Optimisation of Machining Factors for Surface Roughness and Mean Cutting Force of AISI 52100 Steel During Turning Under Microlubrication Condition

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Abstract: ***This research work is conducted inorder to find the best practicable turning factors to achieve enhanced surface quality cylindrical AISI52100 steel components under microlubrication condition. The turning operation is performed in a turning centre (All Geared Lathe) with CBN insert of 0.8mm nose radius. The turning factors namely feed rate, cutting velocity and depth of cut are preferred to accomplish the experimentation based on Taguchi's $L_{25}(5^3)$ orthogonal array, simultaneously the cutting forces such as feed force, tangential force and thrust force are observed using a calibrated lathe tool dynamometer adapted in the tool holder. The surface roughness of the turned steel alloy components is deliberated by means of a precise surface roughness apparatus. A prediction model in lieu of average surface roughness and mean cutting force is created by means of nonlinear regression examination with the aid of MINITAB software. The most favorable machining settings for surface roughness and mean cutting force are recognized by Taguchi's method and verified with a confirmation trial.***

Index Terms*: *AISI52100; Microlubrication condition; Surface roughness; Cutting force; Lathe; Regression analysis; Taguchi method.

I. INTRODUCTION

In the present industrialized circumstances, machining operations are highly unavoidable. The preferred surface quality and geometry of a raw material could be obtained by the most versatile production process known as machining [1 – 2]. Above 90% of total power fed on machine will convert into warmth energy, because of the relative movement connecting the workpiece and cutting tool [3 – 5]. This form of heat energy is considered to be waste and such form of generated heat causes poor product surface quality and tool wear [6 – 7]. So, the extreme heat generated could overcome by applying cutting fluids on the tool-work interface [4, 8]. The utilization of cutting fluid in any machining operations has a crucial advantage that, it cools down the tool-workpiece interface, consequently by lessening the friction between tool-work interface, which brings about better clean item surface and enhanced tool life [9 – 13]. However, mistreatment of cutting fluid and incorrect method of its clearance could be a great threat to the machine tool operator's health and to the environment [14]. Also, cutting fluid accounts almost 16.9% of the total manufacturing cost in a production sector [15].

In addition, mineral-based coolants affect machining workers' fitness leading to skin cancer [14]. Among a variety of methods accessible on the use of the cutting fluids, researchers, as of late, have been focusing on microlubrication as it diminishes the utilization of cutting fluid in any machining operation by showering the blend of cutting liquid and compacted air in a managed way [16]. The microlubrication method has turned out to be appropriate on the grounds that it satisfies the prerequisites of green manufacturing [17 – 21].

In this background, the research being narrated in this manuscript is to utilize microlubrication unit for applying the coolant in the form of mist in machining AISI52100 using CBN insert. The initial segment of this manuscript reports the means did to devise a method and equipment that productively blends an almost little amount of coolant with rushed air and conveys as persistent mist. The second segment of this manuscript displays the outcome of factors on surface roughness and cutting forces during turning of AISI52100 steel.

A. Microlubrication Unit

Schema of microlubrication unit used for the present research work is shown in Figure 1.

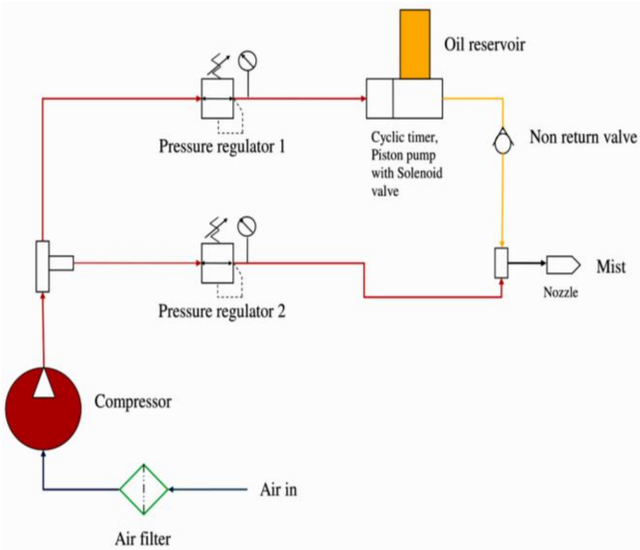

Fig. 1: Schema of microlubrication unit [12]

