) at the highest value of C_S (270 m/min) and the lowest value of F_R (0.08 mm/rev) and D_C (0.1 mm) have been achieved using MQL because during MQL high-pressure mist removes the chips which reduce the friction, no thermal shocks and fewer vibrations induced in a rotating tool which minimizes wear and tear leading to improved surface finish as compared to flood lubrication [36]. The minimum quantity lubrication produces a smoother surface, i.e. the difference between peak and valley is less than other conditions (flood lubrication) generated. In flood lubrication, traces of feed are more visible, which increases the average surface roughness [37].

For in-depth analysis, the adequacy of developed models has been checked by ANOVA as a statistical tool. The most significant parameter indicates the highest F-value. The predictor's main and interaction effects on *Ra* are significant where $p < 0.05$. The significant terms for *Ra* are depth of cut; depth of cut squared; feed rate; cutting speed; cutting speed squared for flood while the depth of cut; depth of cut squared; cutting speed; feed rate; cutting speed squared; feed rate × depth of cut for MQL. The regression models for the prediction of *Ra* under flood and MQL system are given in Eq. 2 and 3 respectively.

$$\begin{aligned} Ra_{flood} = \; & -0.1328 + 2.52540\mathrm{E}-003 \cdot C_S - 1.458 \cdot F_R + 0.85137 \cdot D_C \\ & -003 \cdot C_S \cdot F_R + 7.85715\mathrm{E}-004 \cdot C_S \cdot D_C - 1.375 \cdot F_R \cdot D_C \\ & -7.24671\mathrm{E}-006 \cdot C_S^2 + 6.97511 \cdot F_R^2 - 1.55947 D_C^2 \end{aligned} \tag{2}$$

$$\begin{aligned} Ra_{MQL} = \; & -0.13714 + 1.66455\mathrm{E}-003 \cdot C_S + 0.18179 \cdot F_R + 0.82542 \cdot D_C - 1.78571 \\ & -004 \cdot C_S \cdot F_R + 6.07143\mathrm{E}-004 \cdot C_S \cdot D_C - 3.18750 \cdot F_R \cdot D_C \\ & -4.34468\mathrm{E}-006 \cdot C_S^2 + 4.81404 \cdot F_R^2 - 0.93881 \cdot D_C^2 \end{aligned} \tag{3}$$

