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To cite this article: S K Thangarasu *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **310** 012119

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Prediction of Cutting Force in Turning Process-an Experimental Approach

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Abstract: This Paper deals with a prediction of Cutting forces in a turning process. The turning process with advanced cutting tool has a several advantages over grinding such as short cycle time, process flexibility, compatible surface roughness, high material removal rate and less environment problems without the use of cutting fluid. In this a full bridge dynamometer has been used to measure the cutting forces over mild steel work piece and cemented carbide insert tool for different combination of cutting speed, feed rate and depth of cut. The experiments are planned based on taguchi design and measured cutting forces were compared with the predicted forces in order to validate the feasibility of the proposed design. The percentage contribution of each process parameter had been analyzed using Analysis of Variance (ANOVA). Both the experimental results taken from the lathe tool dynamometer and the designed full bridge dynamometer were analyzed using Taguchi design of experiment and Analysis of Variance.

Keywords: Turning Process, Cemented Carbide, Lathe Dynamometer, ANOVA, Full Bridge Dynamometer, Taguchi Design of Experiments.

1. Introduction
One of the most promising techniques for detection of cutting condition involves the measurement of cutting forces. Cutting forces are important to achieve its dimensional accuracy, and machining system stability. In all classical metal cutting procedures in the area of contact between tool and material appears a cutting force, which can be decomposed after three orthogonal components. In practice, the resulting value of the cutting force is less of importance, relevant being its components, which are used in calculations of fixing devices for the material, tools, resistance of the various parts of the machine tools, to calculate the propulsion power of the driving electric motors, and the calculation of processing accuracy. Moreover, the need for measurement of all cutting force component arises from many factors, but probably the most important is the need for correlation with the progress of tool wear.

2. Literature Review
Samuel G L *et al.*, (2012) made an attempt to analyses the influence of cutting speed, feed rate, depth of cut and machining time on machinability characteristics such as machining force, surface roughness

and tool wear using response surface methodology (RSM) during turning of AISI 4340 high strength low alloy steel using coated carbide inserts. The results show that the combination of low feed rate, low depth of cut and low machining time with high cutting speed is beneficial for minimizing the machining force [1].

Lalwani D I *et al.,* (2007) investigated the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces (feed force, thrust force and cutting force) and surface roughness in finish hard turning of MDN250 steel (equivalent to 18Ni(250) maraging steel) using coated ceramic tool. The results show that cutting forces and surface roughness do not vary much with experimental cutting speed and the suggested non-linear quadratic models of cutting forces and surface roughness adequately map within the limits of the cutting parameters considered [2].

Manoj Nayak *et al.,* (2015) investigated the microstructural, mechanical, and machining behavior of AISI D6 steel in annealed and hardened conditions. It was found that the depth of cut, feed, and approach angle are the most significant factors affecting the surface roughness and depth of cut and feed affect the main cutting force. Cutting speed has no effect on surface roughness and main cutting force in machining of the steel in annealed condition [3].

Yigit *et al.,* (2010) found that multilayer coating on carbide substrate enhances the tool life performance and cutting force decreases using high temperature chemical vapour deposition (HTCVD) multilayer carbide tools when compared touncoated carbide tools [4].

Gaitonde *et al.,* (2009) explored the effects of depth of cut and machining time on machinability aspects such as machining force, power, specific cutting force,surface roughness, and tool wear by using second-order mathematical models during turning of high chromium content AISI D2 cold work tool steel with CC650,CC650WG and GC6050WH ceramic inserts [5].

Suleyman Yaldiz and Faruk Unsacar (2005) designed and developed a strain gauge based dynamometer. The obtained results of machining tests performed at different cutting parameters shows that the dynamometer can be used reliably to measure cutting forces [6].

Daniel Kirby E *et al*., (2006) discussed the development of an in-process surface roughness adaptive control system for a CNC turning operation, using fuzzynets modelling and tool vibrations measured with an accelerometer. The goal of this system is to predict the surface roughness of a surface being turned, determine if the surface roughness being generated is higher than the desired specification, and if so to adapt the feed rate of the turning operation in order to obtain a surface roughness no higher than that specified [7].