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II. EXPERIMENT DETAILS

- Selection of workpiece – AISI 52100 (ϕ80mm x 150mm)
- Cutting tool used – CBN (Cubic Boron Nitride) insert
- Machine tool – All Geared Lathe (turning centre)
- Machining Condition – Microlubrication
- Planning of experiment – Taguchi's L_{25} (5^3) orthogonal array
- Optimization Technique used – Taguchi
- Repeatability of experiments – 3 times
- Output response –Surface roughness, cutting forces

A. Work Piece

AISI 52100 is a high carbon alloy steel and it is familiar for its excellent wear resistance behaviour. Many automotive mechanisms such as steering wheel, gears, brakes, and precision bearings are manufactured using AISI 52100 steel alloy. The chemical composition of AISI52100 alloy steel is specified in Table 1.

Table 1: Chemical composition

Element	% Composition	
	Standard	Actual
Cr	1.30-1.60	1.43
C	0.98 – 1.10	1.01
Mn	0.25-0.45	0.37
Si	0.15-0.35	0.27
S	$\leq$ 0.0250	0.023
P	$\leq$ 0.0250	0.024
Fe	Rest	96.91

B. Cutting Tool

The cutting tool insert used for this investigation is an ISO CODE - CNGA120408S01030A 7025, which is a CBN substance with a TiN ceramic phase added and it is fixed onto a tool holder (ISO code PSBNR2525K12).

C. Cutting Fluid

Mineral oil blended with a stream of water was utilized as cutting fluid for this investigation. The properties of the base oil are specified in Table 2.

Table 2: Properties of oil

Property	Value
Flash Point(^{0}C)	150
Kinematic Viscosity at 40^{0}C(cSt)	20
Specific gravity(No Unit)	0.877

D. Experimental Conditions

The machining factors to be feed rate, depth of cut and cutting velocity are considered for the experimentation and their levels are indicated in Table 3. The trials were arranged in view of Taguchi's orthogonal array in a turning centre (Pinacho SC200 an All Geared Lathe), appeared in Figure 2. The conditions of the lathe are specified in Table 4.

Table 3: Machining factors and their levels

Factors	Unit	Notation	Levels				
			1	2	3	4	5
Cutting velocity	m/min	v	125	150	175	200	225
Feed rate	mm/rev	f	0.05	0.10	0.15	0.20	0.25
Depth of Cut	mm	d	0.1	0.2	0.3	0.4	0.5

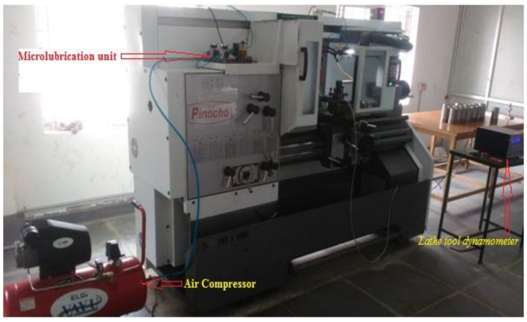

Figure 2: Experimental setup

Table 4: Conditions of the lathe

Condition	Range
Speed range, rpm	40-2800
Cross feed, mm	0.025 – 0.376
Longitudinal feed, mm	0.05 – 0.752

The turning operation was done on AISI 52100 cylindrical components of 80 mm diameter by utilizing CBN insert in microlubrication condition. The surface roughness of the turned steel alloy parts were deliberated by means of a precise surface roughness apparatus (Mitutoyo SJ 310) appeared in Figure 3, and the machined steel alloy parts are shown in Figure 4.

