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ORIGINAL ARTICLE

Performance Evaluation and Experimental Investigations in Turning of Iron Based A286 Nickel Alloy under Various Machining Conditions

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ABSTRACT – The advancement of materials in the last few decades has guided the development of many hard-to-machine materials, such as superalloys. These alloys have poor machinability characteristics. This paper examines the machinability performance characteristics of Iron-based A286 Nickel superalloy by varying the turning process parameters using uncoated and physical vapor deposition (PVD) coated inserts. Experiments were performed with an L16 orthogonal array using minimum quantity lubrication (MQL) machining and dry machining environments. The accomplishment of the turning process was evaluated in reference to the cutting forces and surface roughness. Optimum turning parameters to decrease the surface roughness and cutting forces using MQL and dry machining environments with PVD-coated and uncoated tools were found using analysis of means methodology. Results have indicated that feed rate would greatly influence surface roughness when using the uncoated tool in dry and MQL machining circumstances. The depth of cut would affect the cutting force and feed force more by using uncoated tools and PVD coated tools with MQL and dry machining environments. Tool wear results have revealed that PVD coated tool inserts by MQL machining would result in less tool wear than uncoated tools. Regression models were developed from the experimental outcomes to predict the performance characteristics. The coefficient of determination observed was more than 98%.

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1.0 INTRODUCTION

Superalloys are used where high-temperature resistance, corrosion resistance and high strength are needed. These alloys are used in aerospace industries, nuclear power plants, medical applications, and more. Several types of superalloys are used in different applications. One of these superalloys is A286 alloy. It is an Iron-based Nickel superalloy. This alloy is employed in superior strength, lower stress and corrosion resistance applications even at higher temperatures. The tensile and yield strength of this alloy are 620 MPa and 275 MPa, respectively. This superalloy is mostly used in reciprocating engine parts, aerospace parts, gas turbines, airplane engines, biomedical and turbine power plant applications. The high cutting force and reduced surface finish with rapid tool wear have been examined in the turning of Iron-based nickel superalloys using current techniques [1]. Cutting fluids in various forms are applied to understand the surface morphology of the machined surface, the wear behavior of the tool inserts and the morphology of chips in turning the A286 superalloy. The minimum quantity lubrication (MQL) and cooling method significantly decreased the roughness and tool wear. Thus, the current study sought to examine the strategy of combining sustainable MQL machining with multiple nozzles and different cutting tools in turning A286 alloy. This study aimed to optimize the turning conditions and assess the effectiveness of various cutting tool inserts, namely PVD coated and uncoated inserts under sustainable and eco-friendly MQL and dry turning of A286 alloy material. The optimum process parameters and best suitable tool insert with an optimal flow rate of cutting fluid may be found from the investigational results to improve the machinability and reduce the usage of coolant quantity in turning of A286 superalloy. The effectiveness of the MQL on the tool wear was also examined.

2.0 STATE-OF-THE-ART

In the manufacturing sector, machining is a very important process to obtain the desired dimensions and surface finish compared to other manufacturing processes. Different methods are used to improve surface finish in the machining process. A utility concept tool is employed for optimization, for example, an L8 orthogonal array (O.A.) is used to perform the trials, which are carried out on AISI 202 using Chemical Vapour Deposition (CVD) coated carbide tool [2]. According to optimization results, a higher nose radius, greater depth of cut, higher speed, and lower feed are the ideal turning parameters to decrease the roughness and increase the volume removal. Experimental investigations have been conducted on surface morphology and cutting forces with various chamfered angle tools in the machining of 718 Inconel alloy. The decline in cutting forces is observed with chamfered and honed edges [3]. The optimum settings to reduce the roughness

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and wear in dry cutting of A286 superalloy have been found. The impact of turning variables on chip structure, tool wear and roughness has also been examined [4]. Ultrasonic-assisted vibration machining (UAVM) was used with liquid carbon dioxide (LCO_2) and MQL to enhance the machinability of Ti6Al4V alloy. Experiments have been conducted to compare the machinability of Ti6Al4V alloy using conventional turning and ultrasonic-assisted turning under various cooling environments. The LCO_2 and UAVM have substantially reduced the specific cutting energy. LCO_2 and ultrasonic-assisted turning processes would encourage sustainability [5]. The milling of Incoloy A286 under various machining parameters has been performed. The milled parts' fatigue lifetime and surface integrity have also been investigated. The optimal process parameters have been suggested based on the results of surface integrity and fatigue life [6]. The different cooling techniques for machining alloys, such as conventional cutting fluids, MQL and liquid nitrogen (LN_2) have been reviewed. A nano additive MQL system has been suggested for the machining process towards sustainable machining. This technique has been proven to dissipate more heat [7]. The newly built-up nano PVD coated inserts have been used for continuous dry and MQL machining of Nickel alloys. It has been established that the performance of the cutting tool would improve, and friction would reduce when machining with MQL [8]. The machinability of superalloys such as Inconel 603XL, Incoloy 825, and others has been analyzed using the wire-cut electrical discharge machining (WEDM) process with varying process parameters. The results have shown that Monel K400 would exhibit superior performance compared to the other superalloys [9].

Iron aluminium oil with the near dry machining of Titanium alloy with a hard carbide insert (uncoated) has been assessed. The tool failure observed has been due to high adhesion, diffusion, abrasion and chipping under dry and MQL approaches. A total of 280% of the life of the tool has been found to have enhanced in MQL machining as contrasted with dry machining under the same machining conditions, and 12.38% of the cost decreased with MQL machining compared to dry turning [10]. The surface morphology of superalloys in the tuning process has been reviewed. The effects of various turning parameters and mechanical properties on surface reliability have also been reviewed. In addition, the changes in microstructure and residual stresses on the surface morphology have also been investigated [11]. The influence of various metal cutting conditions such as dry, MQL and hexagonal boron nitride (hBN) dispensed nanofluid MQL on several machining performance characteristics have been studied. It has been observed that roughness would reduce considerably with nanofluids associated to the dry machining environment. Furthermore, a notable drop in cutting temperature and forces has been attained with the nanofluid machining environment [12].

The working of textured tools under several cutting fluid conditions, including dry, nanofluids and Nitrogen cooling have been analyzed. The results of these studies have confirmed that textured tools with nanofluids would yield greater results than other cooling environments. It has also been observed that textured tools may be used as a sustainable alternative to the present cutting tools [13]. The state of the art of eco-friendly turning of Nickel superalloys with different tools have been reviewed. This review has been focused mainly on the tool wear analysis and cutting forces. The utilization of coatings on cutting inserts in dry machining has been found to be reasonably more efficient than that of uncoated tools [14]. The impact of coatings on tool wear with MQL and dry conditions has been studied. The results of these studies have shown that AlTiN, TiAlNþ AlCrN and AlCrN coatings exhibited superior performance than those TiAlNþ WC/C and Diamond-Like Carbon (DLC) coatings. Similarly, DLC and TiAlNþ coatings on Tungsten Carbide (WC) inserts have been found to exhibit enhanced performance on built-up edge development [15].

The impact of cryogenic and dry turning on chip morphology and shear angle in high-speed cutting of Ti6Al4V alloy has been studied. The results of these studies have indicated that cryogenic turning minimized the strain hardening influence and residual stresses due to the lower temperatures. This has led to enhanced tool life and diminished energy consumption. Higher shear angles have been observed in cryogenic turning [16]. The position of MQL nozzles to enhance the machining of Nimonic80 alloy has been examined. Tool wear has been found to be nearly 60% lesser for MQL with nano than in a dry machining environment. The findings of past studies have also confirmed that adhesion and abrasion wear-inducing tool wear systems are monitored with dry turning [17]. The inducement of graphite and Molybdenum disulfide (MoS_2) with various concentrations of nanofluid MQL on surface roughness, microhardness, temperature and tool wear in the machining of Inconel 625 has been scrutinized. It has been discovered that sunflower oil combined with MoS_2 produces exceptional surface quality compared to dry, nano MQL (nMQL) and MQL environments. The effectiveness of nano MQL with MoS_2 and graphite has been perceived in the lower tool wear development. The MQL, MQL with nano (Graphite) and nMQL with MoS_2 would lead to lesser machining temperatures as assessed to dry turning [18]. The precision machining execution of selective laser melting of additive manufactured Titanium alloy and the wear phenomena of TiAlN/AlCrN coated tools using dry as well as MQL machining environments have been examined. The surface quality has been found to be superior under MQL, which is associated with dry machining. The adhesive wear is more prominent in coated carbide inserts under MQL machining, whereas abrasive wear is the principal wear mechanism with dry machining [19]. The machinability of Nimonic90 has been evaluated under various lubricating conditions such as dry, hBN nanofluid, alumina nanofluid, hybrid nanofluid and compressed. The outcome of the hybrid nanofluid has shown significant improvement. Adhesion and Abrasion wear are common tool wear phenomena in all coolant conditions observed [20].

Considerable developments in tool wear and surface integrity have been noticed in turning with MQL and dry as compared with conventional flooded machining of SA516 steel using a coated tool [21]. Additionally, the surface topography, surface profile, and tool wear have been analyzed in the milling of Ti6Al4V using different sustainable machining methods. The average flank wear width predicted using the theoretical model has resulted in the prediction of a noticeable error of 15.87%. The performance of CO_2 - oil-on-water based MQL (scCO_2-OoWMQL) has shown better in lowering roughness and tool wear when evaluated by other coolants [22]. Drilling of titanium (Ti) alloy (VT) 20 alloy carried out under different cooling environments has resulted in an indigenously developed hybrid nanoparticle (NPs) immersed in electrostatic MQL (HNPEMQL) technique with improved functioning of drilling with respect to thrust force, tool wear, power consumption, microhardness and quality of hole [23]. Hastelloy is a difficult-to-machine superalloy. Hastelloy C276 has been machined in dry, near dry, and flooded environments. The experimental outcomes have shown that the MQL process would decrease the surface roughness, all forces and temperature by about 20% to 38% [24].

The effectiveness of ceramic cutting insert in the machining of X-750 Nickel based alloy has been demonstrated in various machining environments. The roughness has been decreased with base fluid-MQL without any merged nanoparticles (BF-MQL), and there has been a considerable decrease in cutting forces and temperature with hBN dispersed nanofluid-MQL (NF-MQL). Dry machining has shown lower tool wear than BF-MQL and NF-MQL [25]. The MQL strategy has shown favorable results for tool diameter reduction, flank wear and surface roughness, even though dry milling has yielded improved results in burr formation and residual stress as assessed to MQL machining circumstances [26]. Cryogenic cooling has shown a great influence on tool wear rate, and gradual tool wear in metal cutting of NiTi-shaped memory materials has also decreased considerably [27]. Sustainability machining approaches have been applied in turning Hastelloy C22. In relation to dry machining, the N_2 + MQL hybrid cooling strategy has decreased surface roughness, tool wear, and vibration significantly [28]. The influences of various machining environments in the milling of nickel-based GH4099 superalloy material with ceramic tool material have been studied. The milling force, machining temperature, and tool wear with MQL and MQL with water were reduced significantly, as evaluated by dry milling [29]. The machinability of Inconel 718 alloy has been examined with dry and MQL milling processes. It has been found that MQL machining would generate superior surface topography and increased tool life. The results estimated with machine learning algorithms have been in excellent agreement with the investigational data for sustainable machining processes [30]. UVAM of Ti6Al4V has been carried out using various cooling techniques to analyze the results for sustainable aspects. The machining forces and tool wear have been found to have decreased with UVAM compared to those with other machining strategies. Similarly, the cutting forces and tool wear were decreased with MQL machining compared to those with other cooling techniques [31].

Having reviewed the literature, it is understood that performance parameters can be enhanced by the appropriate choice of input parameters, which can generate a better surface finish and minimize the cutting forces. The current investigation was motivated towards the integration of minimizing the quantity of cutting fluid and eco-friendly cutting fluids. To the best of the author's awareness, experimental analysis in this orientation has not been carried out. The present work also used three nozzles arranged and placed at different angles around the tool and workpiece to supply the minimum quantity of coolant more effectively and concentrate at the tool insert and workpiece interface zone. A286 alloy is a difficult-to-cut material. Studies carried out on the turning of A286 alloy with MQL and dry machining conditions using PVD and uncoated tools have been lacking. Nevertheless, an investigation on the use of multiple nozzles in the MQL machining process, albeit limited, has been conducted. Therefore, a detailed investigation would be required to determine the influence of MQL machining with multiple nozzles and different cutting inserts in turning A286 alloy as the motive of a combined sustainable approach.

