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The Effect of Machining Factors on the Mean Cutting Force and Cutting Power While Turning Steel Alloy AISI 52100 in Dry Condition

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Abstract: ***This paper elucidates the outcome of machining factors such as cutting velocity, feed rate and depth of cut on the mean cutting force and the cutting power on turning cylindrical AISI52100 steel alloy components. The experiments are designed based on the Taguchi's L25(53) orthogonal array and conducted on an All Geared Lathe in dry machining condition, simultaneously cutting forces such as feed force, tangential force and thrust force are observed with a calibrated lathe tool dynamometer adapted in the tool holder. A mathematical expression representing mean cutting force and cutting power is developed using non-linear regression analysis. The most favorable parametric circumstances of turning operation have been tested with the confirmation trial. The outcome of each machining factors on the mean cutting force and the cutting power is studied and presented accordingly.***

Index Terms: ***AISI 52100 steel alloy; Cutting force; Cutting power; Taguchi; Lathe; Regression analysis***

I. INTRODUCTION

As per the economical and dynamic market circumstances, the manufacturing enterprises are enforced to cost-effective turning under troublesome machining circumstances for the parametric enhancement of making processes. [1 – 3]. Producing excellence products with low manufacturing price is the key purpose of all productions [4 – 5]. The turning is the elementary machining practice, inwhich a single point tool abolish surplus stuff from a revolving cylindrical shaped workpiece. The rising importance of quick turning task increases new proportions in the present mechanical age. The quick machining factors like feed, tool geometry, cutting velocity, depth of cut and coolant condition consistently worsen the cutting power acting on the workpiece. The most favourable determination of factors is vital to optimize the cutting power acting on the workpiece [6 – 8]. These days' case-hardened steels are largely employed for different functions in aircraft and automotive enterprises. In the meantime, machining of tough steels is a burdensome matter, which is continually accounted by the researchers and makers [2, 9-11]. Numerous investigations are carried out in the machining of harder steel alloy. Some of the investigation examples are presented below. Chen [12] has revealed when examining the turning of harder steel with CBN tool that the thrust power was the biggest among the three cutting power segments. Likewise, the anticipated power was responsive to the progressions of the tool wear and cutting edge geometry. The surface finish delivered by CBN insert was companionable with the outcome of grinding. Furthermore, it was influenced by cutting velocity, tool wear and the plastic behaviour of the workpiece component. In addition, the cutting powers as the surface roughness are additionally affected by the insert cutting edge geometry as it was specified by Özel et al. [13]. Selvaraj et al. [14] have found the impacts of spindle speed and feed on cutting power and tool wear of two distinct grades of nitrogen alloyed duplex stainless steel in dry turning. Asilturk and Akkus [15] have investigated the impact of machining factors on surface roughness in hard turning by means of Taguchi's approach. Abrao and Benga [16] emphasized that feed is the major elementary factor influencing the surface roughness than the speed for both ceramic inserts and CBN. The later sort of mechanical tool was utilized by Davim et al [17] to look at the machinability of steel. They reasoned that with a proper decision of machining constraints it is feasible to get an ideal surface finish. This infers hard machining is a testing errand, which licenses by reducing the grinding process.

From the journalism expressed above, it ends up being obvious that machining studies have been done by different scientists in the field of machining harder steels. Still there relics some complexity in machining of steel which uncovers that, more examinations must be finished to discover a sensible arrangement. In this way, examination on machining is completed by making utilization of the demonstrated test plan method.

II. EXPERIMENT DETAILS

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

A. Work Piece

AISI 52100 is a high carbon alloy steel and it is familiar for its excellent wear resistance behaviour. Many automotive components such as steering wheel, gears, brakes, and precision bearings are manufactured using AISI 52100 steel alloy.

The chemical composition of AISI 52100 alloy steel is given in Table 1.

