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Prediction of cutting force in turning process: An experimental and fuzzy approach

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Abstract. This paper presents a comparison of experimental results and a fuzzy rule based system model for calculating the cutting force in the turning operation. A full bridge dynamometer was used to measure the cutting forces over the mild steel work piece and Cemented Carbide Insert tool for different combinations of cutting velocity, feed rate and depth of cut. The rake angle, approach angle and nose radius of the cutting tool insert is kept constant throughout the experiment. This fuzzy model consists of 27 rules and Mamdani Max-min inference mechanism was used. The Taguchi designs of experiments were used to determine the number of experiments. Also, an attempt had been made to analyze the influence of the parameters using the regression analysis which yields a maximum error of 3.214% at the time of prediction which was smaller. The experiments are planned based on Taguchi's design and the 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). Experimental results were compared with the regression analysis and predicted fuzzy model. The difference between experimental and predicted results was obtained as around 98.84%.

Keywords: Full bridge dynamometer, cemented carbide tool, regression analysis, fuzzy logic, turning process

1. Introduction

A considerable amount of investigations has been directed towards the prediction and measurement of cutting forces. That is, because the cutting forces generated during metal cutting have a direct influence on the generation of heat and tool wear, quality of machined surface and accuracy of the work piece. The importance of monitoring the cutting force in turning has been well recognized in machine tool communities. The investigations performed on the PTFE composites using a polycrystalline diamond tool in order to analyze the effect of the cutting parameters and insert radius on the cutting force and surface roughness was presented [3]. A strain gauge based dynamometer for the main cutting force measurement in turning was constructed. The force signals were captured and processed using a strain data acquisition system based on the Sider8 and CATMAN software. The relationship between the cutting force and the tool wear for polycrystalline diamond (PCD) tool was proposed. The experimental work was developed by considering the drilling and turning operations, through the continuous measurement of the cutting forces with appropriate piezoelectric dynamometers [9]. The wear type was identified and its evolution with cutting time was measured. A three component strain gauge based dynamometer has been constructed in order to measure cutting forces during the milling process. Signal obtained from the strain gauge is converted into digital signals through the data acquisition system [7]. A turning dynamometer was designed and constructed, that can measure static and dynamic cutting forces using strain gauge and piezoelectric accelerometer [17]. The dynamometer has been subjected to a series of tests to determine its static and

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dynamic characteristics. The importance of the design and construction of dynamometer with linear motion are also discussed [21].

Several parameters like tool wear, temperature of the tool, etc., which are not generally considered in turning process affects the experimentally obtained values from the mathematically predicted values, So a fuzzy based system should be used to design a system with proper prediction. The comparison of the values obtained in turning using the AISI 1040 with the measured value form the fuzzy logic (27 rule) is presented [19]. Similarly the fuzzy based predictive model for the cutting force in the turning process of reinforced PEEK composite was developed [8].

The prediction of surface finish and dimensional deviation is an essential prerequisite for developing an unmanned turning centre [12]. It is also an important parameter for optimization of turning process. The influence of cutting parameters with different drilling of carbon fibre reinforced plastics was investigated [20]. A non-destructive method based on the image analysis was used to measure the delaminated area. The metal matrix composites by a conventional casting process was developed and analysed its machinability characteristics with the turning process using a multi-layer coated carbide tool based on the Taguchi's orthogonal array and concluded that the cutting speed was the most significant variable affecting the flank wear of the tool followed by feed [13]. The usage of Taguchi's method and Pareto ANOVA analysis to optimise the process parameters (cutting speed, feed rate and depth of cut) and minimizing the surface roughness in turning of GFR composite material was discussed [10]. Machinability characteristics of Al/SiCp (10% weight) metal matrix composite with multilayer TiN coated carbide insert under dry cutting condition was studied based on Taguchi's L_9 orthogonal array [11].