From this literature survey, the importance of cutting force measurementwhile manufacturing a quality product is understood and the parameters that influence most on the cutting force are identified as cutting speed, feed rate and depth of cut. Various types of dynamometer are used to measure cutting force and various methods are applied to predict the cutting force. It is assured that the measurement of cutting force is possible with a strain gauge. Hence a full-bridge strain gauge is used in this project and the Taguchi's design of experiments (DOE) is used for planning experiments and ANOVA is employed for analysis.

3. Problem Identification

The main concerns of hard turning are the effect of the process on machinability characteristics and the cost of expensive tool materials. The poor selection of the process parameters may cause excessive tool wear and increased work surface roughness. Studies were made for measuring surface roughness, tool wear. There is no proper comparison between different dynamometers and Taguchi's method.

4. Problem Solution

The cutting force can be measured using a full-bridge strain gauge sensor and the same is acquired through DAQ (Data Acquisition) card. The sensor used for measuring the cutting force is full-bridge strain gauge sensor. The Full-Bridge Type II arrangement utilizes four active gauges subject to a uniaxial stress, with two gauges aligned to measure the maximum principal strain, and the other two aligned to measure the transverse Poisson's strain. A Taguchi's design of experiments (DOE) is developed to predict the values of the cutting force at any operating conditions.

5. Real Time Acquisition of Data

The cutting force is measured with the designed full bridge strain gauge based dynamometer. An analogue strain gauge dynamometer capable of measuring the cutting force during turning is designed and developed. In order to read and save the cutting forcedata automatically on a computer during metal cutting, a data acquisition system with the essential hardware and software is also arranged and connected to the developed dynamometer. The acquiredcutting force data is then used for the further analysis.
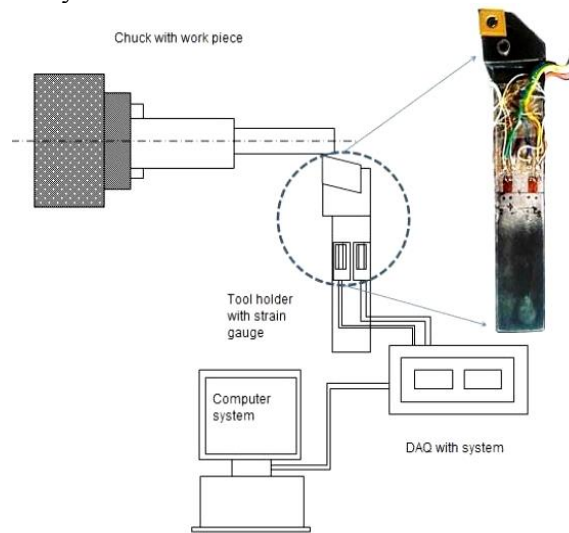
Figure 5. 1 Block diagram of proposed system   **Figure 5. 2** Schematic representation of the experimental set up

For bridge circuit configuration in the flexural members, the full bridge circuit is chosen since it re-joined quite sensitively to small flexural movements as the column is loaded and best sensitivity to bending with temperature compensation. This created exact measurement channels that could be investigated for sensitivity to cutting force. The accuracy of the results mainly depends upon the strain gauge bonding to the surface of the test specimen. Careful bonding ensures the measurement of true strain from the tool holder during the turning operation. The following procedure is adopted for bonding the strain gauge material to the tool holder. The solvent degreasing is performed using isopropyl alcohol or acetone to remove oils, greases and other soluble chemical residues. Surface bonding helps to remove the loosely bonded adherents on the surface of tool holder for developing the surface texture suitable for bonding. The gauge layout line is marked as reference line on the tool holder surface by considering the desired location and orientation of the strain gauge on the test surface. Surface conditioning and neutralizing is important for the strain gauges in order to provide the accurate results. The experimental setup consists of four strain gauges, a Wheatstone bridge and a data acquisition system for logging the measured strain. The strain gauge used in this study has following characteristics: Gauge resistance- 350 Ω, measuring grid- 6 mm, supply voltage -5 V and the Poisson's ratio of 0.3 with a gauge factor of 2.The cutting force (F) will be calculated using the measured strain (ε) and the classical theory for a simple beam under bending. As long as the deformations are within the elastic domain, the strain is proportional to the bending stress. The following equation and is used to calculate the main cutting force for turning process.