3.0 MATERIALS AND METHODS

This section provides details of the workpiece materials, machine tools, cutting tools, and cutting fluid used in the present study.

3.1 Workpiece material and cutting inserts

A286, an iron-based Nickel superalloy was used as a workpiece in the current work. The elemental chemical constitutions of the A286 alloy are specified in Table 1. The experimental details are presented in Table 2.

Table 1: Chemical Composition of A286 alloy (%)

Ni	Cr	Mo	Ti	Si	Mn	V	Al	C	P	B	S	Fe
26	15	1.3	2.1	0.5	1	0.3	0.2	0.04	0.02	0.01	0.02	54

The PVD coated SNMG 120408 MR3 CP200 insert is made with hard micro grain grade which is mainly used for machining hard-to-machine alloys. This insert is coated by (Ti, Al)N + TiN. The MR3 chip breaker is a profile of a positive rake angle which decreases cutting forces and contributes to high edge strength. The uncoated SNMG 120408 MF1 890 is made up of a high hardness micro grain grade which maintains good toughness and is designed for the machining of superalloys and titanium alloys. These inserts are made by SECO. The PSBNR 2525 M12 made by Sandvik Coromant tool holder was used in the current work to perform experiments. The geometry of the insert has an orthogonal rake and inclination angle of -6°, main cutting and auxiliary cutting-edge angles are 75° and 15° respectively, orthogonal and auxiliary clearance angles of 6° and 0.8 mm nose radius. The comprehensive experimental details are illustrated in Figure 1.

Table 2: Experimental details

Machine tool:	Kirloskar Turnmaster 35
Cutting tools:	Seco make Uncoated SNMG120408-MF1 890 and PVD coated with (Ti, Al) N + TiN; SNMG120408-MR3 CP200
Feed rate (F):	0.2, 0.25, 0.28, 0.315 mm/rev
Cutting speed (V):	26, 42, 67, 106 m/min
Depth of cut (D):	0.4, 0.6, 0.8, 1 mm
Air pressure (P):	4, 5, 6, 7 kg/cm^2

3.2 Experimentation

The experiments were conducted on Kirloskar Turnmaster 35, as shown in Figure 1. In this work, PVD coated and uncoated tools were used under MQL and dry machining environments. Orthogonal Array (O.A.) had been chosen based on the number of parameters (4), levels at every factor (4), overall mean (1), and overall degrees of freedom (DoF). Following these, the requisite lowest number of experiments to be performed was 13, and the closest O.A. meeting this requirement was L16. L16 O.A. was thus used to design and carry out the experiments. The principle objective of the current investigation was to assess the functioning of selected cutting tools in terms of machining forces, tool wear, and surface roughness. The optimization of the turning process parameters has arrived with Taguchi's L16 O.A.

Analysis of mean (AoM) is a tool used to find the optimum process variables, while analysis of variance (ANOVA) is a tool applied to find the importance of turning parameters on performance features. Minitab, a statistical tool, is used to obtain data analysis results. The process parameters (D, F and V) as indicated in Table 2 were chosen upon on workpiece material hardness and literature, while different amounts of air pressure (4, 5, 6, 7 kg/cm^2) were chosen based on the flow rate of cutting fluid required.

Experiments were performed under dry and MQL turning conditions on A286 alloy as per L16 O.A. as presented in Table 3 and Table 4. In dry machining, cutting fluid was not used. In Figure 1, the MQL setup is also illustrated. This setup consisted of an air compressor, fluid chamber, air regulator, filter, regulator, and lubricator (FRL) unit, nozzles for mist and timer. The coolant used in MQL machining was CUMI MUNTZOL 119. This fluid is a homogeneous water mixable emulsion type and was mixed with a 1:10 ratio. This fluid was free from chlorine, nitrites and formaldehyde. The MQL was applied to the turning zone with three nozzles. Three nozzles were used with MQL setup: one was placed above the workpiece centrally along the axis and the other two were arranged at an angle of 60° with either side of the central nozzle. The flow rate was calculated as the amount of cutting fluid discharged from each nozzle per unit time. The cutting fluid was supplied with different flow rates of 250, 300, 350 and 400 milliliters/hour (ml/hr) at the machining zone.

The length of the specimen and diameter chosen were 130 mm and 30 mm, respectively. The length of the machining was worked to 50 mm. Data for L16 O.A. with its controllable parameters and its levels are presented in Table 3 and Table 4. Experiments were conducted by varying the machining conditions as per the L16 O.A. under the dry machining process and MQL machining environments. Cutting forces and surface roughness were measured for each experiment. The SJ 411 surface roughness tester made by Mitutoyo was used to determine the surface roughness. Cutting forces were measured with an IEICOS digital multi-component lathe tool dynamometer. Tool wear was examined with the metallurgical microscope XJB-H100. Table 3 and Table 4 present the experimental results.

4.0 RESULTS AND DISCUSSIONS

The results of surface roughness, cutting force, feed force and thrust force for uncoated and PVD coated under dry and MQL machining environments are presented in Table 3 and Table 4, respectively. Consequently, detailed discussions of these results are provided.

4.1 Optimization of process parameters

The aim of the experiments was to decrease the surface roughness and cutting forces. Therefore, the lower they were, the better performance indicators would be used to analyze the results.

The optimization plots for surface roughness using uncoated tools in dry and MQL machining environments are illustrated in Figure 2. Feed rate at 0.2 mm/rev, Depth of cut at 1 mm and cutting speed at 67 m/min were observed to be the optimum process parameters with uncoated tool under dry machining conditions.

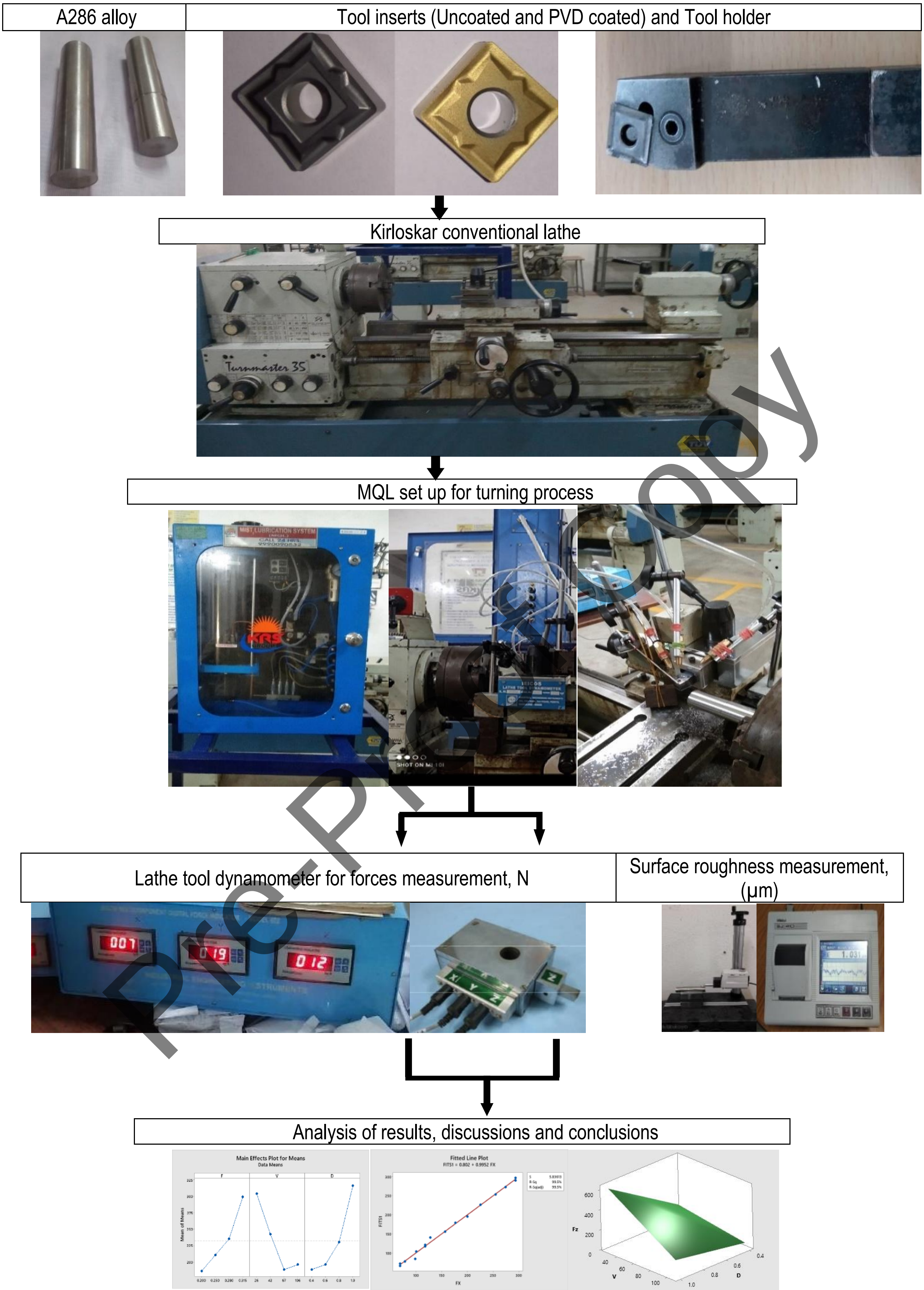


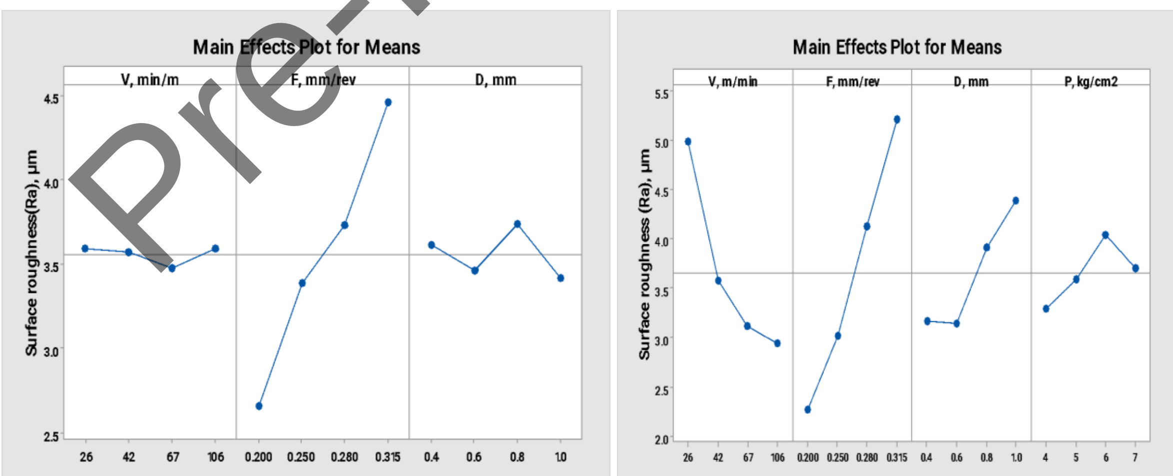
Figure 1. Experimental details

Table 3. Experimental results using uncoated tool

S. No.	V	F	D	P	Surface roughness (Ra), µm	Cutting force (Fz), N	Feed force, (Fx), N	Thrust force (Fy), N	Surface roughness (Ra), µm	Cutting force (Fz), N	Feed force, (Fx), N	Thrust force (Fy), N
					Dry Machining				***MQL Machining***			
1	26	0.2	0.4	4	2.98	220.61	60.34	151.98	2.44	201.00	73.54	142.17
2	26	0.25	0.6	5	3.29	377.50	142.18	210.81	3.54	387.30	161.79	201.01
3	26	0.28	0.8	6	3.71	524.57	210.81	210.81	6.49	534.38	230.42	299.06
4	26	0.315	1	7	4.39	779.50	308.86	250.03	7.51	759.89	299.06	348.08
5	42	0.2	0.6	6	2.59	161.78	44.12	142.17	2.21	279.44	112.76	151.98
6	42	0.25	0.4	7	3.26	230.42	73.54	171.59	2.89	230.42	73.54	161.79
7	42	0.28	1	4	3.85	691.26	249.63	210.81	4.19	701.06	279.45	191.20
8	42	0.315	0.8	5	4.59	642.23	210.81	250.03	5.02	553.99	191.39	201.01
9	67	0.2	0.8	7	2.73	416.45	161.78	161.78	1.80	397.10	171.59	151.98
10	67	0.25	1	6	3.10	416.72	151.98	181.40	3.28	603.01	259.84	171.59
11	67	0.28	0.4	5	3.73	308.86	102.96	181.40	3.19	210.81	73.54	142.18
12	67	0.315	0.6	4	4.35	475.95	151.98	201.01	4.20	406.91	122.57	181.40
13	106	0.2	1	5	2.34	671.64	250.03	220.61	2.60	544.18	289.25	161.78
14	106	0.25	0.8	4	3.91	514.77	203.41	201.01	2.35	387.30	132.37	161.79
15	106	0.28	0.6	7	3.63	514.77	203.35	201.01	2.63	338.28	102.96	171.59
16	106	0.315	0.4	6	4.49	397.11	122.57	201.01	4.16	259.84	83.35	191.20