The individual contribution of process parameter is analysed by ANOVA [4]. Reliable prediction of cutting force is obtained in milling process based on subtractive clustering which filters the noise and the cutting forces was predicted using sensors. The obtained data is used to generate the learning system which is tested by other data's [15]. Recently Grey fuzzy based Taguchi method is used for optimizing the process parameters for submerged arc welding [2]. The proposed constant turning force control system is developed using a combined fuzzy logic and gray algorithm prediction [18]. There are some works in modeling manufacturing process on using TSK-fuzzy model, for surface roughness prediction with genetic algorithm (GA) [1].

The literature reveals that restricted literatures are available on cutting force measurement on full bridge strain gauge based dynamometer in turning of mild steel. In addition to that, there is a need to present the predictive models which correlates the process parameters with the Machinability characteristics. To the best knowledge of the authors there is no comparison model exist which compares the statistical regression model and fuzzy prediction model with the measured experimental values. Hence in the present study, the consideration is given in the direction of cutting force measurement in turning of mild steel and to investigate the influence of process parameters such as cutting speed, feed rate and depth of cut and to correlate the results with the fuzzy and regression predictive models. The Taguchi design of experiments is used for planning experiments and ANOVA is employed for analysis.

In this study mild steel is turned using TiN coated cutting tool, a number of experiments using Taguchi's full factorial DOE table was performed. The cutting force was measured by using the designed strain gauge based full bridge dynamometer. Based on the obtained experimental results, fuzzy inference system was applied to predict the cutting force. The regression model was obtained using the statistical tool. To evaluate the validity of the obtained fuzzy prediction model, the results are compared with the experimental data. Fuzzy model results are also compared with classical polynomial regression based models.

2. Materials and methods

Mild steel in the form of round bar with 70 mm diameter and 200 mm length is used for the present investigation. The hardness of the material is 77 BHN. Mild steel is especially suitable for automotive disc brakes, cylinder liners and driveshaft in automobile sectors.

In the present experimental study, TiN coated cemented carbide inserts are used. The inserts are manufactured by Sandvik Coromant with ISO designation of CNMG 120408 (80° diamond shapes inserts). The inserts are rigidly mounted on a right hand style tool holder designated by ISO as PCLNR2525M12 thus giving back rake angle of −6°, clearance angle of 5°, negative cutting edge inclination angle of −6°, major cutting edge or approach angle of 95°, nose radius of 0.8 mm and insert tightening torque is 3.9 Nm respectively. The provision of a functional TiN outer layer reduces the tendency to built-up edges. Furthermore, the generation of heat is a smaller amount due to the reduction of friction.

3. Cutting conditions and measurement

The turning experiments are carried out using a conventional lathe which has a maximum spindle speed of 3500 rpm and a maximum spindle power of 16 kW. The schematic representation of the experimental set up is shown in Fig. 1.

Three factors with three levels are selected for the present experimentation and their low-middle-high levels are shown in Table 1. 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 force data 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 acquired cutting force data is then used for the further analysis.

For bridge circuit configuration in the flexural members, the full bridge circuit is chosen since it rejoined 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 bondings ensure 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 of 350 Ω, measuring grid of 6 mm, supply voltage of 5V and the Poisson's ratio of 0.3 with a gauge factor of 2. The cutting force (F) during the turning may be calculated using the experimentally 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 main component of the cutting force is calculated based on the following relation [3]. The Equation (1) and (2) is used to calculate the main cutting force for turning process.

Fig. 1. Schematic representation of cutting force measurement.

Table 1
Process parameters and their selected levels

Parameters	Cutting force		
	Level 1	Level 2	Level 3
Cutting speed (v), m/min	90	270	540
Feed rate (f), mm/rev	0.04	0.14	0.29
Depth of cut(d), mm	0.20	0.75	1.00

$$F = \frac{\left(E * b * h^2\right)}{6 * l} \tag{1}$$

$$F \approx k * \varepsilon \tag{2}$$

Where F is the cutting force in N, E = 2.1 * 10^{11} Pa, is the Young's modulus for the cutting tool, b = 25 mm, is the beam width of the tool, h = 25 mm, is the beam height, l = 90 mm, is the distance between the strain gauge and the applied load.