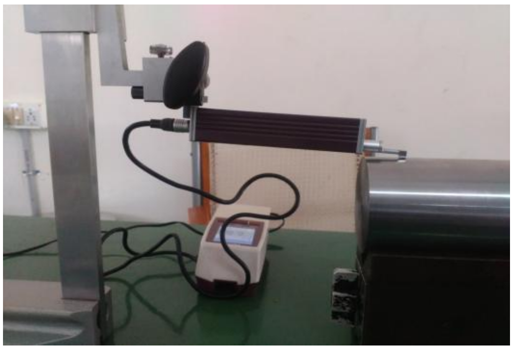

Figure 3: Surface roughness testing

III. RESULTS AND DISCUSSION

A. Optimization by Taguchi Method

A.1. S/N ratio Computation

The quality attribute with the sort of "smaller-the-better" measured in this research work was mean surface roughness and mean cutting force. The S/N ratio for the yield response was computed by means of the following equation (1) for each machining order and their values are given in Table 5.

Figure 4: Machined steel alloy AISI 52100 components

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$$S/N(dB) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Response_i^2\right) \quad (1)$$

Where $i = 1, 2, \ldots, n$ (here $n = 3$)

$$^*Fm = \sqrt{(Fa^2 + Fc^2 + Fp^2)} \quad (2)$$

The mean cutting force (Fm) is calculated using equation (2).

A.2. Analysis of Variance

The noteworthy factor on the response output was analyzed through ANOVA and F-test with a chance of p=0.05, which was given in Table 6 and Table 7.

Table 5: Experimental order and S/N ratio

Sl. No.	Machining Factors			Surface Roughness (µm)					S/N Ratio	Cutting Forces (N)				S/N Ratio
	v	f	d	Ra1	Ra2	Ra3	Ra4	Mean, Ra		Fa	Fc	Fp	Fm	
1	125	0.05	0.1	0.4481	0.4476	0.4438	0.4468	0.4466	7.0021	10.52	16.19	32.49	37.79	-31.55
2	125	0.10	0.2	0.9641	0.9630	0.9604	0.9624	0.9625	0.3322	15.52	19.70	40.93	48.00	-33.62
3	125	0.15	0.3	1.5385	1.5369	1.5369	1.5376	1.5375	-3.7362	35.47	54.39	86.48	108.14	-40.68
4	125	0.20	0.4	2.1724	2.1724	2.1724	2.1724	2.1724	-6.7388	70.38	120.25	169.14	219.14	-46.81
5	125	0.25	0.5	2.8657	2.8678	2.8665	2.8668	2.8667	-9.1476	120.25	217.28	288.92	380.98	-51.62
6	150	0.05	0.2	0.4367	0.4368	0.4359	0.4370	0.4366	7.1983	8.87	13.23	37.31	40.57	-29.38
7	150	0.10	0.3	0.9470	0.9438	0.9460	0.9440	0.9452	0.4895	21.53	30.16	51.16	63.17	-36.01
8	150	0.15	0.4	1.5129	1.5115	1.5140	1.5137	1.5130	-3.5969	49.15	80.02	113.81	147.55	-43.38
9	150	0.20	0.5	2.1390	2.1411	2.1417	2.1404	2.1406	-6.6105	91.73	161.06	213.56	282.78	-49.03
10	150	0.25	0.1	2.1975	2.1980	2.1958	2.1969	2.1971	-6.8368	47.89	80.51	72.68	118.57	-41.48
11	175	0.05	0.3	0.5394	0.5385	0.5373	0.5396	0.5387	5.3731	20.82	27.17	42.49	54.56	-34.74
12	175	0.10	0.4	1.0398	1.0399	1.0384	1.0406	1.0397	-0.3380	41.14	61.04	85.11	112.53	-41.03
13	175	0.15	0.5	1.6016	1.6001	1.6008	1.6000	1.6006	-4.0858	76.42	126.08	164.85	221.16	-46.89
14	175	0.20	0.1	1.4521	1.4470	1.4564	1.4536	1.4523	-3.2410	21.32	34.58	35.47	53.92	-34.64
15	175	0.25	0.2	1.8257	1.8233	1.8239	1.8244	1.8243	-5.2220	59.21	101.20	95.19	151.02	-43.58
16	200	0.05	0.4	0.7531	0.7500	0.7546	0.7547	0.7531	2.4629	46.36	63.30	83.05	114.25	-41.16
17	200	0.10	0.5	1.2479	1.2458	1.2467	1.2468	1.2468	-1.9159	74.35	112.35	142.77	196.30	-45.86
18	200	0.15	0.1	0.8936	0.8920	0.8946	0.8947	0.8937	0.9759	7.97	12.21	36.23	39.05	-28.92
19	200	0.20	0.2	1.1990	1.1986	1.1989	1.1997	1.1991	-1.5767	38.56	60.51	64.59	96.55	-39.69
20	200	0.25	0.3	1.5640	1.5627	1.5643	1.5648	1.5640	-3.8845	84.12	142.31	141.41	217.54	-46.75
21	225	0.05	0.5	1.0796	1.0790	1.0780	1.0815	1.0795	-0.6647	85.49	119.86	147.32	208.28	-46.37
22	225	0.10	0.1	0.5215	0.5213	0.5201	0.5228	0.5214	5.6562	7.85	6.45	40.93	42.18	-32.50
23	225	0.15	0.2	0.7600	0.7606	0.7602	0.7596	0.7601	2.3826	31.15	41.07	60.63	79.58	-38.02
24	225	0.20	0.3	1.0581	1.0575	1.0595	1.0571	1.0581	-0.4901	69.41	106.87	117.43	173.29	-44.78
25	225	0.25	0.4	1.4158	1.4168	1.4147	1.4156	1.4157	-3.0196	122.63	203.85	211.34	318.21	-50.05