Table 4. Experimental results using PVD Coated tool

S. No.	V	F	D	P	Surface roughness (Ra), µm	Cutting force (Fz), N	Feed force, (Fx), N	Thrust force (Fy), N	Surface roughness (Ra), µm	Cutting force (Fz), N	Feed force, (Fx), N	Thrust force (Fy), N
					Dry Machining				***MQL Machining***			
1	26	0.2	0.4	4	2.68	220.61	102.95	171.59	3.22	191.40	103.50	161.78
2	26	0.25	0.6	5	2.38	406.91	201.01	250.03	3.62	377.88	201.76	240.23
3	26	0.28	0.8	6	3.45	485.35	289.25	269.64	3.81	308.86	289.55	250.03
4	26	0.315	1	7	6.47	740.28	348.08	473.84	4.23	769.70	349.48	573.60
5	42	0.2	0.6	6	2.00	308.86	151.98	201.00	2.82	318.66	152.48	191.20
6	42	0.25	0.4	7	2.90	220.62	83.35	171.59	3.23	269.64	82.90	201.01
7	42	0.28	1	4	3.63	695.34	348.08	290.55	3.16	681.85	347.58	308.06
8	42	0.315	0.8	5	4.70	612.82	259.84	307.29	4.29	622.62	260.24	279.45
9	67	0.2	0.8	7	1.77	387.30	201.00	181.39	1.97	406.91	201.55	191.20
10	67	0.25	1	6	2.56	583.40	269.64	230.42	3.35	563.79	268.99	210.41
11	67	0.28	0.4	5	2.85	279.45	93.15	210.81	3.47	299.06	92.80	201.01
12	67	0.315	0.6	4	4.57	455.94	171.59	269.64	4.09	151.98	171.44	406.91
13	106	0.2	1	5	2.22	475.54	210.81	181.39	2.54	475.54	210.46	543.73
14	106	0.25	0.8	4	2.75	504.96	240.63	230.42	2.77	426.31	240.03	387.30
15	106	0.28	0.6	7	3.44	377.50	142.18	201.01	3.24	308.86	142.88	338.78
16	106	0.315	0.4	6	4.46	269.64	73.56	201.01	4.65	269.64	72.94	260.24



(a) (b)

Figure 2. Optimization plots using uncoated tools for surface roughness for (a) Dry machining, and (b) MQL machining

The prediction of performance characteristics under optimum conditions is essential and was achieved using Equation (1) and Equation (2).

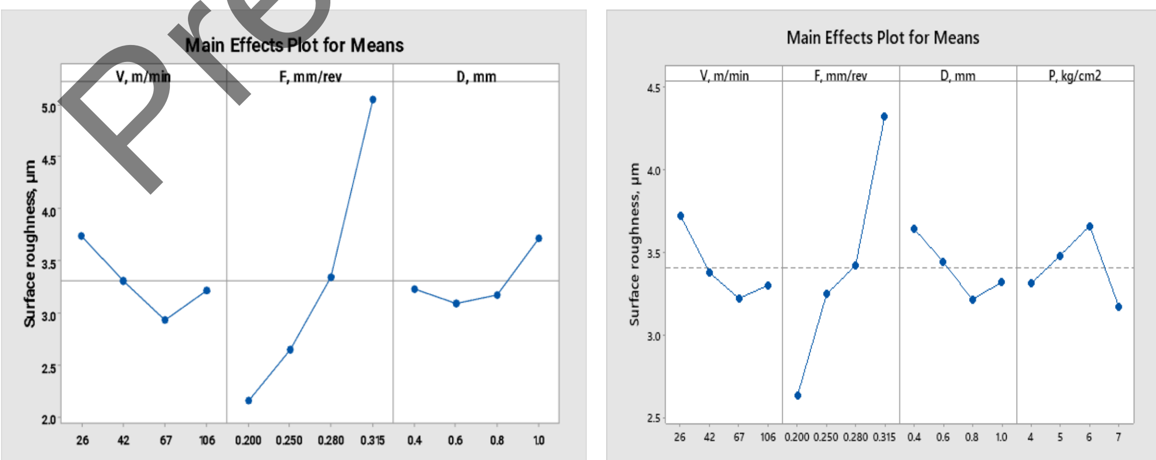
$$\eta_{predicted} = \eta + (\overline{Xo} - \eta) + (\overline{Yo} - \eta) + (\overline{Zo} - \eta)] \text{ for dry machining} \quad (1)$$

$$\eta_{predicted} = \eta + (\overline{Xo} - \eta) + (\overline{Yo} - \eta) + (\overline{Zo} - \eta) + (\overline{Wo} - \eta)] \text{ for MQL machining} \quad (2)$$

where Xo, Yo, Zo and Wo indicate the optimum levels for cutting speed, feed rate, depth of cut, and air pressure respectively.

The anticipated surface roughness was calculated using Equation 1. The surface roughness obtained with the verification experiment under optimum conditions was 2.514 µm and the anticipated surface roughness with optimum conditions was 2.436 µm. The percentage error between the confirmation experiment and the predicted result was 3.2 %. Similarly, the optimum conditions obtained under MQL machining using uncoated tool were feed at 0.2 mm/rev, depth of cut at 0.6 mm, machining speed at 106 m/min and air pressure of 4 kg/cm^2, respectively. The MQL flow rate obtained with 4 kg/cm^2 air pressure was 250 ml/hr. The surface roughness obtained with the confirmation experiment under optimum conditions was 0.715 µm. Predicted surface roughness had been calculated using equation (2) with optimum conditions. The predicted surface roughness was 0.67 µm. The percentage error between the confirmation experiment and the predicted result was 6.71 %. These results have clearly indicated that MQL machining would reduce the surface roughness owing to sufficient cooling and lubrication and cooling being produced at the cutting region. As shown in Figure 2, it has been noted that there was a decline in roughness with a rise in speed commencing from 26 m/min to 67 m/min because of extreme friction produced along the work metal and tool interface zone thus causing a thermal softening influence on the component. As the feed rate rose, the roughness increased because of an increase in tool chatter, vibration and an increase of contact region across the tool and workpiece. Similarly, with a rise in depth of cut, a rise in surface roughness was noticed. A rise in air pressure in the MQL system from 4 kg/cm^2 to 6 kg/cm^2 an increase in surface roughness was observed. This indicates that low pressure provided sufficient cooling and lubrication, thereby surface roughness would be less at lower pressure.

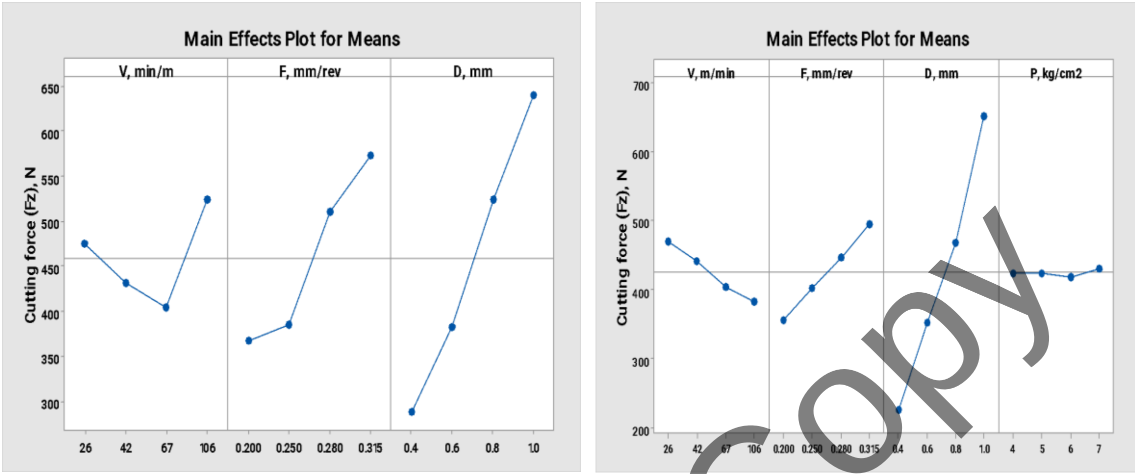
The optimization plots for surface roughness using PVD coated tool are illustrated in Figure 3. The machining speed at 67 m/min, 0.60 mm depth of cut and feed at 0.20 mm/rev were found to be the optimum levels under dry tuning using PVD coated tools. Equation 1 was used to calculate the predicted surface roughness. The roughness attained from the validation experiment under optimum conditions was 1.635 µm compared to the estimated surface roughness with optimum conditions of 1.593 µm. The percentage error across the verification experiment and predicted result was 2.63%. Similarly, the optimum conditions obtained with MQL machining using PVD coated tools were depth of cut at 0.8 mm, feed rate at 0.2 mm/rev, cutting speed at 67 m/min and air pressure at 7 kg/cm^2. The MQL flow rate obtained with 7 kg/cm^2 of air pressure was 400 ml/hr. The predicted surface roughness was calculated using Equation 2. The roughness obtained with the confirmation experiment under optimum conditions was 1.926 µm and the predicted roughness with optimum conditions was 2.022 µm. The percentage of error connected with the validation experiment and the predicted result was 4.74%. These results have indicated that MQL machining would reduce roughness because of sufficient cooling and lubrication produced at the machining region [5]. As presented in Figure 3, in the present study, the roughness reduced with the enhancement of the machining speed from 26 to 67 m/min owing to more friction having been created across the tool and workpiece, thus causing a thermal softening influence on the workpiece. As the feed rate rose, the roughness also increased because of rise in the tool vibration, chatter and interaction length across the tool and the workpiece. The change in roughness was noticed with the change in air pressure in the MQL system. It has been noted that at higher pressure, the roughness would be less because of the existence of adequate cooling and lubrication at the cutting region, which would decrease the friction.



(a) (b)

Figure 3. Optimization plots using PVD coated tools for surface roughness for (a) Dry machining, and (b) MQL machining

The optimization plots for the cutting force with uncoated tools are illustrated in Figure 4. It has been noted that the optimum levels of 0.2 mm/rev of feed rate, 67 m/min of cutting speed and depth of cut at 0.40 mm were achieved using dry machining with uncoated tool. The predicted cutting force was computed using Equation 1. The cutting force obtained with the confirmation experiment under optimum conditions was 152.53 N, whereas the anticipated cutting force under optimum conditions was 143.34 N. The percentage error between the confirmation experiment and the predicted result was 6.41%. Similarly, the optimum conditions obtained under MQL machining using uncoated tools were feed rate at 0.20 mm/rev, depth of cut at 0.40 mm, cutting speed at 106 m/min and air pressure at 6 kg/cm^2. The MQL flow rate obtained with 6 kg/cm^2 air pressure was 350 ml/hr. The predicted cutting force was determined using Equation 2. The cutting force obtained with the confirmation experiment under optimum conditions was 114.12 N, while the predicted cutting force under optimum conditions was 108.46 N. The percentage of error between the confirmation and predicted results was 5.21%.