3.1. Calibration of dynamometer

After the development of dynamometer, it was calibrated to determine the elastic deflection of the tool holder (simple cantilever beam type) for the applied load and corresponding strain value. Linear calibration under static load had been made individually. Figure 2

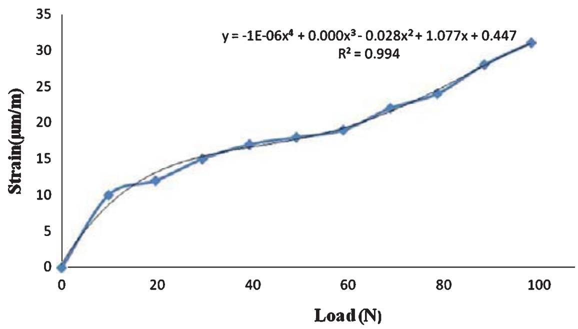

Fig. 2. Calibration curve for the main cutting force.

shows the calibration curve for the main cutting force. The static loads up to 100 N were applied by 10 N intervals in steps, corresponding strain values were recorded.

The calibration curve had high linearity ($R^2 = 0.994$) of weight and sensor output voltage (strain) and it may be used to convert the measured strain into cutting force values within the measured range.

3.2. Taguchi's experimental design

Taguchi's statistical design is a dominant technique which is used to recognize the most considerable process parameter for the conduct of relatively fewer experiments [5]. Taguchi's DOE is widely used for optimization of all manufacturing process like submerged arc welding and friction welding [14]. The experimental design was designed using Taguchi's DOE [16]. Then, the cutting force was measured on-line using a strain gauge dynamometer. Three controllable factors such as cutting speed, feed rate, and depth of cut was used to develop the design. Three levels of spindle speed (90, 270, and 540 m/min), three levels of feed rate (0.04, 0.14 and 0.29 in mm/rev), and three levels of depth of cut (0.2, 0.75, and 1.00 mm) were used as the variables as shown in the Table 1. TiN coated cemented carbide insert was selected to cut the mild steel work piece. The plan of the experiment follows the standard orthogonal array L_{27} which needs 27 runs and 26 degrees of freedom. The total tests of each cutting tool were 27 (3^3) owing to the combination of these factors and levels. The tests were repeated for 3 times to ensure stability in the machining process. Therefore, a total of 81 experiments were conducted in this test.

3.3. Influence of the cutting parameters on the cutting force

Each experiment was repeated for three times to ensure stability in the machining process, the values of strain were taken from the strain gauge bridge circuit and the average values were used to calculate the main cutting force using Equation (2). The results for the cutting force from L_{27} Taguchi standard orthogonal array was shown in Table 2.

Table 2
Experimental plan L_{27}, main cutting force

Trial No.	V (m/min)	f (mm/rev)	DoC (mm)	Measured force (N)	S/N ratio
1	90	0.04	0.20	725.98	−57.2149
2	90	0.04	0.75	731.63	−57.2521
3	90	0.04	1.00	739.15	−57.4120
4	90	0.14	0.20	742.91	−57.3804
5	90	0.14	0.75	744.79	−57.4330
6	90	0.14	1.00	750.43	−57.5522
7	90	0.29	0.20	744.79	−57.4827
8	90	0.29	0.75	745.56	−57.4911
9	90	0.29	1.00	774.39	−57.6958
10	270	0.04	0.20	800.97	−58.0384
11	270	0.04	0.75	797.36	−58.0751
12	270	0.04	1.00	805.17	−58.1097
13	270	0.14	0.20	800.67	−58.1504
14	270	0.14	0.75	814.51	−58.2026
15	270	0.14	1.00	818.69	−58.1964
16	270	0.29	0.20	823.72	−58.2682
17	270	0.29	0.75	822.52	−58.2762
18	270	0.29	1.00	820.49	−58.3556
19	540	0.04	0.20	823.34	−58.3492
20	540	0.04	0.75	838.66	−58.4634
21	540	0.04	1.00	840.39	−58.4603
22	540	0.14	0.20	842.59	−58.4694
23	540	0.14	0.75	848.80	−58.5991
24	540	0.14	1.00	844.82	−58.5553
25	540	0.29	0.20	866.89	−58.7646
26	540	0.29	0.75	877.48	−58.8501
27	540	0.29	1.00	879.28	−58.8918