Table 6: Analysis of variance for surface roughness

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
v	1	1.24107	13.58%	0.04037	0.04037	17.29	0.001
f	1	5.46697	59.82%	2.59166	2.59166	1110.11	0.000
d	1	1.46468	16.03%	0.00470	0.00470	2.02	0.173
vf	1	0.83463	9.13%	0.59686	0.59686	255.66	0.000
vd	1	0.08001	0.88%	0.07561	0.07561	32.39	0.000
fd	1	0.00926	0.10%	0.00926	0.00926	3.97	0.062
Error	18	0.04202	0.46%	0.04202	0.00233		
Total	24	9.13863	100.00%				
R^2 – 0.99				**R^2 (adj) – 0.99**			

Table 7: Analysis of Variance for mean cutting force

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
v	1	87	0.04%	363	362.7	17.10	0.001
f	1	68264	30.96%	4808	4808.3	226.73	0.000
d	1	127540	57.84%	9174	9174.4	432.61	0.000
vf	1	20	0.01%	13015	13014.6	613.69	0.000
vd	1	1028	0.47%	15723	15723.0	741.41	0.000
fd	1	23177	10.51%	23177	23177.0	1092.90	0.000
Error	18	382	0.17%	382	21.2		
Total	24	220498	100.00%				
R^2-0.99				**R^2(Adj)-0.99**			

The estimation of "Prob.>F" in Table 6 and Table 7 for the representation is under 0.05, which demonstrates that the representation is important, which is enviable as it shows that the terms in the representation significantly affect the yield response. From ANOVA comes about, it is obvious that feed rate impacts more on the surface roughness, trailed by the depth of cut, spindle speed, tool nose radius and cutting liquid. Similarly, in case of mean cutting force, depth of cut is the most influencing factor trail by feed rate and cutting velocity. This is harmonizing with the current hypotheses of machining.

A.3 Prediction Model

By means of regression examination with the aid of MINITAB17 numerical software, the outcome of machining factors on mean surface roughness (Ra) and mean cutting force (Fm) was modeled as follows;

Ra = -0.2173+0.0836v+0.6697f-0.0636d-0.12090vf+0.02303vd+0.01506fd (3)

Fm = 65.75 + 7.92v +28.85f -93.76d -20.853vf+19.623vd+23.824fd (4)

For equation (3) and equation (4), it was found that R^2 is 0.994 & 0.991 respectively. Where 'R' is the correlation coefficient and the value of 'R^2' indicates the nearness of the mathematical representation for the yield response.