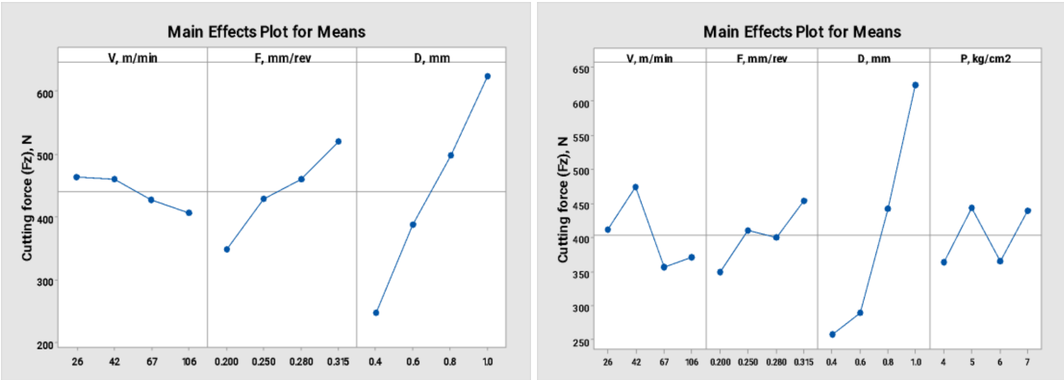


(a) (b)

Figure 4. Optimization plots for cutting force (Fz) using uncoated tools for (a) Dry machining, and (b) MQL machining

The results, as illustrated in Figure 3 and Figure 4, have indicated that MQL machining would reduce the cutting force due to sufficient lubrication and cooling produced at the cutting region. As indicated in Figure 4, apparently, cutting force would be reduced through enhancement in cutting speed from 26 to 67 meters per minute with dry machining. MQL machining would decrease the cutting force with a rise in speed. This is because more friction would be generated across the work metal and tool, leading to a thermal softening result on the workpiece. It may be understood from Figure 4 that a step up in the feed rate from 0.20 to 0.315 mm/rev would result in an upsurge in the cutting force, as observed using dry machining and MQL machining environments. It has also been noted that the cutting force would rise with an enhance in the depth of cut. This was due to the presence of high tool chatter, vibration and contact region across the tool insert and the work material. The change in the cutting force was noticed with the change in air pressure in the MQL system. As pressure increased, the volume of cutting fluid flow rate would also increase, leading to the breaking of chips into small pieces and rapid removal of heat from the machining zone.

Figure 5 shows the optimization graphs for the cutting force using PVD coated inserts. The feed rate at 0.20 mm/rev, 0.40 mm depth of cut and cutting speed at 106 m/min were attained to be the optimum turning levels under dry machining with PVD coated inserts. The anticipated cutting force was determined using Equation 1. The cutting force obtained with the confirmation experiment under optimum conditions was 129.34 N and the predicted surface roughness under optimum conditions was 124.5 N. The percentage of error involved in the confirmation experiment and the predicted result was 3.88%. Similarly, the optimum parameters achieved with MQL machining and uncoated tools were 0.2 mm/rev of feed rate, cutting speed at 67 m/min and 0.4 mm of depth of cut and air pressure with 4 kg/cm^2. The MQL flow rate obtained with 4 kg/cm^2 air pressure was 250 ml/hr. These results have indicated that MQL machining would reduce the cutting force because sufficient lubrication and cooling would be produced at the cutting zone. The predicted cutting force was determined using Equation 2. The cutting force obtained with the confirmation experiment under optimum conditions was 109.12 N and the anticipated cutting force with optimum conditions was 115.87 N. The error percentage among the confirmation experiment and the predicted result was 5.82%. As shown in Figure 5, it has been noticed that the cutting force would reduce with an increase in the cutting speed under dry cutting. This was due to the high friction produced next to the tool and the workpiece boundary zone, which caused a thermal softening influence on the workpiece. Figure 5 also illustrates the rise in the cutting force which corresponded with a rise in the depth of cut using dry and MQL cutting processes. It can also be seen in Figure 5 that the cutting force increased with the rise in the feed rate under dry machining process. This was due to a rise in the tool chatter, vibration and interaction region between the tool and the specimen.

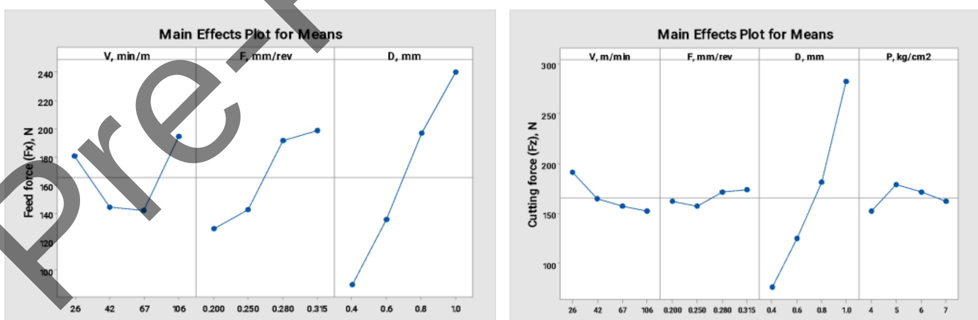


(a) (b)

Figure 5. Optimization plots for cutting force (Fz) using PVD coated tools for (a) Dry machining, and (b) MQL machining

The optimization plots for the feed force with the uncoated tools are illustrated in Figure 6. It has been evident that 0.2 mm/rev of feed, 67 m/min of cutting speed and 0.4 mm depth of cut were found to be the optimum turning process levels under dry machining with the uncoated tools. The predicted feed force was determined using Equation 1. The feed force obtained with the confirmation experiment under optimum conditions was 31.16 N, while the predicted feed force under optimum conditions was 30.04 N. The percentage error between the confirmation experiment and the predicted result was 3.69%. Similarly, the optimum conditions obtained under MQL machining using uncoated tools were 0.25 mm per revolution of feed, 106 m/min of cutting speed, 0.4 mm of depth of cut and air pressure at 4 kg/cm^2. The MQL flow rate obtained with 4 kg/cm^2 air pressure was 250 ml/hr. The predicted feed force was calculated using Equation 2. The feed force obtained with the confirmation experiment under optimum conditions was 41.26 N and the predicted feed force under optimum conditions was 38.574 N. The error percentage between the confirmation experiment and the predicted result was 6.96%.

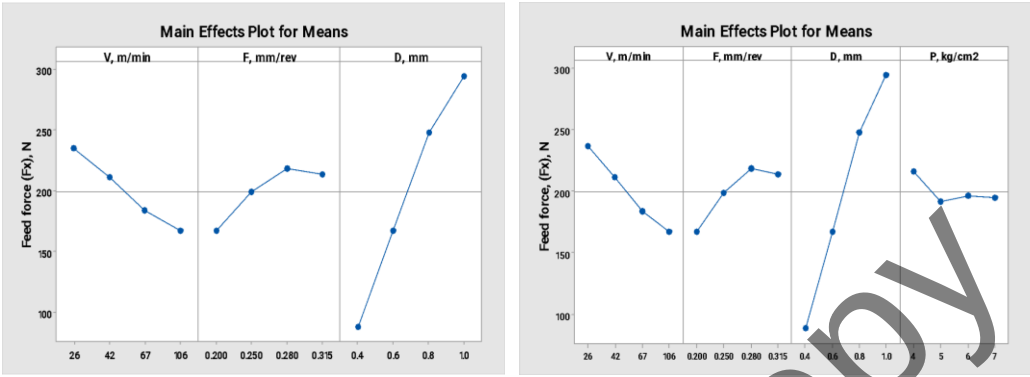
Figure 6 shows that a reduction in the feed force was observed with a rise in the machining speed from 26 to 67 m/min with dry machining. This is because of excessive friction produced across the tool and the work metal directing to a thermal softening cause on the workpiece. In MQL machining, a greater reduction in the feed force was noted with a raise in machining speed starting from 26 to 106 m/min. It can also be seen as shown in Figure 6, that the feed force increased with increasing depth of cut and feed rate under both the dry machining and MQL conditions. This was due to an increase in the tool chatter, vibration and interaction region along the tool insert and the specimen. The change in the feed force has been noticed with the change in air pressure in the MQL system. It has been observed that the feed force would decrease with rising air pressure from 5 to 7 kg/cm^2. This was due to the presence of sufficient infringement of the coolant at extreme pressure in the interaction zone across the tool–chip interface.



(a) (b)

Figure 6. Optimization plots for feed force (Fx) using uncoated tools for (a) Dry machining, and (b) MQL machining

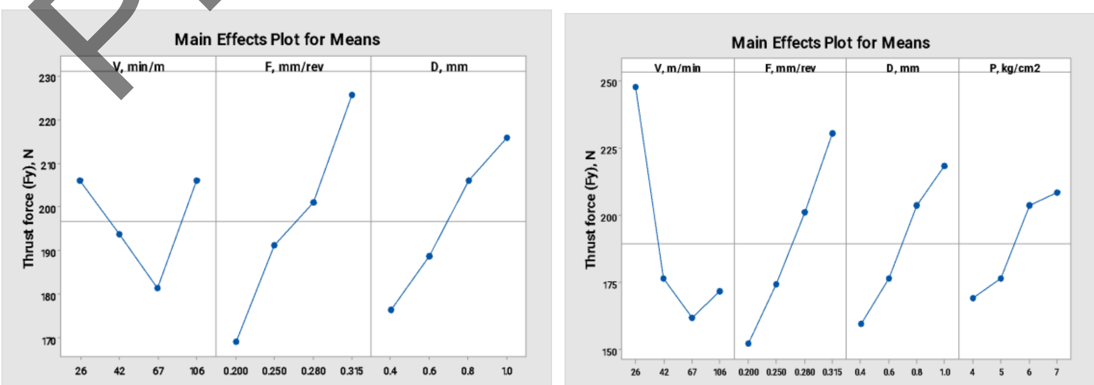
The optimization plots using PVD coated tools for the feed force are shown in Figure 7. It has been observed that 106 m/min of cutting speed, depth of cut at 0.40 mm and 0.20 mm/rev of feed rate were the optimum turning levels under dry machining. The predicted feed force was determined using Equation 1. The feed force obtained with the confirmation experiment under optimum conditions was 25.18 N, whereas the predicted feed force under optimum conditions was 23.34 N. The percentage error between the confirmation experiment and predicted result was 7.88%. Similarly, the optimum conditions obtained with MQL machining were the feed of 0.20 mm/rev, depth of cut at 0.40 mm, machining speed at 106 m/min and air pressure at 5 kg/cm^2. The MQL flow rate obtained with 5 kg/cm^2 air pressure was 300 ml/hr. The predicted feed force was calculated using Equation 2. The feed force obtained with the confirmation experiment under optimum conditions was 14.54 N, while the predicted feed force under optimum conditions was 15.06 N. The percentage error between the confirmation experiment and the predicted result was 3.45%. These results have indicated that MQL machining would reduce the feed force due to sufficient lubrication and cooling produced at the machining zone. As shown in Figure 7, it was noted that feed force declined with an increase in the machining speed in both dry and MQL machining processes. This was due to the high friction generated across the tool and the work metal, causing a thermal softening effect on the workpiece. It was also noted that the feed force rises with an increase in the feed rate in both dry and MQL machining processes from 0.2 to 0.28 mm per revolution. This was due to rising tool chatter, vibration and interaction regions among the cutting tool and work metal. As illustrated in Figure 7, the feed force rose with the rising depth of cut in both dry and MQL machining processes. This was due to an increase in the tool chatter and vibrations at the contact region between the workpiece and the tool [20].