From Table 2, the main effects on the cutting force were due to the feed rate and depth of cut, respectively. The cutting force was almost constant with respect to cutting speed and insert radius. To systematically investigate the influence of the cutting parameters on the cutting force, main effects plots for cutting force were constructed.

Figure 3 shows that, among the main effects, the cutting speed and feed rate were the most significant factors on the cutting force because of the parameters had an increasing effect. To obtain the optimal combination of cutting parameters, including the minimization of cutting force, the smaller the best performance characteristic for the cutting force was considered and as given in Equation 3. The smaller the best quality characteristics may be formulated as [6]

$$S/N(\eta) = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) dB \qquad (3)$$

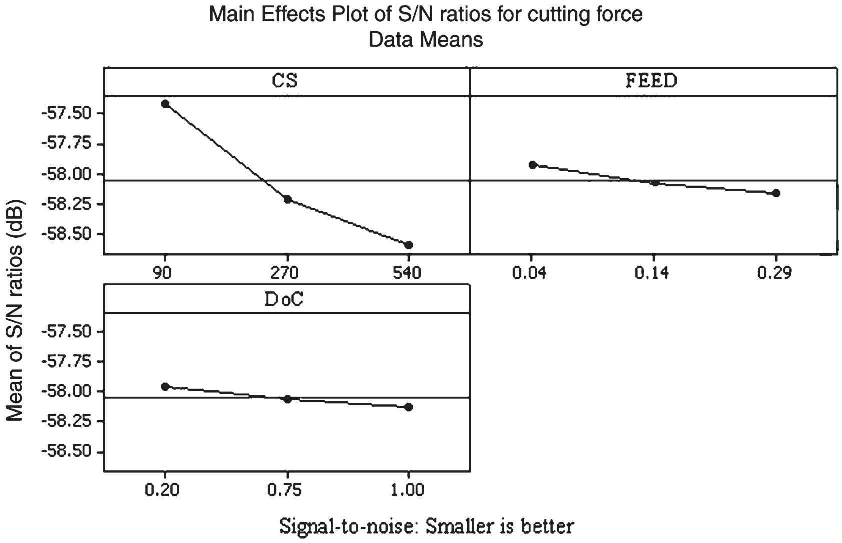

Fig. 3. Main effects plot of S/N ratios for cutting force.

Where n is the number of measurements in the experimental work and y_i is the i^{th} measured value of the characteristic (the response of the machining characteristic). The signal-to-noise ratios of the cutting force for each experiment were shown in Table 2. The uppermost S/N ratio for each factor shows the most significant level which had an effect on the cutting force. The influence of each process variable can be clearly seen in Fig. 3. The slope of the line which connects the levels of the process variables shows the power of influence of each variable.

3.4. *Cutting force model*

The purpose of developing mathematical models was to understand the effects of the parameters involved in the machining process on different Machinability aspects. In general, the cutting force model was a function of cutting parameters and work piece material. The experimental data shown in Table 2 was applied in statistical analysis software Minitab 15 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 Equation (4).

$$\text{Cutting force(F)} = 707 + 0.23 * \text{v} + 112 * \text{f} + 13.4 * \text{d} \qquad (4)$$

Table 3
Analysis of variance for force

Source	DF	SS	MS	F	P	$F_{0.05}$	Contribution %
v	2	52603.4	26301.7	475.22	0.00	3.49	90.932
f	2	3572.8	1786.4	32.28	0.00	3.49	6.176
d	2	566.2	283.1	5.12	0.016	3.49	0.978
Error	20	1106.9	55.3				
Total	26	57849.4					

Where, F = Cutting Force (N), V = Cutting Speed (m/min), f = Feed rate (mm/rev) and d = Depth of cut (mm).