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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	≤ 0.0250	0.023
P	≤ 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. *Experimental Conditions*

The machining factors to be feed rate, cutting velocity and depth of cut are decided for the experimentation and their levels are indicated in Table 2. The trials were arranged in view of Taguchi's orthogonal array in a turning centre (All Geared Lathe), appeared in Figure 1. The turning action is completed on AISI 52100 cylindrical components of 80 mm diameter by utilizing CBN insert in dry machining condition.

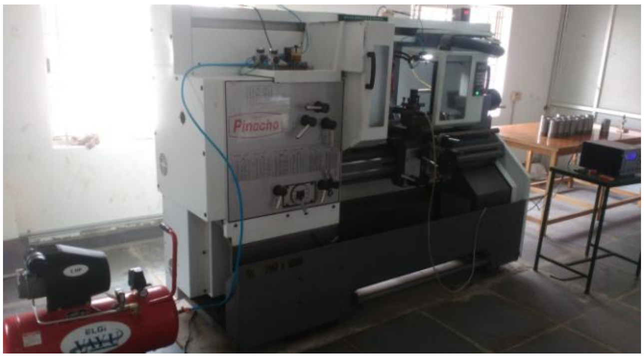

Figure 1: Experimental setup

Table 2: 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

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 cutting force and cutting power. The S/N ratio for the yield response was computed by means of the following Equation (1) for each machining circumstance and their values are specified in Table 3.

$$S/N(\mathrm{dB}) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\mathrm{Response}_i^2\right) \qquad (1)$$

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

A.2 *Analysis of Variance*

The noteworthy factor on the response output (mean cutting force and cutting power) was analyzed through analysis of variance (ANOVA) and F-test with a probability of p=0.05, which was shown in Table 4 and Table 5.

The estimation of 'Prob.>F' in Table 4 and Table 5 for the model 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 responses (mean cutting force and cutting power). From ANOVA results, it is obvious that the depth of cut impacts more on the mean cutting force and cutting power, trailed by the feed rate and cutting velocity. This is harmonizing with the current hypotheses of machining.

Table 3: Experimental Conditions and S/N Ratio

Sl. No.	Machining Factors			Cutting Forces (N)				S/N ratio	Cutting Power	Cutting Power	S/N ratio
	v	f	d	Fa	Fc	Fp	Fm		Cp (W)	Cp (kW)	
1	125	0.05	0.1	12.98	17.39	42.61	47.82	-33.59	36.23	0.036	28.819
2	125	0.10	0.2	16.97	20.90	44.05	51.63	-34.26	43.54	0.044	27.221
3	125	0.15	0.3	36.93	55.59	89.60	111.72	-40.96	115.81	0.116	18.725
4	125	0.20	0.4	71.84	121.45	172.26	222.68	-46.95	253.02	0.253	11.937
5	125	0.25	0.5	121.71	218.48	292.04	384.49	-51.7	455.18	0.455	6.836
6	150	0.05	0.2	10.33	12.67	28.75	33.08	-30.39	37.67	0.038	29.986
7	150	0.10	0.3	22.99	31.36	54.29	66.77	-36.49	78.39	0.078	22.114
8	150	0.15	0.4	50.61	81.22	116.93	151.10	-43.59	203.05	0.203	13.848
9	150	0.20	0.5	93.18	162.26	216.69	286.29	-49.14	405.65	0.406	7.837
10	150	0.25	0.1	49.35	81.71	75.81	121.90	-41.72	204.28	0.204	13.795
11	175	0.05	0.3	22.28	28.37	45.61	58.15	-35.29	82.76	0.083	21.644
12	175	0.10	0.4	42.60	62.24	88.23	116.08	-41.29	181.53	0.182	14.821
13	175	0.15	0.5	77.88	127.28	167.97	224.68	-47.03	371.23	0.371	8.607
14	175	0.20	0.1	22.77	35.78	38.59	57.34	-35.17	104.36	0.104	19.630
15	175	0.25	0.2	60.66	102.40	98.32	154.38	-43.77	298.67	0.299	10.496
16	200	0.05	0.4	47.82	64.51	86.17	117.78	-41.42	215.02	0.215	13.351
17	200	0.10	0.5	75.80	113.55	145.89	199.81	-46.01	378.49	0.378	8.439
18	200	0.15	0.1	9.43	11.09	28.00	31.56	-29.98	36.97	0.037	28.643
19	200	0.20	0.2	40.02	61.71	67.71	99.98	-40	205.71	0.206	13.735
20	200	0.25	0.3	85.58	143.51	144.53	220.93	-46.88	478.37	0.478	6.405
21	225	0.05	0.5	86.95	121.06	150.45	211.78	-46.52	453.98	0.454	6.859
22	225	0.10	0.1	9.30	7.65	44.06	45.67	-33.19	38.68	0.039	30.848
23	225	0.15	0.2	32.60	42.27	63.75	83.15	-38.4	158.53	0.159	15.998
24	225	0.20	0.3	70.86	108.07	120.55	176.73	-44.95	405.28	0.405	7.845
25	225	0.25	0.4	124.08	205.05	214.46	321.61	-50.15	768.93	0.769	2.282