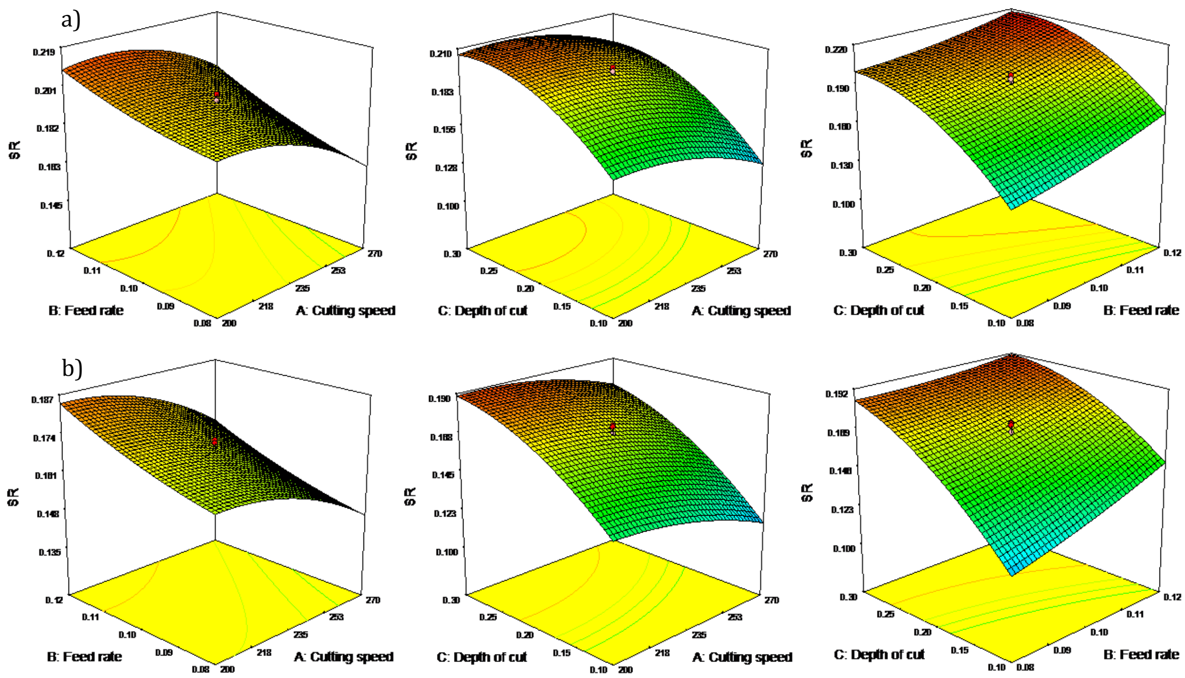

Fig. 3 Effects of process parameters on surface roughness: a) flood, b) MQL

4.2 Analysis of material removal rate

The material removal rate is calculated using Eq. 1 and results are tabulated in table 4. It has been examined that the *MRR* is more influenced by the D_C followed by C_S and F_R. The effects of cutting speed, feed rate, and depth of cut on the material removal rate is shown in Fig. 4. The maximum *MRR* (1.648 cm³/min) is obtained at the highest value of C_S (270 m/min), F_R (0.12 mm/rev), and D_C (0.3 mm) by experimental investigation as given in table 4. The experimental investigation shows that negligible differences present in *MRR* value for MQL and flood.

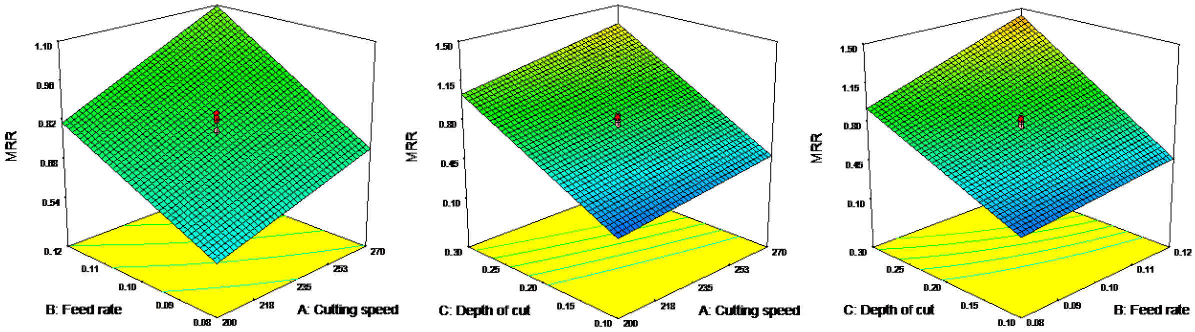

Fig. 4 Effects of process parameters on material removal rate

For more detailed analysis, ANOVA has been carried on the *MRR* data. The F-value indicates that the most significant factor for *MRR* is D_C that boosts production by increasing *MRR*. The significant factors for *MRR* are depth of cut; feed rate; cutting speed; feed rate × depth of cut. The empirical model for the prediction of *MRR* under flood and MQL is given in Eq. 4.

$$\begin{aligned} MRR_{flood=MQL} = \; & +0.50936 - 1.85714\text{E}-003 \cdot C_S - 9.20561 \cdot F_R - 2.23736 \cdot D_C \\ & +0.036607 \cdot C_S \cdot F_R + 7.53571\text{E}-003 \cdot C_S \cdot D_C + 43.68750 \cdot F_R \cdot D_C \end{aligned} \tag{4}$$

4.3 Analysis of strength

Fig. 5 illustrates experimentally the effects of process parameters and lubrication mode on the strength of material. The maximum value of *ST* has been achieved at the highest C_S and the lowest F_R and D_C. The strength has been improved using MQL and percentage improvement is ranging from 1.3-2.3 %. The most prominent observation of the data is less heat is attained at the lowest value of F_R and D_C, which produces a better surface finish and further improves the strength of the material.