Table 3 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.

3.5. *Fuzzy prediction model*

Generally Fuzzy logic is used wherever there is vagueness in the obtained values. From the data's obtained experimentally, it could be understood that there is vagueness and uncertainty in the obtained values. The single value obtained through experiments is conducted number of times (Eg. First value obtained is the average of over 100 values conducted experi-

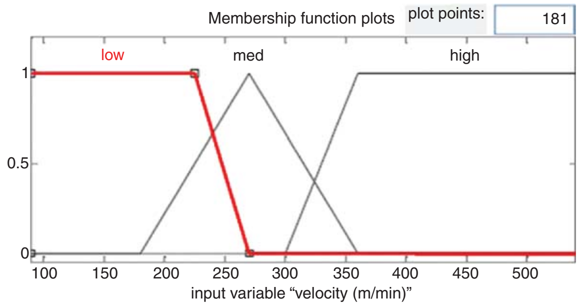

Fig. 4. Input variable velocity (m/min).

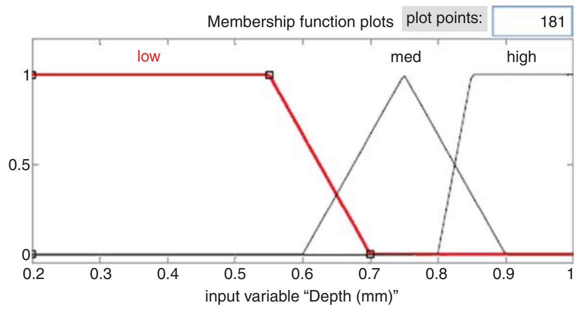

Fig. 5. Depth of cut (mm).

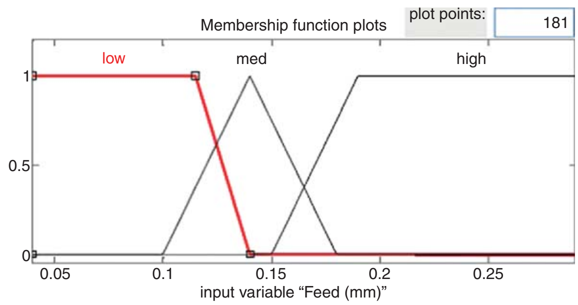

Fig. 6. Feed (mm/rev).

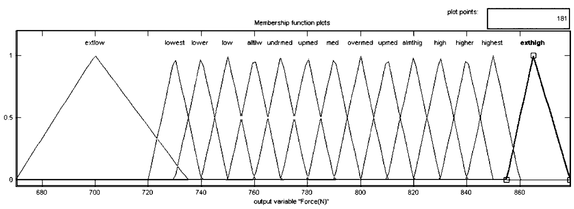

Fig. 7. Output variable force (N).

mentally at different time). So the value varies between maximum and minimum value. Fuzzy modelling will provide a good solution to this problem. In the conventional expert system "rule drought" is the main drawback in the system [19]. This could be overcomes by using the Fuzzy logic technique.

In fuzzy logic the first step involved is defining the inputs and the outputs. The inputs are cutting velocity, Depth of cut and the feed rate and the output is Cutting Force. Fuzzy logic enables to easily model linear and nonlinear mathematical functions which mean that fuzzy systems provide interpolative properties. The set of fuzzy rules defines a fuzzy estimation surface. The accuracy of any Fuzzy logic can be said by the number of membership functions used. In this paper, Mamdani max-min system for inference system is used. In Fuzzy modelling all the numeric values are replaced by the linguistic variables. The first step in the fuzzy logic is listing out the inputs and the outputs.