$$f = \frac{(E * b * h^2)}{(6 * l)} * \varepsilon \tag{1}$$

E = Young's Modulus for the cutting tool (N/mm^2)
b = Beam width of the tool (mm)
h = Beam height of the tool (mm)

l = Distance between the strain gauge and the applied load (mm)
ε = Bending strain
F = Cutting force (N)

Trail No	Spindle Speed (rpm)	Feed Rate (mm/rev)	DOC (mm)	Measured Force (N)	S/N Ratio
1	90	0.2	0.2	366.75	-51.28
2	90	0.2	0.4	372.39	-51.42
3	90	0.2	0.6	380.85	-51.61
4	90	0.4	0.2	393.08	-51.88
5	90	0.4	0.4	400.60	-52.05
6	90	0.4	0.6	410.01	-52.25
7	90	0.6	0.2	423.92	-52.54
8	90	0.6	0.4	433.14	-52.73
9	90	0.6	0.6	444.24	-52.95
10	180	0.2	0.2	472.26	-53.48
11	180	0.2	0.4	478.47	-53.59
12	180	0.2	0.6	492.76	-53.85
13	180	0.4	0.2	505.93	-54.08
14	180	0.4	0.4	513.64	-54.21
15	180	0.4	0.6	523.23	-54.37
16	180	0.6	0.2	534.14	-54.55
17	180	0.6	0.4	541.85	-54.67
18	180	0.6	0.6	551.44	-54.83
19	270	0.2	0.2	583.23	-55.31
20	270	0.2	0.4	589.43	-55.40
21	270	0.2	0.6	598.09	-55.53
22	270	0.4	0.2	608.62	-55.68
23	270	0.4	0.4	616.33	-55.79
24	270	0.4	0.6	624.98	-55.91
25	270	0.6	0.2	637.77	-56.09
26	270	0.6	0.4	646.80	-56.21
27	270	0.6	0.6	656.01	-56.33

Table 6. 1 Strain gauge dynamometer – experimental values

6. Experimental Values – Strain Gauge Dynamometer

From table, the cutting force was almost constant with respect to cutting speed and insert radius. The main effect plot was constructed for systematical investigation.
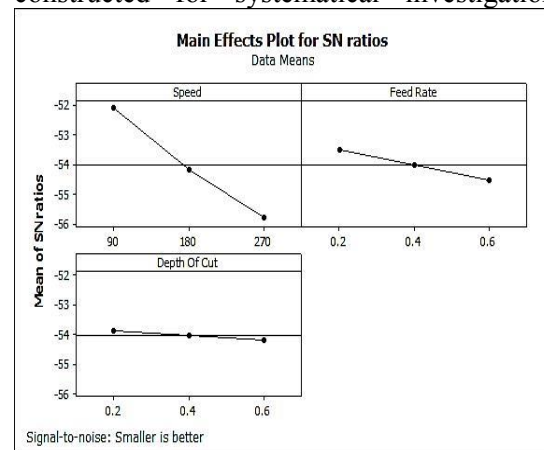
Figure 6. 1 Main effects plot of S/N ratios for cutting force

7. Analysis of data using Taguchi's method

The plot shows that among the main effects, the cutting force and feed rate were the most important factors on the cutting force because it had a increasing effect. In order to get the optimal combination smaller the best performance was considered and given in below equation

$$\frac{S}{N}(\eta) = -10\log_{10}(1/n\sum_{i=1}^{n} y_i 2)dB \qquad (2)$$

8. Cutting force model

The effect of parameters involved in the machining process was understood by using the mathematical model.The experimental data shown in above table was applied in statistical analysis software Minitab16.1 for performing regression analysis. In this approach, the least square estimation was used to determine a model for cutting force in relation to the functions of cutting speed, feed rate and depth of cut. The models for cutting force F were derived from the experimental data and as given in below Equation .The table and figure shows the comparison of experimental values and predicted values.