(a) (b)

Figure 7. Optimization plots for feed force (Fx) using PVD coated tools for (a) Dry machining, and (b) MQL machining

The optimization plots for thrust force with uncoated tools are illuminated in Figure 8. It was perceived that the feed rate of 0.2 mm/rev, the speed of 67 m/min and the depth of cut of 0.4 mm were the optimum levels for uncoated tools under dry machining. The anticipated thrust force was calculated using Equation 1. The thrust force obtained with the confirmation experiment under optimum conditions was 135.38 N, whereas the predicted thrust force under optimum conditions was 133.59 N. The error percentage between the confirmation experiment and the predicted result was 1.33%. Similarly, the optimum conditions obtained under MQL machining using uncoated tools were 0.2 mm per revolution of feed, speed 67 m/min, 0.4 mm of depth of cut and air pressure at 4 kg/cm^2. The MQL flow rate obtained with 4 kg/cm^2 air pressure was 250 ml/hr. The predicted thrust force was calculated using Equation 2. These results have indicated that MQL machining would reduce the thrust force caused by sufficient lubrication and cooling produced at the machining region. The thrust force obtained with the confirmation experiment under optimum conditions was 80.24 N, while the predicted thrust force under optimum conditions was 74.14 N. The percentage error between the validation experiment and the predicted outcome was 8.21%. As can be seen in Figure 8, the thrust force is reduced as the machining speed increases, starting from 26 to 67 m/min, in dry machining and MQL machining processes. This was due to increasing friction, causing thermal softening results on the work material. It is noticeable in Figure 8 that the thrust force rose with increasing feed rate and depth of cut using dry and MQL machining processes. This was due to a rise in the tool chatter, vibration and interaction area across the tool and the workpiece. The variation in the thrust force was noticed with the change in air pressure in the MQL system. It was also noticed that the thrust force increased with the rise in air pressure. This was due to insufficient lubrication and cooling effect at the interface zone between the tool and the chip interface region.

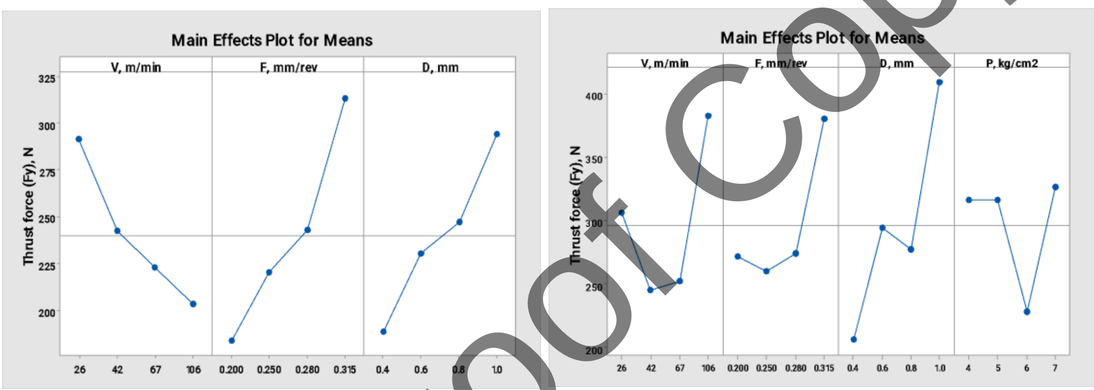


(a) (b)

Figure 8. Optimization plots for thrust force (Fy) using uncoated tools for (a) Dry machining, and (b) MQL machining

The optimization plots for thrust force using PVD coated tools are shown in Figure 9. It was noticed that 106 m/min of cutting speed, 0.20 mm/rev feed rate and 0.40 mm of the depth of cut were the optimum levels with dry machining using PVD coated inserts. The thrust force was predicted using Equation 1. The thrust force obtained with the confirmation experiment under optimum conditions was 101.02 N in contrast to the predicted thrust force under optimum conditions was 95.16 N. The percentage error among the confirmation experiment and the predicted result was 6.15%.

Similarly, the optimum conditions obtained with MQL machining using PVD coated tools were 0.25 mm/rev of feed rate, 42 m/min of cutting speed and 0.4 mm depth of cut and air pressure at 6 kg/cm^2. The MQL flow rate obtained with 6 kg/cm^2 air pressure was 350 ml/hr. The predicted thrust force was calculated using Equation 2. The thrust force obtained with the confirmation experiment under optimum conditions was 49.4 N, which was slightly higher than the predicted thrust under optimum conditions of 48.96 N. The percentage error across the validation experiment and predicted result was 0.89%. These results have indicated that MQL machining decreased with the thrust force owing to the sufficient cooling and lubrication produced at the machining zone. Figure 9 shows that it has been detected that the thrust force reduced with the rising speed in the dry machining process. This was due to elevated friction created between the tool and the specimen, which led to a thermo-softening effect on the work metal. The thrust force rose with an increase in the feed rate and the depth of cut under the dry machining process. This was due to rising tool chatter, vibrations, and contact areas across the tool and the workpiece. The variation in the thrust force has been noticed with a change in air pressure in the MQL system. The summary of each of the optimum process parameters obtained under various machining environments is presented in Table 5 and Table 6 correspondingly. The summary and comparison of performance characteristics under different machining conditions are presented in Table 7.



(a) (b)

Figure 9. Optimization plots for thrust force (Fy) with PVD coated tools for (a) Dry machining, and (b) MQL machining

Table 5. Summary of optimum turning variables with dry machining

Performance characteristics	V, m/min	F, mm/rev	D, mm	Predicted value	Confirmation test value	Percentage error
Dry machining with uncoated tool						
Ra, μm	67	0.2	1.0	2.436	2.514	3.202
Fz, N	67	0.2	0.4	143.34	152.53	6.411
Fx, N	67	0.2	0.4	30.049	31.16	3.697
Fy, N	67	0.2	0.4	133.59	135.38	1.339
Dry machining with coated tool						
Ra, μm	67	0.2	0.6	1.593	1.635	2.637
Fz, N	106	0.2	0.4	124.50	129.34	3.887
Fx, N	106	0.2	0.4	23.34	25.18	7.883
Fy, N	106	0.2	0.4	95.16	101.02	6.158

A confidence interval level was calculated using Equation 3 to confirm the findings. The validation trial test outcome was found to be within the range of the interval level of the confidence interval limits (CIL) of the anticipated outcome [8].

$$CIL = \sqrt{Fe_{\sigma}(1, ferr) * MSS * \left[\frac{1}{n_{effe}} + \frac{1}{Re}\right]} \tag{3}$$

where *ferr* is an error DoF, Fe_{σ} (1, ferr) is a fraction to Fisher's for σ, σ is a risk, MSS is an error variance, n_{effe} is an effectual quantity of replication and is established with empirical Equation (4).

$$\eta_{effe} = \frac{N}{(1+[Total\ DoF\ \ related\ to\ mean\ estimation])} \tag{4}$$

Table 6. Summary of optimum process parameters with MQL machining

Performance characteristics	Cutting speed, m/min	Feed rate, mm/rev	Depth of cut, mm	Pressure, kg/cm^2	Predicted value	Confirmation test value	Percentage error
MQL machining with uncoated tool							
Ra, µm	106	0.2	0.6	4	0.67	0.715	6.716
Fz, N	106	0.2	0.4	6	108.465	114.12	5.214
Fx, N	106	0.25	0.4	4	38.574	41.26	6.963
Fy, N	67	0.2	0.4	4	74.1478	80.24	8.216
MQL machining with coated tool							
Ra, µm	67	0.2	0.8	7	2.022	1.926	4.748
Fz, N	67	0.2	0.4	4	115.87	109.12	5.825
Fx, N	106	0.2	0.4	5	15.06	14.54	3.453
Fy, N	42	0.25	0.4	6	48.96	49.4	0.899

Table 7. Summary and comparison of performance characteristics under various machining conditions

Performance characteristics	Dry machining	MQL machining	Dry machining	MQL machining
	Uncoated tool		Coated tool	
Ra, µm	2.514	0.715	1.635	1.926
Fz, N	152.53	114.12	129.34	109.12
Fx, N	31.16	41.26	25.18	14.54
Fy, N	135.38	80.24	101.02	49.4

$\eta_{effe} = \frac{N}{(1+9)} =$ 3.2; N = 32; fer is error; DoF = 22; $Fe_{0.05,\,(1,22)}$ = 4.30 for dry machining

$\eta_{effe} = \frac{N}{(1+12)} =$ 2.46; N = 32; fer is error; DoF = 19; $Fe_{0.05,\,(1,19)}$ = 4.38 for MQL machining

where Re is the number of repetitions for the confirmation test = 2.

The CIL was determined at 95 percent for each performance characteristic through Expression (3) for PVD coated and uncoated tools. The calculated CIL values and predicted performance characteristics with their CIL are presented in Table 8. The confirmation experimental values were well within the limits of the confidence interval (C.I.) of predicted performance characteristics.

4.2. *Impact of machining process parameters*

The effects of process variables on the turning process were found by performing an analysis of variance (ANOVA). Table 9 presents the impact of turning variable parameters on performance characteristics, which is indicated in percentages. It was detected that the feed contributed to high roughness by 91.0% and 53.68% using uncoated tools with dry and MQL machining, respectively. Correspondingly, the feed was highly influential in determining the roughness of the surface with PVD coated inserts by 83.92% and 78.10% using dry and MQL machining, respectively. The depth of cut also greatly influenced the cutting and feed forces by bare and PVD layered inserts with dry and MQL cutting environments, correspondingly, as presented in Table 8 [9]. This was due to the cutting tool being exposed to horizontal and vertical loads; therefore, the depth of cut was more influential over the cutting speed and the feed. Thus, the cutting and feed forces were identified to be more sensitive than the thrust force. This led to more errors in the thrust force than in the cutting and feed forces. The feed rate affected the thrust force more when uncoated inserts were used as well as in the case of PVD coated inserts with dry machining environments. The depth of cut and the cutting speed contributed to greater thrust force with uncoated and PVD coated tools respectively, with MQL machining environments. The impelling force would push the tool insert out of the machining zone in the opposite direction of the depth of cut. The coefficient of determination (R^2) for all the performance characteristics was nearer to 1. This indicates that the investigational results may be acceptable in order to proceed to further analysis such as regression analysis and the testing of the robustness of the instruments used for experimentation.

The coalesced influence of major process parameters using different tools on surface roughness with MQL and dry cutting conditions are illustrated in Figure 10. It was noticed the combined effects were almost similar with those using uncoated and coated inserts under MQL and dry machining situations. It was perceived that the roughness of the surface rose with a rising feed rate due to raise in vibration and chatter. In addition, the roughness increased with the increased depth of the cut with uncoated tools. The mutual effects of a rise in speed and feed increased the roughness in experiments using coated tools. The combined effects of major turning input parameters on the cutting force with coated and uncoated inserts using MQL and dry metal cutting experiments are illustrated in Figure 11. It was detected that the main force was enhanced with an increase each in the depth of cut using uncoated tools due to increasing contact length and friction under dry and MQL machining processes with uncoated tools. This also indicates that the main force rose with increasing depth of cut because of the rise in chatter with the coated tools.

The combined effects of major turning parameters on the feed force with PVD coated and uncoated inserts using MQL and dry environments are illustrated in Figure 12. The feed force increased with an increase in the depth of cut due to an increasing contact length and friction, which were observed with uncoated inserts and coated inserts in MQL and dry machining environments. At the same time, an increase in the feed force was observed to be less with a rise in the speed. This was due to the rising interaction length between the tool and the specimen, in addition to the friction and chatter at the cutting zone. The combined results of the major turning process parameters on the thrust force with different tools using MQL and dry machining environments are illustrated in Figure 13. As the feed rate increased, a rise in the thrust force was observed with bare coated tools in MQL and dry machining environments. The combined effects of both increasing feed and speed resulted in increasing thrust force because of the increase in the length of cut between the work metal, the tool and the chatter.