The standard three inputs are cutting velocity, depth of cut and feed, for all the three input values (example 90, 270, 540 are used as inputs of cutting velocity) the linguistic variables has been named as low, medium and high. At the same time for the outputs the membership functions named as low, medium etc., in order to clearly understand which membership function corresponds to its output. The output is plotted triangularly by applying the maximum and minimum of each values obtained experimentally since the value is uncertain within that maximum and minimum limits.

The linguistic variables and the range of the individual's inputs like input velocity shown in Fig. 4, depth of cut in Fig. 5 and the feed rate are shown in the Fig. 6 respectively.

Similarly Fig. 7 shows the output linguistic functions and their ranges. The rules have been framed based on the membership function of the input and outputs.

As the number of membership functions and the number of rules increases the accuracy also increases. So here the number of membership functions in output is 27, so the result will be more accurate if the number of rules is also 27 (i.e., for each output membership function each rule has been framed). The fuzzy logic rules framed for predicting the cutting force are shown in Table 4.

4. Results and discussion

A wide ranging set of tests were conducted with a range of conditions and the results were fed into a system that is capable of extracting the valid rules from the data. All the tests were conducted for turning mild steel. From Fig. 3, the optimum cutting force was achieved

Table 4
Fuzzy logic rules for prediction of cutting force

Rule No.	Velocity (m/min)	Feed (mm/rev)	DoC (mm)		Force (N)
1	Low	Low	Low	then	Lowest
2	Low	Low	Medium	then	Lowest
3	low	low	High	then	Lower
4	Low	medium	Low	then	Lower
5	Low	medium	Medium	then	lower low
6	Low	medium	High	then	Low
7	Low	high	Low	then	Low
8	Low	high	Medium	then	Low
9	Low	high	High	then	Under medium
10	Medium	low	Low	then	Over medium
11	Medium	low	Medium	then	Over medium
12	Medium	low	High	then	upper medium
13	Medium	medium	Low	then	Over medium
14	Medium	medium	Medium	then	upper medium
15	Medium	medium	High	then	Almost high
16	Medium	high	Low	then	Almost high
17	Medium	high	Medium	then	Almost high
18	Medium	high	High	then	Almost high
19	High	low	Low	then	Almost high
20	High	low	Medium	then	Higher
21	High	low	High	then	High
22	High	medium	Low	then	High
23	High	medium	Medium	then	highest
24	High	medium	High	then	Higher
25	High	high	Low	then	Ext high
26	High	high	Medium	then	Ext high
27	High	high	High	then	Ext high

when the cutting speed, feed rate and depth of cut were set to their low value (level 1) of the experimental range (90 m/min, 0.04 mm and 0.20 mm), A1B1C1. The S/N ratio plots in the analyzed range conveyed that the effect of depth of cut was insignificant.

The analysis of variance for force was performed to find the statistical significance of the process variables on the cutting force in turning of mild steel with TiN coated cemented carbide inserts for a confident level an alpha of 0.05. Table 3 shows the analysis of variance results of mild steel with TiN coated cemented carbide inserts with the cutting speed, feed rate and depth of cut were statistically significant. Hence the developed model is significant. It had a physical significance on the cutting force because the *p*-value of these factors were less than 0.05 and the F-values of feed rate, depth of cut and cutting speed was greater than the 0.05. The cutting speed and feed rate had the percentage contribution of 90.932% and 6.176% respectively and depth of cut contributes only 0.978% of the total variability, this factor can be ignored.