The response surface plots describe the effects of C_S, F_R, and D_C on strength of the material as shown in Fig. 6. The strength of the material is more influenced by C_S as compared to D_C and F_R. The strength of the material is increased with the increase of C_S and decreased by increasing D_C and F_R. The maximum strength has been achieved at the highest C_S with the lowest F_R and D_C. Moreover, a greater value of strength is observed using MQL than flood lubrication. The maximum value of *ST* (1142MPa) at C_S (270 m/min), F_R (0.08 mm/rev) and D_C (0.1 mm) is attained using MQL. Further, it has been investigated that surface is finer at the lowest value of D_C and F_R, which produces less heat generation and greater strength.

The F-value suggests that C_S is the most important factor for strength followed by D_C and F_R. The significant terms are cutting speed; depth of cut; feed rate; feed rate squared; cutting speed squared for flood while cutting speed; depth of cut; feed rate; cutting speed squared; feed rate squared; depth of cut squared for MQL. The regression models for the prediction of *ST* under flood and MQL are given in Eq. 5 and Eq. 6, respectively.

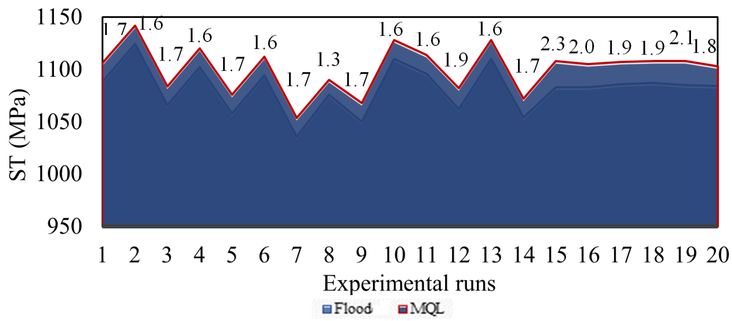

Fig. 5 Experimental results with percentage (%) improvement in strength

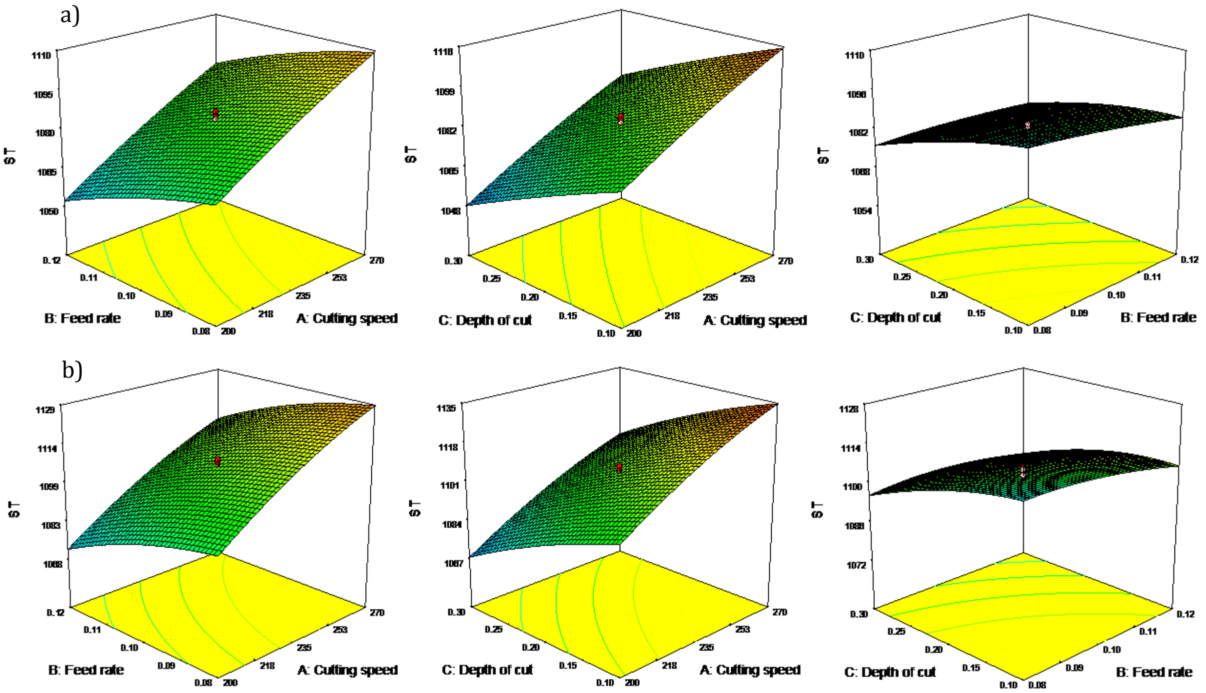

Fig. 6 Effects of process parameters on strength: a) flood, b) MQL

$$\begin{aligned} ST_{flood} = {} & +951.72416 + 1.01899 \cdot C_S + 221.67035 \cdot F_R - 178.38573 \cdot D_C \\ & +0.71429 \cdot C_S \cdot F_R + 0.14286 \cdot C_S \cdot D_C + 250.00 \cdot F_R \cdot D_C \\ & -1.27288\text{E}-003 \cdot C_S^2 - 4782.07149 \cdot F_R^2 - 85.21684 \cdot D_C^2 \end{aligned} \tag{5}$$