A.4 Response Curves

Response curves are graphical depiction of the adjustment in execution uniqueness for the variety in factor levels. Figure 5 outlines the response graph for the outcome mean surface roughness with three variables and five levels. From Figure 5, the peak points were picked as the ideal levels of machining factors i.e. cutting velocity at the fifth level, the feed rate at the first level and depth of cut at the first level. Similarly, for Figure 6, cutting velocity at the second level, the feed rate at the first level and depth of cut at the first level.

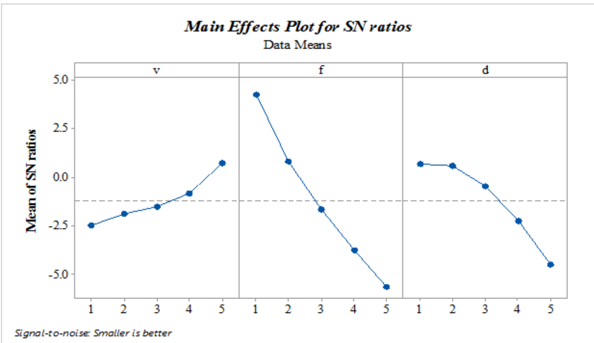

Figure5: Response graph for mean surface roughness

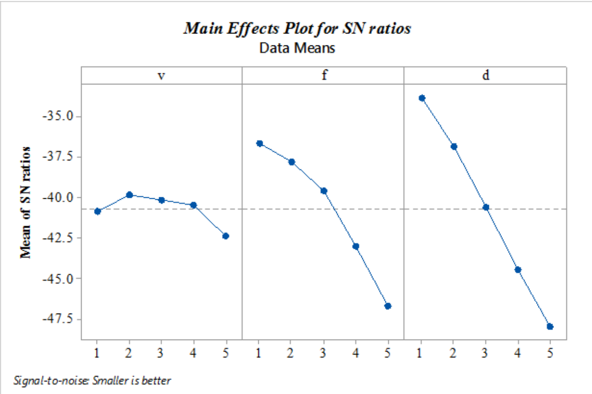

Figure 6: Response Graph for mean cutting force

A.5 Confirmation Test

The confirmation test was directed at the ideal levels of machining factors and the outcomes for mean surface roughness and mean cutting force is given in Table 8 and Table 9 respectively.

Table 8: Confirmation Experiment for surface roughness

Factors			Surface roughness (Ra) in µm		Deviation %
v	f	d	Experimented	Predicted	
5	1	1	0.3501	0.3325	5.29

Table 9: Confirmation Experiment for mean cutting force

Factors			Mean cutting force (Fm) in N		Deviation %
v	f	d	Experimented	Predicted	
2	1	1	37.91	36.044	5.18

A.6 Effect of Machining Factors

The effect of machining factors on the mean surface roughness was studied and presented in the below section.

Figure 7 depicts the outcome of cutting velocity and feed rate on the mean surface roughness, where the depth of cut is kept constant. From Figure 7 it is so obvious that feed rate and cutting velocity influences more on surface roughness, at minimum cutting velocity and

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minimum feed rate minimum surface roughness was observed, the interaction between feed rate and cutting velocity seems significant on surface roughness. Figure 8 depicts the outcome of cutting velocity and depth of cut on the mean surface roughness, where feed rate is kept constant. From Figure 8 it is obvious that at a maximum cutting velocity and a minimum depth of cut better surface quality products could be produced. Figure 9 depicts the outcome of feed rate and depth of cut on the mean surface roughness, where cutting velocity is kept constant. From Figure 9 it is obvious that feed rate has the most influence on surface roughness than the depth of cut, at a minimum feed rate and a minimum depth of cut minimum surface roughness could be achieved.

Figure 10 depicts the outcome of cutting velocity and feed rate on the mean cutting force, where the depth of cut is kept constant. From Figure 10 it is so obvious that at minimum cutting velocity and minimum feed rate minimum cutting force was observed. Figure 11 depicts the outcome of cutting velocity and depth of cut on the mean cutting force, where feed rate is kept constant. From Figure 11 it is obvious that at a maximum cutting velocity and a minimum depth of cut minimum cutting force was observed. Figure 12 depicts the outcome of feed rate and depth of cut on the mean cutting force, where cutting velocity is kept constant. From Figure 12 it is obvious that depth of cut has a noteworthy role on mean cutting force than feed rate and the interaction between the feed rate and depth of cut is also important on the mean cutting force.