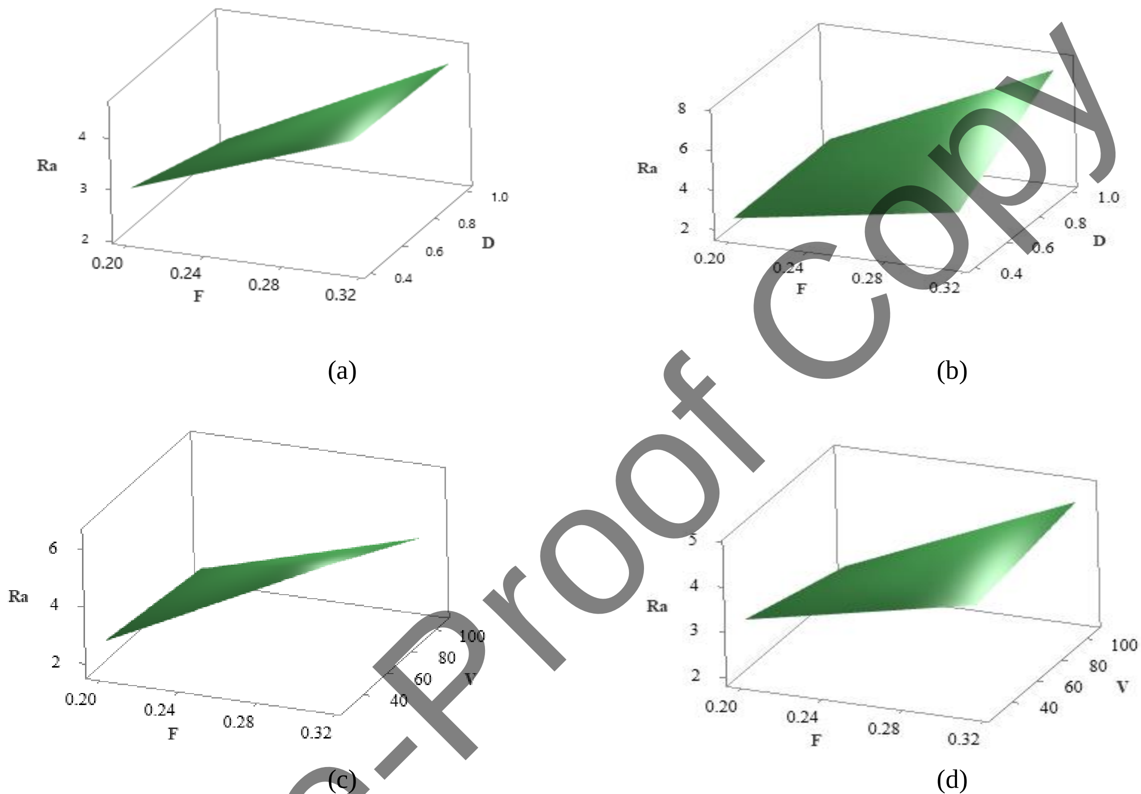


Figure 10. Surface plots for major influence parameters as combined effects on surface roughness for (a) Dry turning with uncoated tool, (b) MQL turning using uncoated tool, (c) Dry turning using PVD coated tool, and (d) MQL turning using PVD coated tool

Table 8. Confidence interval level (CIL) values

Type of tool	**Uncoated tool**								**PVD coated tool**							
Machining environment	**Dry - Uncoated**				**MQL - Uncoated**				**Dry - Coated**				**MQL - Coated**			
Performance characteristic	**Ra**	**Fz**	**Fx**	**Fy**	**Ra**	**Fz**	**Fx**	**Fy**	**Ra**	**Fz**	**Fx**	**Fy**	**Ra**	**Fz**	**Fx**	**Fy**
Fe_{α} (1, fer)	4.3	4.3	4.3	4.3	4.38	4.38	4.38	4.38	4.3	4.3	4.3	4.3	4.38	4.38	4.38	4.38
MSS	0.071	3115	48.7	74.9	0.056	1824.6	63.1	22.05	0.11	217	32	77.12	0.2008	258	8.2	62.35
$1/n_{effe}$	0.3125	0.312	0.312	0.312	0.406	0.406	0.406	0.406	0.31	0.3125	0.3125	0.312	0.406	0.406	0.406	0.406
$1/Re$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
C.I.L	0.499	104.3	13.043	16.17	0.474	85.09	15.82	9.35	0.62	27.53	10.57	16.41	0.89	31.99	5.70	15.72
Predicted Performance characteristic (Pre)	2.436	143.3	30.04	133.59	0.67	108.46	38.57	74.14	1.59	124.50	23.34	95.16	2.022	115.87	15.06	48.96
Pre-C.I	1.936	39.01	17.00	117.41	0.195	23.37	22.75	64.79	0.972	96.96	12.76	78.74	1.130	83.87	9.35	33.23
Pre+C.I	2.935	247.6	43.09	149.76	1.144	193.55	54.39	83.50	2.21	152.03	33.91	111.57	2.915	147.86	20.76	64.69
Confirmation experiment	1.945	64.85	49.05	107.91	0.715	124.52	43.56	83.14	1.82	142.34	26.48	109.02	1.754	99.42	18.65	40.24

Table 9. Impact of machining process parameters on surface roughness, cutting force, feed force and thrust force

Parameters	**Percentage Contribution, %**															
	Surface roughness, µm				**Cutting force, N**				**Feed force, N**				**Thrust force, N**			
	Dry	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**	**Dry**	**MQL**
	Uncoated		**PVD coated**		**Uncoated**		**PVD coated**		**Uncoated**		**PVD coated**		**Uncoated**		**PVD coated**	
Cutting Speed	0.481	27.897	5.876	7.849	6.910	4.010	2.247	7.0760	9.972	3.594	9.139	9.358	11.304	**38.495**	19.840	20.725
Feed rate	**91.00**	**53.687**	**83.92**	**78.103**	24.623	9.395	15.682	4.753	17.441	0.774	5.415	5.363	**44.854**	28.709	**41.279**	16.130
Depth of cut	3.427	11.883	4.243	5.491	**59.612**	**86.097**	**78.808**	**71.027**	**63.420**	**91.868**	**82.931**	**82.795**	25.116	17.418	26.519	**36.339**
Air pressure		3.010		7.213		0.0670		5.0636		1.623		1.229		9.427		10.8581
Error	5.085	3.520	5.957	1.341	8.853	0.429	3.260	12.0793	9.165	2.139	2.513	1.253	18.724	5.950	12.360	15.946
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
R^2 (%)	94.91	96.48	94.04	98.66	91.15	99.57	96.74	87.92	90.83	97.86	97.49	98.75	81.28	94.05	87.64	84.05

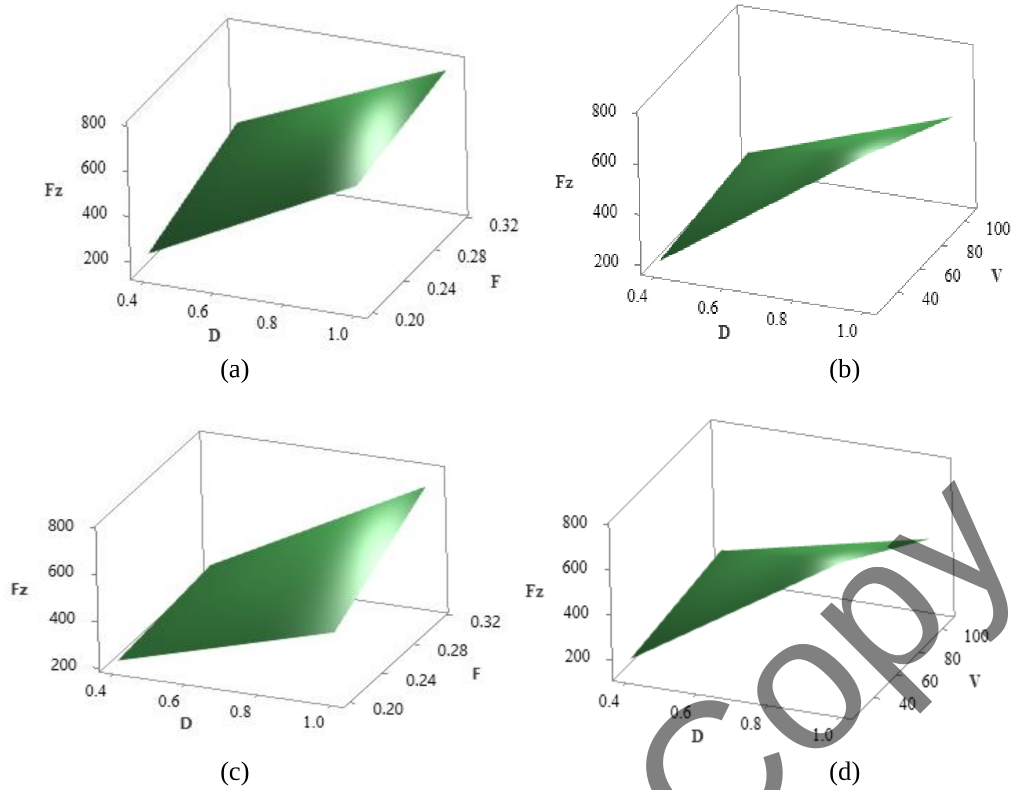


Figure 11. Surface plots for major influence parameters as combined effects on cutting force for (a) Dry turning with uncoated tool, (b) MQL turning using uncoated tool, (c) Dry turning using PVD coated tool, and (d) MQL turning using PVD coated tool

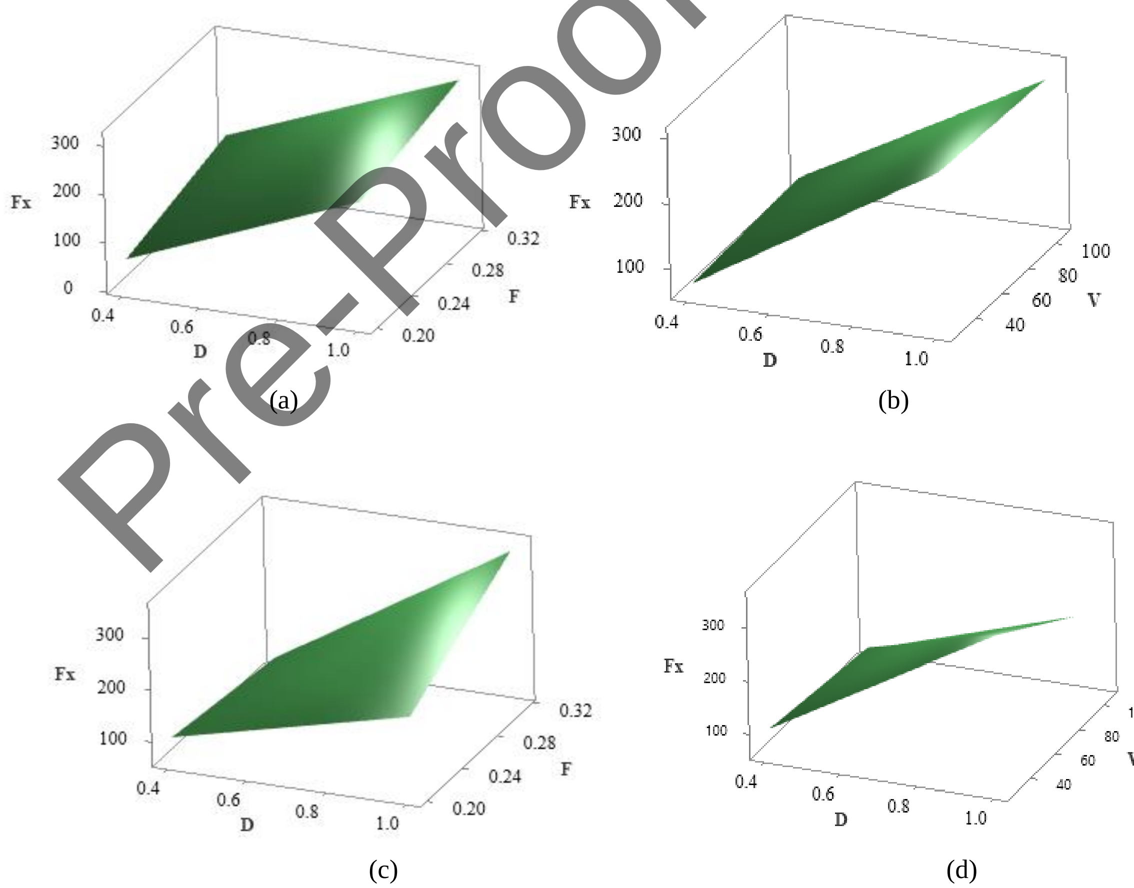


Figure 12. Surface plots for major influence parameters as combined effects on feed force for (a) Dry turning with uncoated tool, (b) MQL turning using uncoated tool, (c) Dry turning using PVD coated tool, and (d) MQL turning using PVD coated tool