The analytical verification of the model had been carried out using the residual analysis and the outcomes were presented in Fig. 8. It revealed that the residuals

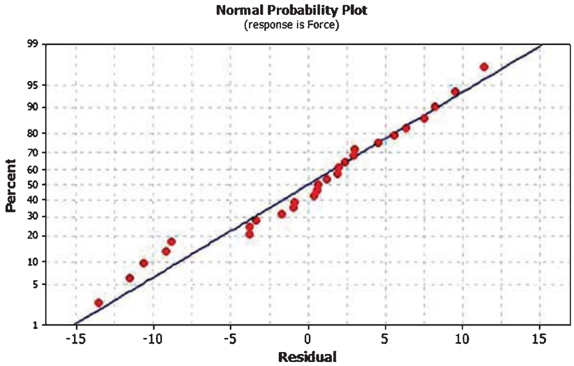

Fig. 8. Normal probability plot of residuals for cutting force.

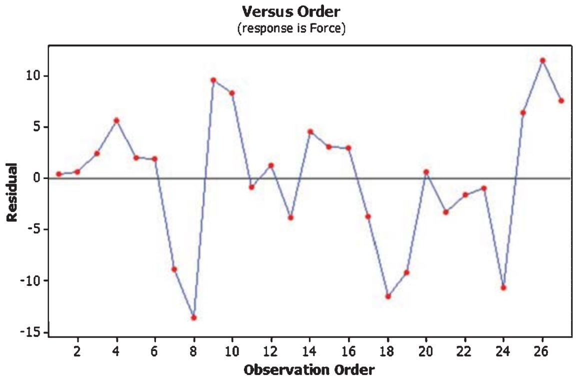

Fig. 9. Residuals vs run numbers for cutting force.

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 Figs. 8 and 9 respectively. Figure 9 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.

Table 5 also indicates that using the prediction model constructed with the regression analysis yields a maximum error of 3.214% at the time of prediction, which was smaller. Hence more accurate results were obtained from a model constructed with a regression analysis.

The study of fuzzy based cutting force measurement was carried out on the lathe. The machine is capable of a two axis movement (along the x and z axis). The results of the individual values are compared in the Table 6.

Table 5
Experimental vs. Predicted values

Trial No.	Measured force (N)	Predicted force (N)	Residual	% Error
1	725.98	734.95	8.966204	1.22
2	731.63	742.32	10.69384	1.441
3	739.15	745.67	6.520694	0.874
4	742.91	746.15	3.23912	0.434
5	744.79	753.52	8.728333	1.158
6	750.43	756.87	6.435972	0.85
7	744.79	762.95	18.15833	2.38
8	745.56	770.32	24.76191	3.214
9	774.39	773.67	−0.71961	−0.093
10	800.97	776.53	−24.4387	−3.147
11	797.36	783.90	−13.4647	−1.718
12	805.17	787.25	−17.9232	−2.277
13	800.67	787.73	−12.9383	−1.642
14	814.51	795.10	−19.414	−2.442
15	818.69	798.45	−20.238	−2.535
16	823.72	804.53	−19.1885	−2.385
17	822.52	811.90	−10.6173	−1.308
18	820.49	815.25	−5.23996	−0.643
19	823.34	838.90	15.55689	1.854
20	838.66	846.27	7.610133	0.899
21	840.39	849.62	9.233383	1.087
22	825	850.10	7.507407	0.883
23	848.8	857.47	8.674196	1.012
24	844.82	860.82	16.00338	1.859
25	866.89	866.90	0.009332	0.001
26	870	874.27	−3.20724	−0.367
27	875	877.62	−1.65922	−0.189

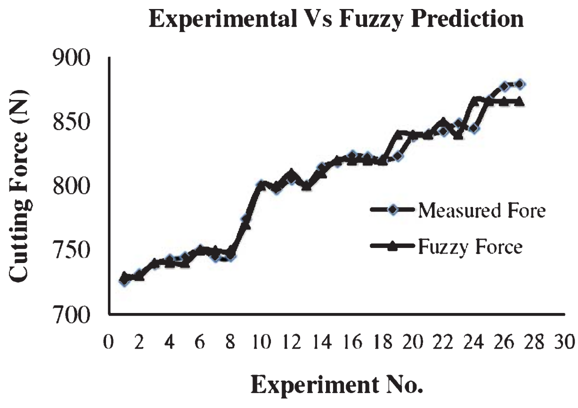

Fig. 10. Measured force vs the fuzzy force.