The surface roughness of the machined steel alloy components increases with an increase in all the machining factors [2]. When the cylindrical steel alloy components AISI52100 were machined at lower cutting velocities under microlubrication condition, rough surface a sign of poor quality components were obtained due to chip fracture and the increase in cutting velocity from 125m/min to 225 m/min decreases the chip fracture and hence the roughness of the machined components were also found decreased. At higher feed rate and depth of cut, more material has to be removed which resulted in increased cutting forces on the tool and concurrently increased the energy required to machine the steel alloy components. These increased cutting forces diminished the surface quality of the steel alloy components.

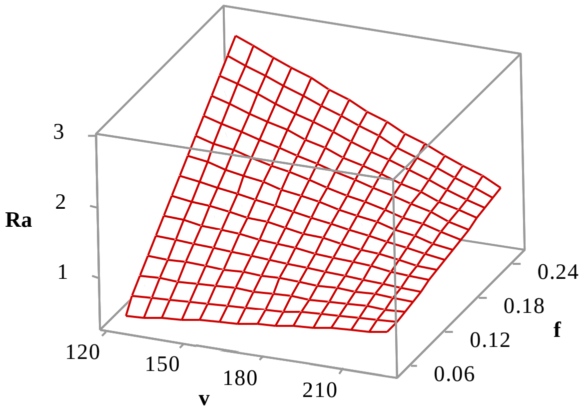

Figure 7: Plot of mean surface roughness versus cutting velocity and feed rate

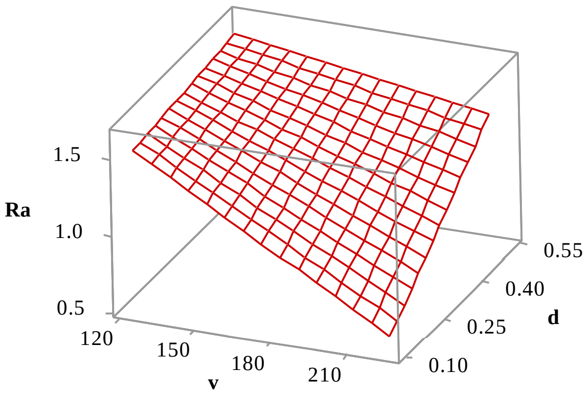

Figure 8: Plot of mean surface roughness versus cutting velocity and depth of cut