$$\text{Cutting force (F)} = 219 + 1.20 \text{ x N} + 148.63 \text{ x f} + 43.31 \text{ x d} \qquad (3)$$

F = Cutting Force (N) ,   d = Depth of Cut (mm)
N = Spindle Speed (rpm),
f = Feed Rate (mm/rev),

| Trail No	Measured Force (N)	Predicted Force (N)	Residual	% Error
1	366.75	365.15	-1.59	-0.43
2	372.39	373.81	1.42	0.38
3	380.85	382.47	1.61	0.42
4	393.08	394.88	1.79	0.45
5	400.60	403.54	2.93	0.72
6	410.01	412.20	2.19	0.53
7	423.92	424.60	0.67	0.15
8	433.14	433.27	0.12	0.02
9	444.24	441.93	-2.30	-0.52
10	472.26	472.72	0.45	0.09
11	478.47	481.38	2.91	0.60
12	492.76	490.04	-2.71	-0.55
13	505.93	502.45	-3.47	-0.69
14	513.64	511.11	-2.52	-0.49
15	523.23	519.77	-3.45	-0.66
16	534.14	532.17	-1.96	-0.36
17	541.85	540.84	-1.01	-0.18
18	551.44	549.50	-1.94	-0.35
19	583.23	580.29	-2.93	-0.50
20	589.43	588.95	-0.48	-0.08
21	598.09	597.62	-0.47	-0.07
22	608.62	610.02	1.40	0.22
23	616.33	618.68	2.35	0.37
24	624.98	627.34	2.36	0.37
25	637.77	639.74	1.97	0.30
26	646.80	648.41	1.60	0.24
27	656.01	657.07	1.05	0.16
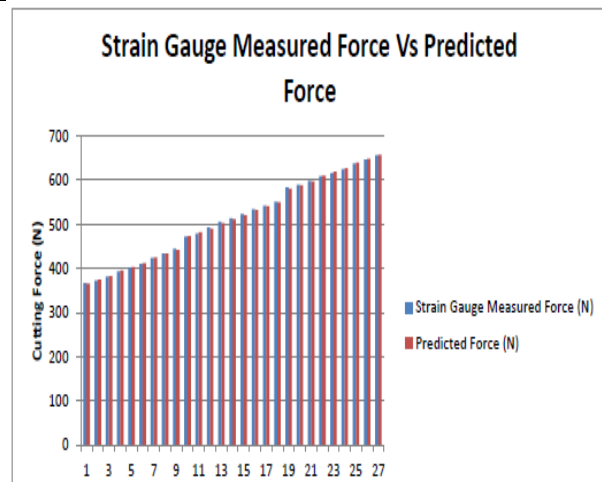
Figure 8. 1 Strain Gauge vs Predicted Force

Table 8. 1 Experimental Values vs Predicted values

9. Analysis of Variance (ANOVA)

The anova for force was carried out to get the statistical significance of the process variables on the cutting force in turning of mild steel with TiCN coated cemented carbide inserts for a confident level an alpha of 0.05.Below Table shows the analysis of variance results of mild steel with TiCN coated cemented carbide inserts with the cutting speed, feed rate and depth of cut were statistically significant. Hence the developed model is significant.It also indicates the analysis of variance for cutting force. It concluded that the correlation coefficient R was very close to unity, while the tables also indicates that the relationship between the cutting force and the cutting parameters was well represented by the anticipated model, as like the relationship between the prediction model on the cutting force. It had physical significance on the cutting force because the S-value of these factors was 1.89888.The cutting speed and feed rate had the percentage contribution of 92.316% and 7.05% respectively and depth of cut contributes only 0.603% of the total variability, this factor can be ignored.