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

$$^{*}Cp = Fc * v \qquad (3)$$

The mean cutting force (Fm) and the cutting power (Cp) is calculated using equation (2) and equation (3) respectively.

Table 4: Analysis of Variance for cutting force

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
v	1	84	0.04%	363	362.8	17.30	0.001
f	1	68103	30.91%	4776	4776.3	227.72	0.000
d	1	127554	57.89%	9165	9164.7	436.94	0.000
vf	1	19	0.01%	12999	12999.4	619.76	0.000
vd	1	1017	0.46%	15696	15695.5	748.31	0.000
fd	1	23185	10.52%	23185	23185.1	1105.38	0.000
Error	18	378	0.17%	378	21.0		
Total	24	220340	100.00%				
R^2 - 0.99				**R^2 (adj) – 0.99**			

Table 5: Analysis of Variance for cutting power

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
v	1	0.098103	11.79%	0.011406	0.011406	28.85	0.000
f	1	0.235972	28.36%	0.006087	0.006087	15.40	0.001
d	1	0.351365	42.23%	0.039869	0.039869	100.85	0.000
vf	1	0.032852	3.95%	0.009738	0.009738	24.63	0.000
vd	1	0.053597	6.44%	0.106297	0.106297	268.89	0.000
fd	1	0.052997	6.37%	0.052997	0.052997	134.06	0.000
Error	18	0.007116	0.86%	0.007116	0.000395		
Total	24	0.832001	100.00%				
R^2 - 0.99				**R^2 (adj) - 0.98**			

A.3 Prediction model

By means of regression examination with the aid of MINITAB17 numerical software, the effect of machining factors on mean cutting force (Fm) and cutting power (Cp) was modeled as follows.

$$Fm = 69.42 + 7.92v + 28.75f - 88.72d - 19.842v*f + 19.606v*d + 23.829f*d \quad (4)$$

$$Cp = 0.1864 - 0.06443\,v + 0.003246\,f - 0.185d - 0.01544v*f + 0.05102v*d + 0.03603f*d \quad (5)$$

For equation (4), it was found that $r^2 = 0.99$ and for equation (5) also, $r^2 = 0.99$. 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 a graphical depiction of the adjustment in execution uniqueness for the variety in factor levels. Figure 2 & Figure 3 outlines the response graph for the outcomes mean cutting force and cutting power with three variables and five levels. From Figure 2, the peak points were picked as the ideal levels of machining factors i.e. cutting velocity at the second level, the feed rate at the first level and depth of cut at the first level. Similarly, from Figure 3, cutting velocity at the first level, the feed rate at the second level and depth of cut at the first level.