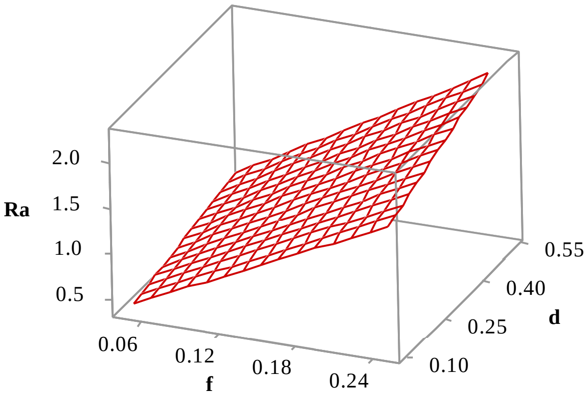

Figure 9: Plot of mean surface roughness versus feed rate and depth of cut

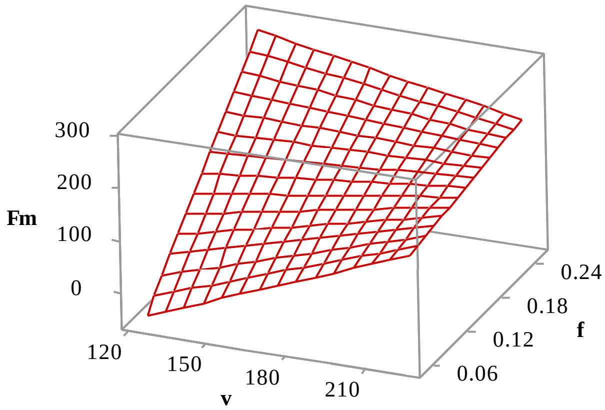

Figure 10: Plot of mean cutting force versus cutting velocity and feed rate

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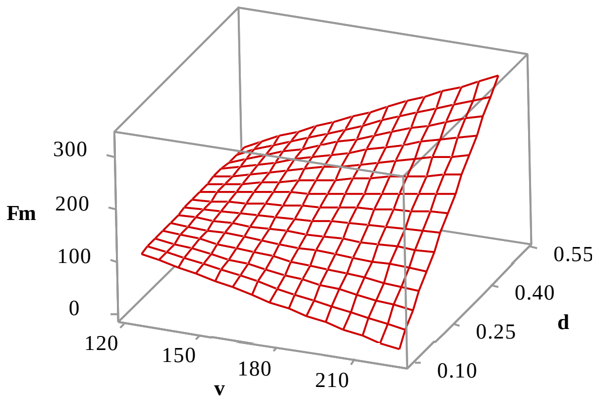

Figure 11: Plot of mean cutting force versus cutting velocity and depth of cut

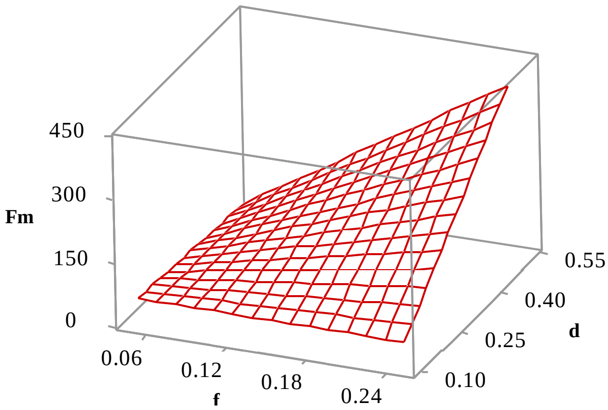

Figure 12: Plot of mean cutting force versus feed rate and depth of cut

IV. CONCLUSION

In this background, the study reported in this paper was mean surface roughness and mean cutting force test conducted during turning operation of AISI 52100 steel with CBN insert in microlubrication condition. The subsequent conclusions were drawn out from the present study;

i. The ANOVA and F-test of the experimented results publicized that the feed rate has a superior influence on the mean surface roughness, subsequently by the cutting velocity and the feed rate. Similarly, in case of mean cutting force, depth of cut influences more trialed by feed rate and cutting velocity.

ii. Generalized mathematical models were developed through regression analysis by means of MINITAB numerical software for mean surface roughness (Ra) and mean cutting force (Fm). From those equations, the mean surface roughness and the mean cutting force values could be calculated if the factors namely feed rate, cutting velocity, and depth of cut are known.

iii. The combined effect on the machining factors such as cutting velocity, feed rate and depth of cut on mean surface roughness was studied, the plot reveals that cutting velocity and feed rate combinedly has a superior influence on surface roughness.

iv. In lieu concern of the above said facts, the optimum condition for mean surface roughness such as 225m/min of cutting velocity, 0.05mm/rev of feed rate and 0.1mm of depth of cut was observed for producing the best steel alloy component at a constant flow rate of cutting fluid at 22.4ml/hr under microlubrication condition.

v. The confirmation trial ensured that the most favourable machining conditions resulted in minimum surface roughness and minimum cutting force based on the Taguchi's L_{25} orthogonal array.

vi. The optimum turning conditions found in this research work can be used when AISI 52100 steel alloy are turned for the typical functions like gears and precision bearings.

NOMENCLATURE

v	Cutting velocity in m/min
f	Feed rate in mm/rev
d	Depth of cut in mm
CBN	Cubic Boron Nitride
Ra	Mean surface roughness in µm
Fm	Mean cutting force in N
Fa	Feed force in N
Fp	Thrust Force in N
Fc	Tangential Force in N
R	Correlation coefficient
Mn	Manganese
C	Carbon
S	Sulphur
P	Phosphorus
Si	Silicon
Fe	Iron
AISI	American Iron and Steel Institute

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