| Source	DF	SS	MS	F	$F_{0.05}$	Contribution %	Rank
Spindle Speed	2	208317	104159	28886.80	3.49	92.316	1
Feed Rate	2	15909	7954	2205.99	3.49	7.05	2
Depth of Cut	2	1360	680	188.52	3.49	0.603	3
Error	20	72	4				
Total	26	225657					

Table 9. 1 Analysis of variance

The analytical verification of the model had been carried out using the residual analysis and the outcomes were presented in 9.1 figure. It revealed that the residuals fall on closeness to the straight line implying that the errors were distributed uniformly. The normal probability plot of residuals for cutting force and residuals versus run numbers for the cutting force is shown in the below figures 9.1 & 9.2 respectively. Figure 9.2 shows the residuals with respect to the twenty seven experimental runs. The residuals did not show any recognizable pattern and were distributed in both positive and negative directions.

This implies that the model was adequate and there was no reason to suspect any violation of the independence or constant variance assumption.
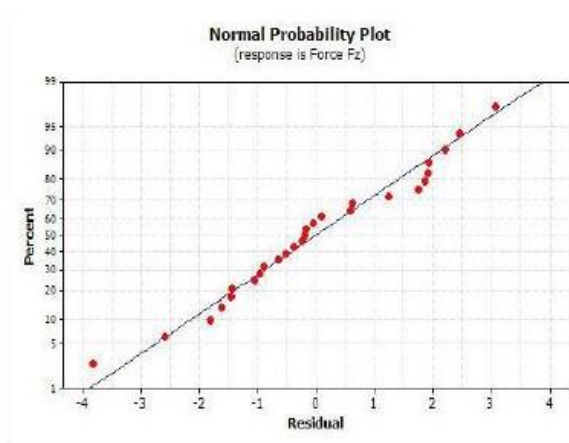
Figure 9. 1 Normal probability plot of residuals for cutting force
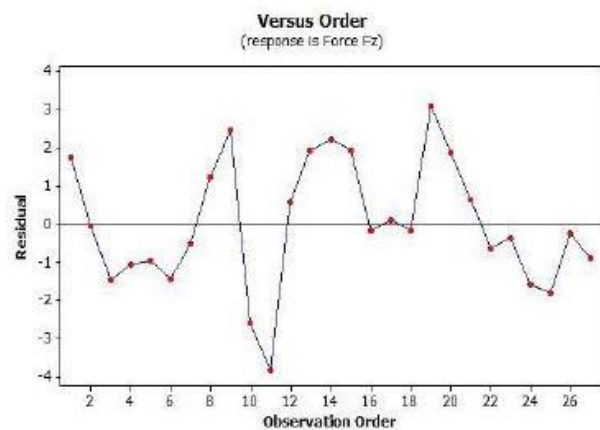
Figure 9. 2 Residuals Vs Run numbers for cutting force

10. Experimental Values – Lathe Tool Dynamometer

 The turning experiments are carried out using a conventional lathe which has a maximum spindle speed of 3000 rpm and a maximum spindle power of 16 kW.

The schematic representation of the experimental set up is shown in the picture. The cutting force measured from the lathe tool dynamometer is in terms of Kilogram force (Kgf). So, it is converted into Newton (N) by multiplying the cutting force with the value 9.81. Then the measured force value is used for further analysis and comparison of results. From the table, the feed rate and depth of cut causes the main effect the force which used for cutting is almost constant Figure with respect to cutting speed and insert radius. In order to find the cutting parameters on cutting force main effect plots was constructed.