$$\begin{aligned} ST_{MQL} = {} & +846.59134 + 1.68089 \cdot C_S + 1003.59014 \cdot F_R - 63.28968 \cdot D_C \\ & -2.48622\text{E}-003 \cdot C_S^2 - 7614.03485 \cdot F_R^2 - 233.85072 \cdot D_C^2 \end{aligned} \tag{6}$$

4.4 Sustainable machining model

The sustainable machining model is shown in Fig. 7. It has been found that as a technical aspect *Ra* is improved up to 17 %, and *ST* improved up to 2.3 % using minimum quantity lubrication as a sustainable approach. It is also examined that using MQL reduces cutting fluid (CF) consumption that minimizes waste disposal, saves the environment, and reduces machining costs up to 17 %. It has been further noticed that using MQL reducing health hazards and improve worker's safety.

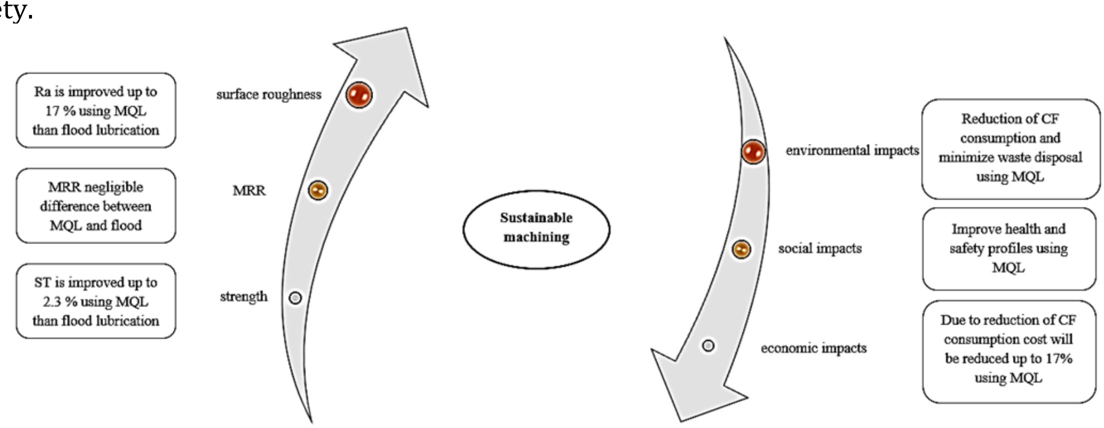

Fig. 7 Sustainable machining model

4.5 Multi-objective optimization associated with sustainability

Sustainable machining aims to achieve a better surface finish, high productivity, and strength of the material. Simultaneous optimizations of these objective functions lead to minimizing environmental damage with worker's safety and thus ensures sustainable production. The performance measures for the current research include *Ra*, *MRR*, and *ST*. To achieve a compromise between performance measures, this research proposed a desirability function-based multi optimization solution. The sustainability function is the combination of these objective functions and is given by relation 7.