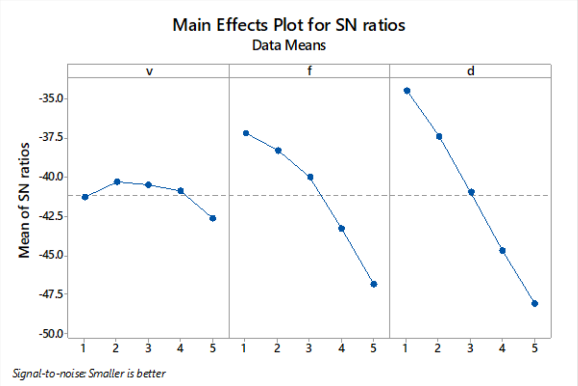

Figure 2: Response Graph for mean cutting force

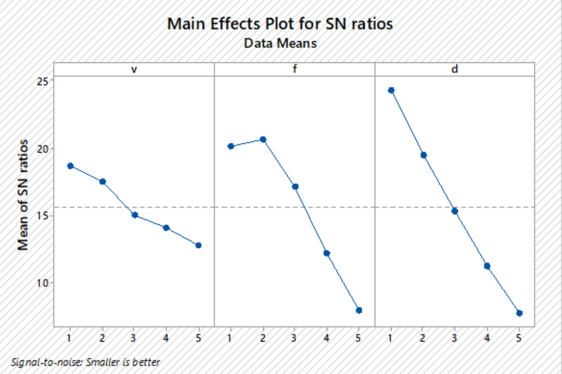

Figure 3: Response Graph for cutting power

While machining cylindrical AISI52100 steel alloy components in dry condition, the cutting forces observed axially, tangentially and radially and the corresponding cutting power played a significant role. Maximum cutting forces and cutting power was observed at higher levels of machining factors such as 225m/min of cutting velocity, 0.25mm/rev of feed rate and 0.4mm of the depth of cut, Table 3. The cutting forces might increase in the increase of the above-mentioned machining factors. The increase in cutting forces ultimately reduces the tool life, which reflects poorly in the production economy. In lieu consideration of the above said facts, the optimum condition for mean cutting force such as 150m/min of cutting velocity, 0.05mm/rev of feed rate and 0.1mm of depth of cut and for optimum cutting power it is 125m/min of cutting velocity, 0.10mm/rev of feed rate and 0.1mm of depth of cut was observed.

A.5 Confirmation test

The confirmation test was directed at the ideal levels of machining factors and the outcome is specified in Table6 and Table 7.

Table 6: Confirmation Experiment for mean cutting force

Factors			**Mean Cutting Force (Fm)**		**Deviation %**
v	**f**	**d**	**Experimented (Fm)**	**Predicted (Fm)**	
2	1	1	47.71	50.65	5.8

A.6 Effect of Machining Factors

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

Table 7: Confirmation Experiment for cutting power

Factors			**Mean Cutting Force (Cp)**		**Deviation %**
v	**f**	**d**	**Experimented (Cp)**	**Predicted (Cp)**	
1	2	1	0.035	0.036	2.8

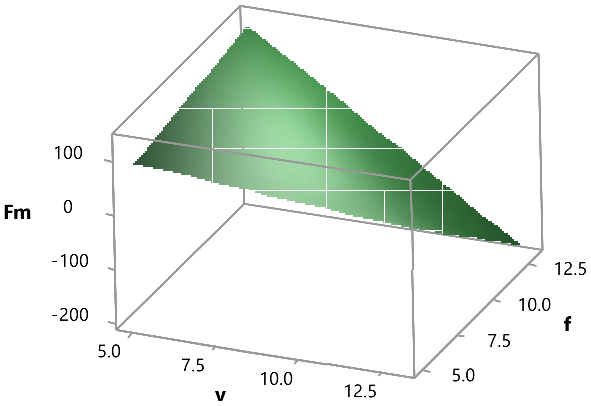

Figure 4: Surface plot of mean cutting force versus cutting velocity and feed rate