Table 10. 1 Lathe tool dynamometer – experimental values

Trail No	Spindle Speed (rpm)	Feed Rate (mm/rev)	DOC (mm)	Measured Force (N)	S/N Ratio
1	90	0.2	0.2	374.74	-51.46
2	90	0.2	0.4	381.60	-51.63
3	90	0.2	0.6	386.38	-51.73
4	90	0.4	0.2	394.36	-51.99
5	90	0.4	0.4	403.19	-52.12
6	90	0.4	0.6	412.02	-52.23
7	90	0.6	0.2	421.83	-52.27
8	90	0.6	0.4	436.54	-52.85
9	90	0.6	0.6	447.33	-53.01
10	180	0.2	0.2	475.78	-53.54
11	180	0.2	0.4	480.69	-53.63
12	180	0.2	0.6	494.42	-53.88
13	180	0.4	0.2	510.12	-54.14
14	180	0.4	0.4	520.91	-54.33
15	180	0.4	0.6	527.77	-54.44
16	180	0.6	0.2	544.45	-54.71
17	180	0.6	0.4	551.32	-54.82
18	180	0.6	0.6	558.18	-54.93
19	270	0.2	0.2	591.54	-55.43
20	270	0.2	0.4	594.48	-55.48
21	270	0.2	0.6	606.25	-55.65
22	270	0.4	0.2	613.12	-55.75
23	270	0.4	0.4	626.85	-55.94
24	270	0.4	0.6	637.65	-56.09
25	270	0.6	0.2	644.51	-56.18
26	270	0.6	0.4	659.23	-56.38
27	270	0.6	0.6	668.06	-56.49

Figure 10. 1 Schematic representation of the experimental set up

11. Analysis of data using Taguchi's method

The figure shows that,the important effect in cutting force are cutting speed and feed rate because of the parameters had an increase in values. As told in the earlier method the smaller the best quality has been used in order to get opimal combination.The smaller the best quality characteristics may be formulated as shown in the equation..
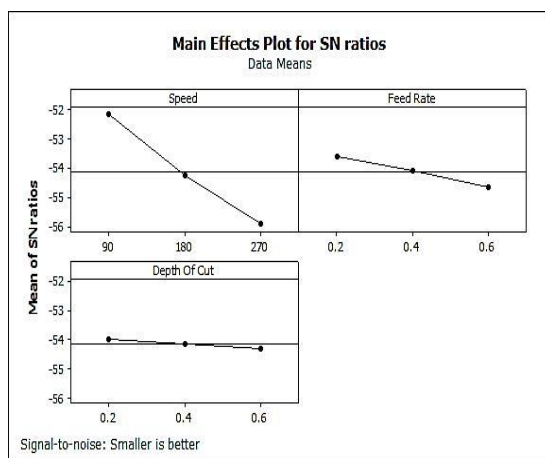
Figure 11. 1 Main effects plot of S/N ratios for cutting force
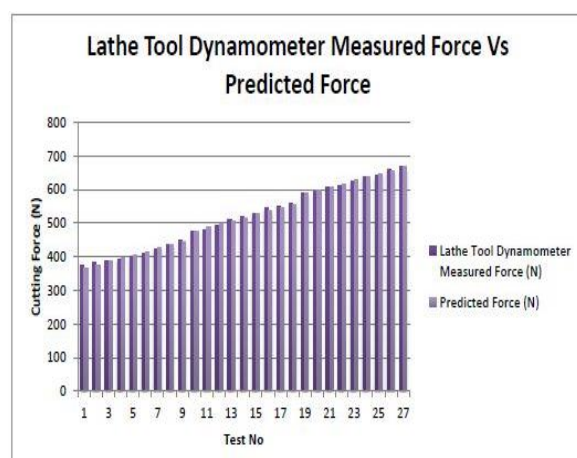
Figure 11. 2 Lathe tool dynamometer measured force Vs Predicted force

12. Cutting force model

Trail No	Measured Force (N)	Predicted Force (N)	Residual	% Error
1	374.74	367.33	-7.40	-2.01
2	381.60	376.64	-4.95	-1.31
3	386.38	385.96	-0.44	-0.10
4	394.36	397.64	3.27	0.82
5	403.19	406.95	3.76	0.92
6	412.02	416.26	4.24	1.02
7	421.83	427.95	6.12	1.43
8	436.54	437.26	0.72	0.16
9	447.33	446.57	-0.75	-0.16
10	475.78	477.54	1.75	0.36
11	480.69	486.85	6.16	1.26
12	494.42	496.16	1.74	0.35
13	510.12	507.85	-2.26	-0.44
14	520.91	517.16	-3.74	-0.72
15	527.77	526.47	-1.30	-0.24
16	544.45	538.16	-6.29	-1.16
17	551.32	547.47	-3.84	-0.70
18	558.18	556.78	-1.40	-0.25
19	591.54	587.74	-3.79	-0.64
20	594.48	597.06	2.57	0.43
21	606.25	606.37	0.11	0.01
22	613.12	618.05	4.93	0.79
23	626.85	627.37	0.51	0.08
24	637.6	636.68	-0.96	-0.15
25	644.57	648.36	3.85	0.59
26	659.22	657.68	-1.55	-0.23
27	668.01	666.99	-1.06	-0.16