$$Sustainability = \begin{Bmatrix} Minimize\ Ra \\ Maximize\ MRR \\ Maximize\ ST \end{Bmatrix} \tag{7}$$

Mostly, multi-response optimization techniques are used to produce a set of optimal solutions instead of a single solution. In this research, surface roughness, material removal rate, and strength have been designated as responses and optimized simultaneously. The responses are conflicting with each other due to which optimal solutions have been obtained through a numerical technique called the desirability approach in RSM established by Derringer and Suich [38] and mostly used for multi-response optimization problems [39, 40]. The desirability functions are smooth piecewise objective functions. In desirability profiling, a desirability function for each response is specified. The desirability values switch between the maximize (*higher is better*), target (*nominal/the best*), and minimize (*smaller is better*) values. Desirability function-based approach comprise of transforming the estimated quadratic response models into individual desirability functions that are then cluster into combined function. This function is generally a geometric or an arithmetic mean, which will be maximized or minimized, respectively. The processing and execution steps of desirability function method for calculating the desirability value and calculating the overall desirability function value and its optimization is taken care by the response surface methodology approach. Finally, it gives the optimum process parametric setting and minimizes *Ra*, maximize *MRR* and *ST* at optimum combinations. In this research, the combined desirability of 57.5 % for MQL and 56.6 % for flood lubrication has been achieved, which provides optimal solutions for minimum *Ra*, and maximum *MRR* and *ST* simultaneously. The optimization results are summarized in Table 5 which shows MQL is more desirable than flood lubrication.

Table 5 Optimization results are tabulated against the respective objectives

Response variable being optimized		Optimum process parameters			Optimum response values		
		C_S (m/min)	F_R (mm/rev)	D_C (mm)	*Ra* (μm)	*MRR* (cm^3/min)	*ST* (MPa)
Min. *Ra*	MQL	270	0.08	0.1	0.098	0.392	1142
	Flood	270	0.08	0.1	0.112		1124
Max. *MRR*	MQL	270	0.12	0.3	0.181	1.648	1090
	Flood	270	0.12	0.3	0.206		1076
Max. *ST*	MQL	270	0.08	0.1	0.098	0.575	1142
	Flood	270	0.08	0.1	0.112		1124
Min. *Ra*, Max. *MRR*, and Max. *ST*	MQL	270	0.09	0.15	0.131	0.64	1132
	Flood	270	0.09	0.14	0.144	0.609	1113

5. Conclusion

This research aimed to achieve sustainable machining by simultaneously optimizing sustainable machining drivers during high-speed machining of 15CDV6 HSLA steel under MQL and flood lubrication. The following conclusions are drawn from the research:

- It is concluded that minimum surface roughness and maximum strength have been achieved at the highest C_S and the lowest F_R and D_C with compromising *MRR*. Also, the maximum material removal rate is attained at the highest C_S, F_R, and D_C with negotiating surface roughness, and strength of the material. The optimal parameter combinations for best responses under MQL and flood lubrication are given in table 5.
- Optimization associated with sustainability produced compromising optimal results (Min. *Ra* (0.131μm), Max. *MRR* (0.64cm^3/min), and Max. *ST* (1132MPa) at the highest cutting speed 270m/min and the lowest feed rate 0.09mm/rev and depth of cut 0.15 mm for minimum quantity lubrication and confirmed that MQL is an alternative of a flood to enhance

the quality, productivity and strength of the material. The combined desirability for MQL (57.5 %) and flood (56.6 %) showed that MQL is more desirable than the flood.

- The results from experimental runs showed that an improvement in surface roughness (1.1-16.6 %), and strength (1.3-2.3 %) of the material using minimum quantity lubrication has been witnessed.

The research confirmed that minimum quantity lubrication has a potential for practitioners to improve the quality and strength of the material during high-speed machining under the umbrella of sustainability. The work would be beneficial in the field of aviation, defense, and aeronautical applications under the principles of sustainable manufacturing paradigms. The developed models will help the shop floor technician to predict the responses before experimenting. The evolutionary techniques can be explored to further investigate 15CDV6 HSLA steel.

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