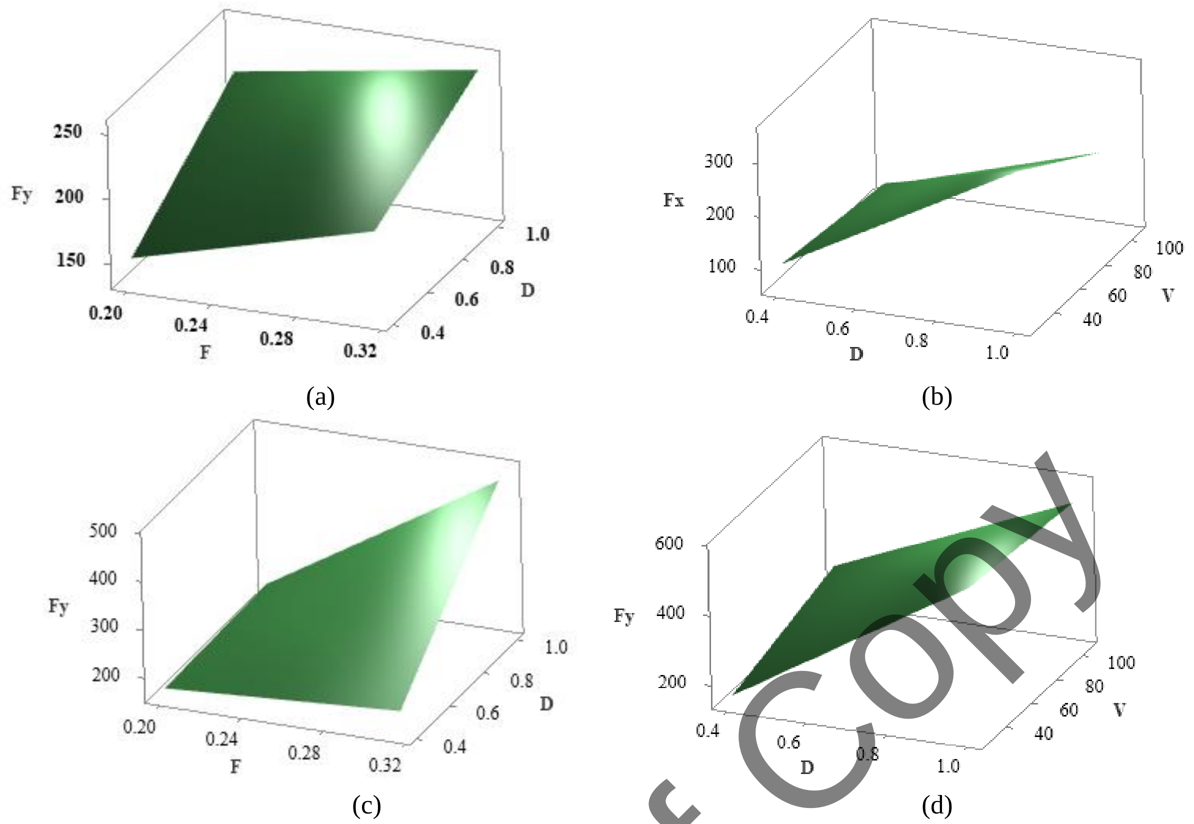


Figure 13. Surface plots for major influence parameters as combined effects on thrust force for (a) Dry turning with uncoated tool, (b) MQL turning using uncoated tool, (c) Dry turning using PVD coated tool, and (d) MQL turning using PVD coated tool

4.3 Regression Analysis

Mathematical equations are exploited to estimate the surface roughness, cutting force, thrust and feed forces using regression analysis. Equations 5 to 20 give the mathematical models (regression equations) for surface roughness, thrust, feed and cutting forces individually for uncoated and PVD coated tools with dry machining and MQL machining conditions.

Figure 14 reveals the scatter plot among predicted and experimental outcomes for roughness using hard PVD coated tool with dry and MQL machining processes. These results are reasonably near the straight line, with evidence that only significant terms were included in the model. From the regression models, the coefficients of determination (R^2) for surface roughness with an uncoated insert under dry and MQL machining obtained were 0.997 and 0.995 respectively. Similarly, the R^2 with PVD coated tool using dry and MQL machining were 0.98 and 1.0 respectively.

Surface roughness (Ra) using uncoated tool with dry machining condition

$$= (0.0031 * V) + (13.97 * F) - (0.80 * D) + (0.000021 * V * V) - (11.3 * F * F) - (1.505 * D * D) - (0.0081 * F * V) - (0.0017 * D * V) + (10.87 * D * F) \quad (5)$$

Surface roughness (Ra) using uncoated tool with MQL machining condition

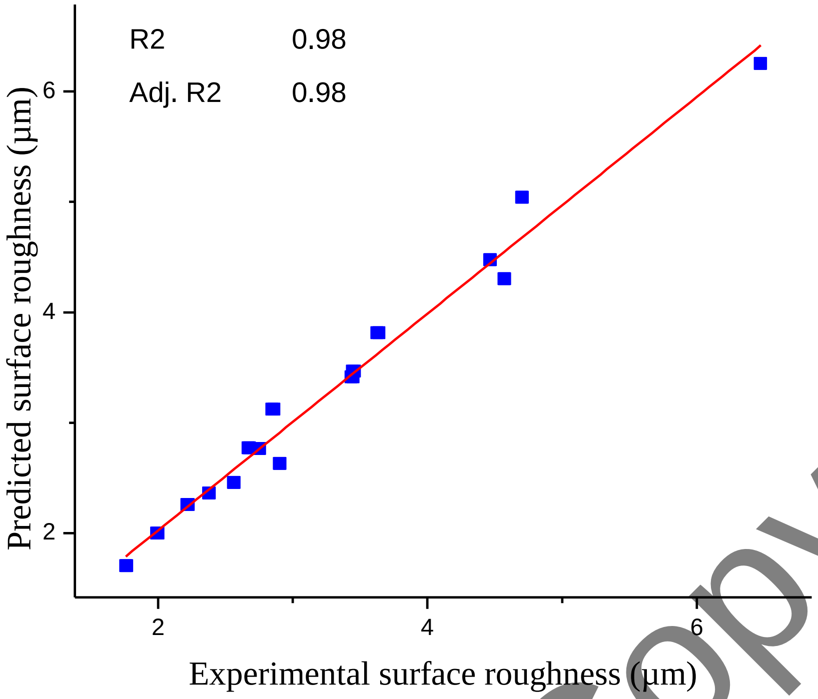
$$= (-0.0250 * V) - (0.8 * F) + (10.7 * D) - (0.94 * P) + (0.00049 * V * V) + (74.4 * F * F) + (0.94 * D * D) + (0.0005 * P * P) - (0.073 * V * F) - (0.0279 * V * D) - (0.00612 * V * P) - (45.1 * F * D) + (3.85 * F * P) + (0.565 * D * P) \quad (6)$$

Surface roughness (Ra) using PVD coated tool with dry machining condition

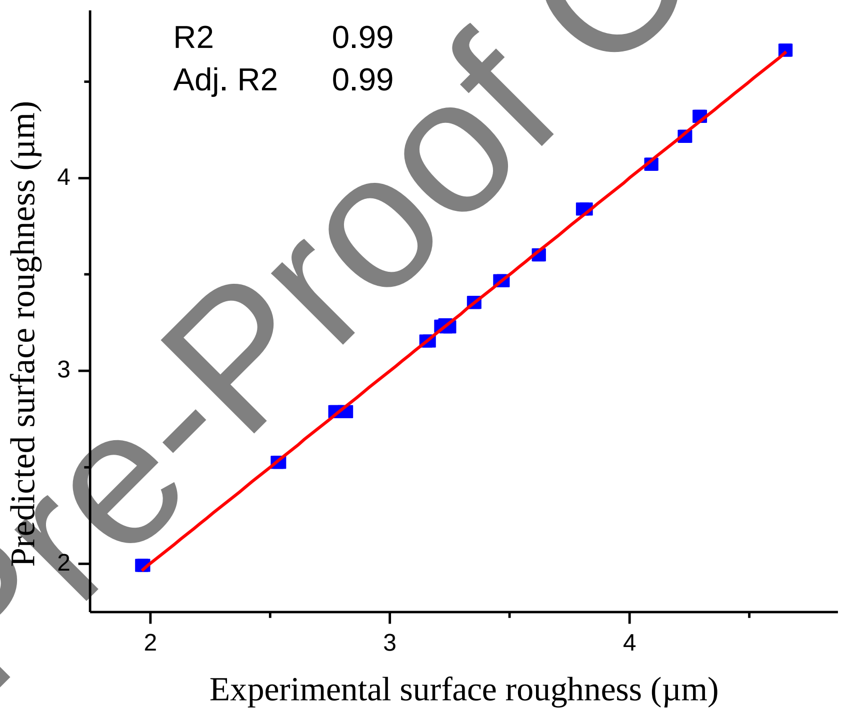
$$= 21.19 + (0.0234 * V) - (130.0 * F) - (16.78 * D) + (0.000218 * V * V) + (254.9 * F * F) + (4.170 * D * D) - (0.1537 * F * V) - (0.01084 * D * V) + (44.80 * D * F) \quad (7)$$

Surface roughness (Ra) using PVD coated with MQL machining condition

$$= (-0.16670 * V) - (5.09 * F) - (17.26 * D0 + (4.213 * P) + (0.000505 * V * V) + (67.73 * F * F) +` (5.594 * D * D) - (0.23653 * P * P) + (0.26925 * F * V) + (0.05322 * D * V) - (0.001547 * P * V) + (15.94 * D * F) - (6.655 * F * P) + (0.4580 * D * P) \quad (8)$$



(a)



(b)

Figure 14. Experimental results vs predicted results with PVD coated tools for surface roughness for (a) Dry machining, and (b) MQL machining

The coefficients of determination (R^2) values of the regression equations for the cutting force using uncoated tools in dry and MQL machining conditions were 0.99 and 0.99 respectively. The R^2 values in experiments using PVD inserts in dry and MQL machining environments were 0.99 and 0.98 respectively. Similarly, the scatter plot among predicted and experimental outcomes for the cutting force with uncoated and PVD coated tools in dry and MQL machining processes were developed. The R^2 values obtained were 0.93, 0.99, 0.98 and 0.98 respectively. These results exhibited reasonably near to the straight line with evidence that only significant terms were included in the model.

Cutting force (Fz) with uncoated tool under dry machining condition

$$= (5.97 * V) - (1614 * F) + (47 * D) + (0.0553 * V * V) + (10755 * F * F) + (83 * D * D) - (46.0 * F * V) - (0.59 * D * V) + (1027 * D * F) \quad (9)$$

Cutting force (Fz) with uncoated tool under MQL machining condition

$$= (-7.74 * V) + (1383 * F) + (235 * D) - (21.2 * P) + (0.02829 * V * V) + (3636 * F * F) + (479.4 * D * D) + (6.33 * P * P) + (1.36 * F * V) + (0.948 * D * V) + (0.2904 * V * P) - (947 * D * F) - (239 * F * P) \quad (10)$$

Cutting force (Fz) with PVD coated tool using dry machining condition

$$= (-1.04 * V) + (510 * F) - (48 * D) - (0.00535 * V * V) - (1997 * F * F) - (108 * D * D) + (2.70 * F * V) + (1.42 * D * V) + (2859 * D * F) \quad (11)$$

Cutting force (Fz) with PVD coated tool under MQL machining condition

$$= -27947 - (166.4 * V) + (157180 * F) - (65825 * D) + (12152 * P) + (1.473 * V * V) - (90014 * F * F) + (18430 * D * D) - (420.0 * P * P) - (121.1 * V * F) + (21.37 * V * D + 2.572 * V * P + 117072 * F * D - 33054 * F * P + 1477 * D * P) \quad (12)$$

The R^2 values obtained for the feed force using bare coated and hard PVD layered tools with dry and MQL metal cutting processes were 0.99, 0.99, 0.97 and 0.99 respectively. These results exhibited positions reasonably near to the straight line with evidence that only substantial terms were added in the predictor. The R^2 values of the regression models for the feed force with uncoated tools with dry and MQL machining were 0.99 and 0.99, respectively. Correspondingly, the R^2 values for the feed force in experiments using PVD coated tools in dry and MQL machining processes were 0.99 and 0.99, respectively.