Table 12. 1 Experimental values Vs Predicted values

The experimental data shown in above table was applied in statistical analysis software Minitab 16.1 for performing regression analysis. In this approach, the least square estimation was used to determine a for cutting force in relation to the functions of cutting speed, feed rate and depth of cut. The models for cutting force F were derived from the experimental data and as given in below Equation . The below table and graph shows the comparison of experimental values and predicted values.

$$Cutting force (F) = 217.51 + 1.22*N + 151.55*f + 46.56*d \quad (4)$$

F = Cutting Force (N), N = Spindle Speed (rpm), f = Feed Rate (mm/rev), d = Depth of Cut (mm)

13. Analysis of Variance (ANOVA)

Table below shows the analysis of variance results of mild steel with TiCN coated cemented carbide inserts with the cutting speed, feed rate and depth of cut were statistically significant. Hence the developed model is significant.

| Source	DF	SS	MS	F	$F_{0.05}$	Contribution %	Rank
Spindle Speed	2	218632	109316	6798.85	3.49	92.226	1
Feed Rate	2	16548	8274	514.59	3.49	6.98	2
Depth of Cut	2	1561	780	48.54	3.49	0.658	3
Error	20	322	16				
Total	26	237062					

Table 13. 1 Analysis of variance for force

It also indicates the analysis of variance for cutting force. It concluded that the correlation coefficient R was very close to unity, while the tables also indicates that the relationship between the cutting force and the cutting parameters was well represented by the anticipated model, as like the relationship between the prediction model on the cutting force. It had physical significance on the cutting force because the S-value of these factors was 4.00981.

The cutting speed and feed rate had the percentage contribution of 92.226% and 6.98% respectively and depth of cut contributes only 0.658% of the total variability, this factor can be ignored.
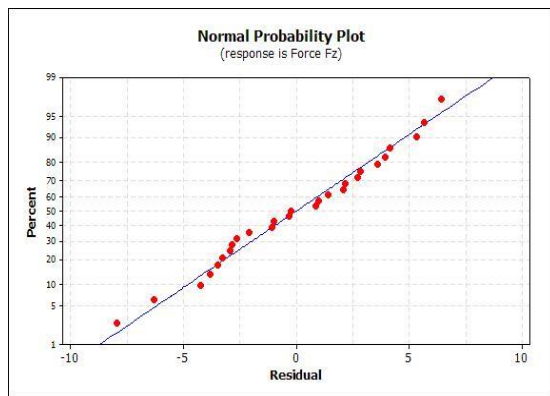
Figure 13. 1 Normal probability plot of residuals for cutting force
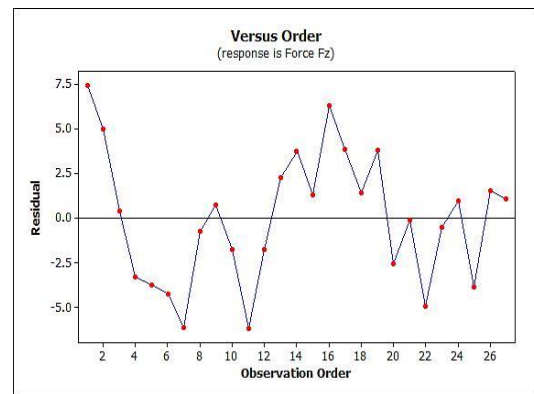
Figure 13. 2 Residuals Vs Run numbers for cutting force

The analytical verification of the model had been carried out using the residual analysis and the outcomes were presented in figure 13.1. It revealed that the residuals fall on closeness to the straight line implying that the errors were distributed uniformly**.** The normal probability plot of residuals for cutting force and residuals versus run numbers for the cutting force is shown in figures 13.1 and 13.2 respectively. Figure 13.2 shows the residuals with respect to the twenty seven experimental runs. The residuals did not show any recognizable pattern and were distributed in both positive and negative directions. This implies that the model was adequate and there was no reason to suspect any violation of the independence or constant variance assumption.