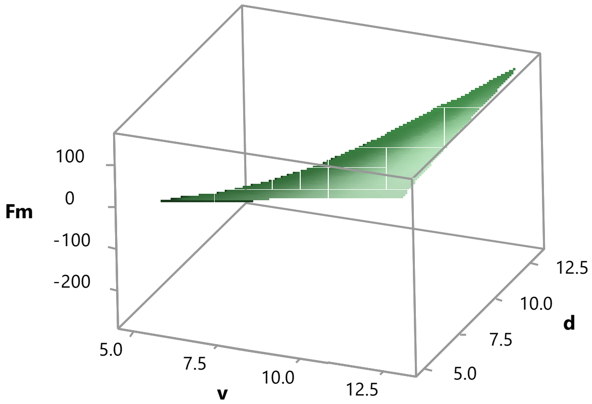

Figure 5: Surface plot of mean cutting force versus cutting velocity and depth of cut

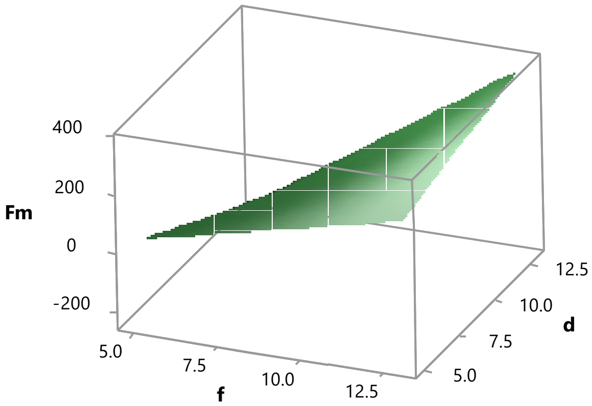

Figure 6: Surface plot of mean cutting force versus feed rate and depth of cut

Figure 4 depicts the outcome of cutting velocity and feed rate on the mean cutting force, where the depth of cut is kept constant. From Figure 4 it is obvious that feed rate influences more than the cutting velocity, at maximum feed rate and minimum cutting velocity, increased cutting forces were observed. Figure 5 depicts the outcome of cutting velocity and depth of cut on the mean cutting force, where feed rate is kept constant. From Figure 5 it is obvious that the depth of cut influences more than the cutting velocity, at a maximum depth of cut and maximum cutting velocity, increased cutting forces were observed. Figure 6 depicts the outcome of feed rate and depth of cut on the mean cutting force, where cutting velocity is kept constant. From Figure 6 it is obvious that feed rate has the influence of cutting forces but the depth of cut influences more than feed rate on cutting forces, at a maximum feed rate and a maximum depth of cut, increased cutting forces were observed.

IV. CONCLUSION

In this background, the study reported in this paper was mean cutting force and cutting power test conducted during turning operation of AISI52100 steel with CBN The ANOVA and F-test of the experimented results revealed that insert. The subsequent conclusions were drawn out from the present study; the depth of cut has a greater influence on the mean cutting force and cutting power, subsequently by the feed rate and cutting velocity. Generalized mathematical models were developed through regression analysis using Minitab statistical software for mean cutting force and cutting power. From those equations, the mean cutting force and cutting power values could be computed if the factors namely feed rate, cutting velocity and depth of cut are known. The confirmation trial ensured that the optimum machining conditions resulted in minimum mean cutting force and cutting power based on the Taguchi's L_{25} orthogonal array.

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

f	Feed rate in mm/rev
v	Cutting velocity in m/min
d	Depth of cut in mm
CBN	Cubic Boron Nitride
Fc	Thrust force in N
Fa	Feed force in N
Fp	Tangential force in N
Fm	Mean cutting force in N
Cp	Cutting power in W
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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