Feed force (Fx) with uncoated tool under dry machining condition

$$= (3.91 * V) - (584 * F) - (93 * D) + (0.02754 * V * V) + (2980 * F * F) - (2.4 * (D * D)) - (22.88 * F * V) - (1.47 * D * V + (1298 * D * F) \quad (13)$$

Feed force (Fx) with uncoated tool under MQL machining condition

$$= (-1.31 * V) + (305 * F) + (1032 * D) - (111.0 * P) + (0.00461 * V * V) + (1771 * F * F) + (172.0 * D * D) + (3.17 * P * P) - (4.28 * F * V) - (0.374 * D * V) + (0.1514 * P * V) - (3397 * D * F) + (274 * P * F) - (6.30 * P * D) \quad (14)$$

Feed force (Fx) with PVD coated tool under dry machining condition

$$= (-2.64 * V) + (219 * F) + (276 * D) + (0.00764 * V * V) - (2046 * F * F) - (168.6 * D * D) + (4.87 * F * V) - (0.263 * D * V) + (132 * D * F) \quad (15)$$

Feed force (Fx) with PVD coated tool under MQL machining condition

$$= (4.17 * V) + (840 * F) + (1492 * D) - (208.6 * P) - (0.01048 * V * V) - (4812 * F * F) - (437.2 * D * D) + (9.09 * P * P) - (2.72 * F * V) - (3.598 * D * V) - (0.1104 * P * V) - (888 * D * F) + (435.9 * P * F) - (17.34 * P * D) \quad (16)$$

The R^2 values obtained for the thrust force using uncoated and PVD layered inserts with dry cutting and MQL machining processes were 0.91, 0.97, 0.90 and 0.87 respectively. These results exhibited positions reasonably near to the straight line with evidence that only significant terms were included in the model. The R^2 values of the mathematical models for the thrust force with uncoated tools under MQL machining and dry machining conditions were 0.99 and 0.99, respectively. Correspondingly, the R^2 values in experiments using PVD coated tools in dry and MQL metal cutting were 0.99 and 0.98 respectively.

Thrust force (Fy) with uncoated tool under dry machining condition

$$= (-0.63 * V) + (581 * F) + (124.3 * D) + (0.01584 * V * V) + (1620 * F * F) - (21.9 * D * D) - (8.48 * F * V) + (0.898 * D * V) - (450 * D * F) \quad (17)$$

Thrust force (Fy) with uncoated tool under MQL machining condition

$$= (-1.97 * V) + (1459 * F) + (626 * D) - (95.5 * P) + (0.03219 * V * V) - (214 * F * F) - (79 * D * D) + (6.44 * P * P) - (1.31 * F * V) - (1.810 * D * V) - (0.3406 * P * V) - (2036 * D * F) + (112 * P * F) + (37.5 * P * D) \quad (18)$$

Thrust force (Fy) with PVD coated tool using dry machining condition

$$= (7.08 * V) + (26 * F) - (217 * D) + (0.01056 * V * V) + (1238 * F * F) - (32 * D * D) - (24.47 * F * V) - (3.68 ** VD) + (2084 * D * F) \quad (19)$$

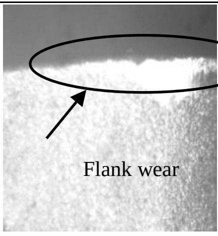
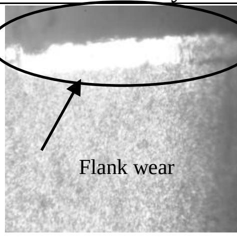
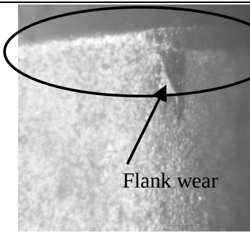
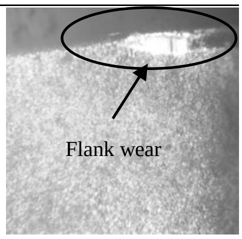
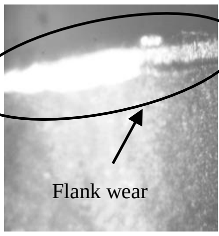
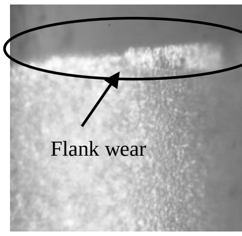
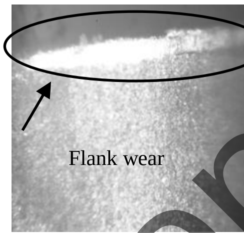
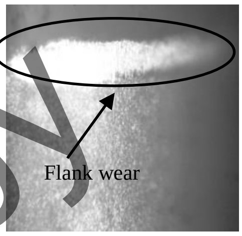
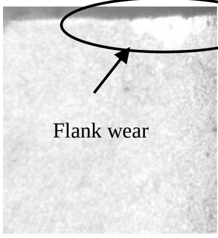
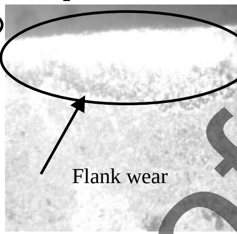
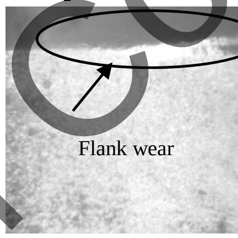
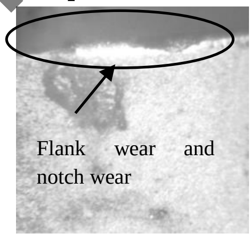
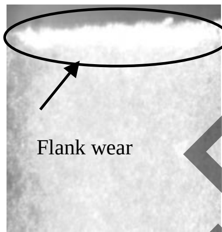
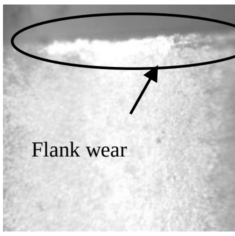
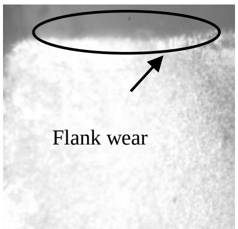
Thrust force (Fy) with PVD coated tool under MQL machining condition

$$= (-5.44 * V) + (3530 * F) - (3683 * D) + (304 * P) + (0.1435 * V * V) + (13898 * F * F) + (1182 * D * D) + (8.9 * P * P) - (46.4 * F * V) + (3.66 * D * V) - (0.324 * P * V) + (4637 * D * F) - (1781 * P * F) + (119.9 * P * D) \quad (20)$$

4.4. *Analysis of tool wear*

The behavior of the tool wear mechanism was analyzed on the flank face of the cutting inserts. Table 10 depicts flank wear of typical tool inserts with an optical microscope. These images were captured at a magnification of 100X.

Table 10. Analysis of tool wear

Uncoated: Dry machining	 **Experiment: 1**	 **Experiment: 4**	 **Experiment: 11**	 **Experiment: 12**
Uncoated: MQL machining	 **Experiment: 3**	 **Experiment: 6**	 **Experiment: 8**	 **Experiment: 14**
PVD Coated: Dry machining	 **Experiment: 2**	 **Experiment: 4**	 **Experiment: 5**	 **Experiment: 6**
PVD Coated: MQL machining	 **Experiment: 2**	 **Experiment: 6**	 **Experiment: 9**	 **Experiment: 15**

These images clearly indicate that the flank wear width and length were lower in MQL machining process compared to those in dry cutting with a PVD coated tool. This shows that MQL machining using PVD coated inserts reduced the tool wear due to the presence of sufficient cooling with air pressure, lubrication and cooling by supplying the coolant among the tool flank face and the work piece. The notch wear on the PVD coated inserts was noticed.

The position of nozzles supplied the air and the cutting fluid mixture uniformly and effectively at the machining region, thus reducing friction across the work metal-tool contact zone and lowering tool wear in the MQL machining process [13]. It was also detected that the flank wear was minimal in experiments using PVD coated tool inserts when contrasted with the uncoated tools. The images have revealed the impact of the machining parameter on the tool flank wear. The impact of the cutting speed was greater on the flank wear. The depth of cut increased the contact length across the tool cutting edge and the workpiece which increased the friction and stresses eventually resulting in increasing flank wear.

To sum up, it has been evident that the optimum process parameters for surface roughness and cutting forces were different in the experiments using uncoated tools compared to those using PVD coated tools. This indicates that choosing the proper process parameters is important to obtain the desired performance characteristics. The impact of cutting parameters on the machining performance were decided using ANOVA. ANOVA outcomes indicated the ultimate influential process parameter for the performance characteristics, which was different for each characteristic. These results have also indicated that controlling the process parameters would be important in any process in the industry. The variation in the performance characteristics has been discussed, aided by the illustrations of the surface plots. The surface plots can be used to know the impact of combined process parameters; hence, proper selection of process parameters can be used to enhance the machining performance characteristics. The regression analysis was used to develop mathematical models. These models have been used to forecast the output performance characteristics. The literature reviewed has also showed that the use of minimum quantity lubrication in the machining process would enhance the surface finish, lower the cutting forces and enhance machinability of materials [5, 8, 10, 24, 28, 31].

5. 0 CONCLUSIONS

The current study examined the strategy of combining sustainable MQL machining with multiple nozzles and different cutting tools in turning A286 alloy. It therefore achieved its aim of optimizing the turning environments and assessing the effectiveness of various cutting tool inserts, namely PVD coated and uncoated inserts under sustainable and eco-friendly MQL and dry turning of A286 alloy material. In the present work, MQL with three nozzles was utilized to provide the cutting fluid at the machining zone. These three nozzles were positioned in such a way that the cutting fluid would be focused on the rake surface, flank surface and chips to minimize the friction and cutting temperature. The MQL would lower the quantity of the cutting fluid used in the machining industries, thus reducing machining costs and pollution. The MQL initial set up cost was slightly high as it required a skilled operator, proper ventilation and maintenance on a daily basis. The optimum process parameters obtained from the AoM may be implemented in the machining industries to increase productivity. The machining industries may also use the regression models developed to predict the required performance characteristics from which selected process parameters in the regression models may then be used to machine the components.

The investigational results have specified that MQL machining with PVD coated tool decreased the cutting forces when assessed with the uncoated tool. The coated insert has been found to have good wear and shock resistance in addition to the coating materials, which would lower the friction across the tool insert and workpiece zone. The coatings (i.e., (Ti, Al) N + TiN) on the PVD inserts have exhibited higher temperature resistance, hardness, and hot hardness. It has been evident that the MQL machining with three nozzle spray positions have effectively supplied cutting fluid to the chip-tool interface region. This would lead to a high transfer of heat from the machining zone, thus minimizing the friction at the workpiece and the tool region. Hence, MQL machining has shown higher performance than dry machining. Cutting fluid would play a substantial role in decreasing friction, thereby, forces, tool wear and roughness would decrease in the MQL metal cutting process. The findings from ANOVA results have indicated that the feed rate was affecting machined surface roughness more with the PVD coated insert and uncoated tool under MQL and dry cutting, respectively. Depth of cut significantly influenced feed force and cutting force using uncoated tools and PVD coated tools under MQL and dry machining environments. The mutual influences of the machining process parameters have been studied with the surface plots to recognize the impact of process parameters on output characteristics. Regression models were generated to predict the performance characteristics. The experimental results found were in good agreement with the predicted results.

As such, the following key conclusions can be drawn from the present experimental results:

- The surface roughness was reduced by 71.5% with MQL using an uncoated tool, while the cutting force was decreased by 15.63% and 25.18% with MQL with PVD coated and uncoated tools, respectively. Similarly, the thrust force was decreased by 51.63% and 40.72% with MQL using PVD coated and uncoated tools, respectively, whereas the feed force was increased by 32.41% with MQL using a PVD coated insert.
- The optimum process parameters have indicated that a lower depth of cut (i.e., 0.4 mm) would have to be maintained to minimize the cutting force.
- The flank tool wear results have shown that PVD coated insert would result in lower tool wear than an uncoated tool.

6.0 CONFLICT OF INTEREST

The authors of this article state that they have no disagreements of interest with this work.

7.0 AUTHORS CONTRIBUTION

M. Venkata Ramana (Conceptualisation; Formal analysis; Approach; Guidance, Writing - Original draft)
G. Krishna Mohana Rao (Conceptualization; Methodology; Supervision)
E. Nitheesha (Conceptualization; Formal analysis; Methodology; Data curation; Visualisation; Resources)
B.V. Raja Ravi Kumar (Data curation; Resources)

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ABBREVIATIONS

- ANOVA - Analysis of variance
- D – Depth of cut, mm
- DoF – Degrees of Freedom
- F – Feed rate, mm/rev
- MQL - Minimum quantity lubrication
- O.A. - Orthogonal Array
- P – Air pressure, kg/cm^2
- Ra – Arithmetic mean of surface roughness, µm
- R^2 - Coefficient of determination
- V – Cutting speed, m/min