14.Results And Discussion
Comparison Of Different Measured Values

Trail No	Strain Gauge Measured Force (N)	Dynamometer Measured Force (N)	Residual	% Error
1	366.75	374.74	7.98	2.13
2	372.39	381.60	9.21	2.41
3	380.85	386.38	5.52	1.42
4	393.08	394.36	1.27	0.32
5	400.60	403.19	2.58	0.64
6	410.01	412.02	2.00	0.48
7	423.92	421.83	-2.09	-0.47
8	433.14	436.54	3.39	0.78
9	444.24	447.33	3.09	0.61
10	472.26	475.78	3.51	0.79
11	478.47	480.69	2.21	0.41
12	492.76	494.42	1.65	0.35
13	505.93	510.12	4.18	0.81
14	513.64	520.91	7.26	1.35
15	523.23	527.77	4.54	0.80
16	534.14	544.45	10.30	1.83
17	541.85	551.32	9.46	1.77
18	551.44	558.18	6.74	1.27
19	583.23	591.54	8.39	1.44
20	589.43	594.48	5.03	0.89
21	598.09	606.25	8.16	1.37
22	608.62	613.12	4.50	0.74
23	616.33	626.85	10.52	1.69
24	624.98	637.65	12.66	1.96
25	637.77	644.51	6.74	1.06
26	646.80	659.23	12.42	1.85
27	656.01	668.06	12.04	1.82

Table 14. 1 Strain gauge measured force Vs Dynamometer measured force

In this study a strain gauge model is used to measure the cutting force. The results showed that developed strain gauge dynamometer is sufficient for measuring the cutting force for the above mentioned parameter. The accuracy of the proposed model is expressed through the error percentage. The comparison between the strain gauge measured force and the predicted cutting force using Taguchi's method is shown in the table. Similarly, lathe tool
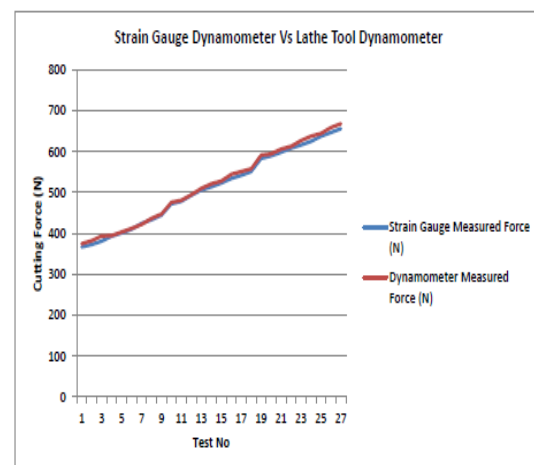
Graph showing the accuracy of the Strain gauge dynamometer

dynamometer is used to measure the cutting force. The comparison between the lathe tool dynamometer measured force and the predicted cutting force using Taguchi's method is shown in the table . The strain gauge measured force is compared with the lathe tool dynamometer measured force and the residual and percentage error is shown the table.

The graph indicates that the measured values of the proposed model are good correlation with the lathe tool dynamometer experimental data. The developed strain gauge model shows an error percentage less than 2.5%.

CONCLUSION

This paper proposed a novel model for predicting the cutting force. The graph shows that the measured values (obtained from strain gauge model) are in correlation with the experimentally lathe tool dynamometer measured force. The accuracy of the strain gauge model is about 97.59%. By choosing proper operating conditions such that the cutting force should be minimum, the surface roughness and tool wear can be controlled.

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