The error value for the individual inputs is calculated and the respective error percentage is also calculated from which it could be concluded that the system is less deviating. Figure 10 shows the variation between the measured force and the values obtained through the fuzzy logic.

It also implies that there is least deviation between them. Figure 11 reflects the system's prediction capability as well as reliability.

Table 6
Comparison between the measured value and the value obtained using fuzzy logic

Trial No.	Measured force (N)	Fuzzy Force (N)	Error	% Error
1	725.98	730	−4.02	−0.005537
2	731.63	730	1.63	0.002228
3	739.15	740	−0.85	−0.00115
4	742.91	740	2.91	0.003917
5	744.79	740	4.79	0.006431
6	750.43	750	0.43	0.000573
7	744.79	750	−5.21	−0.006995
8	745.56	750	−4.44	−0.005955
9	774.39	770	4.39	0.005669
10	800.97	800	0.97	0.001211
11	797.36	800	−2.64	−0.003311
12	805.17	810	−4.83	−0.005999
13	800.67	810	−9.33	−0.011653
14	814.51	810	4.51	0.005537
15	818.69	820	−1.31	−0.0016
16	823.72	820	3.72	0.004516
17	822.52	820	2.52	0.003064
18	820.49	820	0.49	0.000597
19	823.34	820	3.34	0.004057
20	838.66	840	−1.34	−0.001598
21	840.39	840	0.39	0.000464
22	825	820	5	0.006061
23	848.8	850	−1.2	−0.001414
24	844.82	840	4.82	0.005705
25	866.89	866	0.89	0.001027
26	870	866	4	0.004598
27	875	866	9	0.010286

5. Conclusions

A full bridge strain gauge based dynamometer for measuring the cutting force in turning was designed and constructed. The analysis and measurement of cutting force with strain gauge based dynamometer was studied with the CNMG 12 04 08 TiN coated inserts in turning operation of mild steel. This paper describes the developed fuzzy model consists of 27 rules in order to predict the cutting forces in the turning operations with wide range of conditions. The force signals were acquired using a data acquisition system with LabVIEW. The response was analyzed with S/N ratio and ANOVA, the predicted model that correlates the cutting force with the process variables. Statistical results indicate that the cutting force was considerably influenced (at a 95% confidence level) by cutting speed and feed rate, while depth of cut had a small impact on the cutting force. The cutting force increases with the increase of cutting speed and feed rate. The benefit of the full bridge strain gauge based cutting force measurement system is a low cost measurement system with noble accuracy and repeatability. These results exhibit the potential of

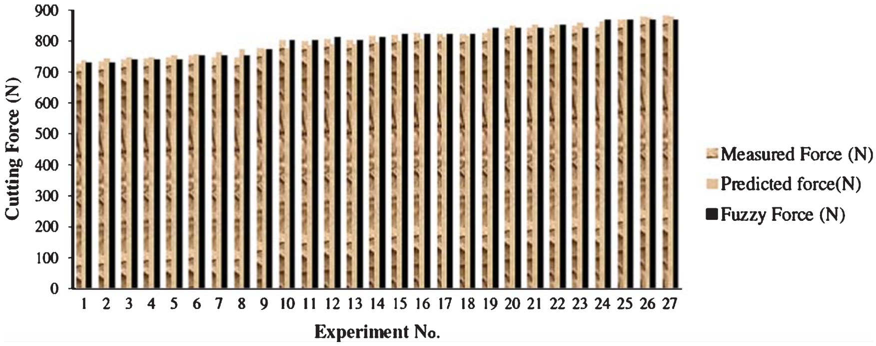

Fig. 11. Difference between the experimental and predicted results.

this model may be simply used in small manufacturing plants to ensure the direct low cost tool for cutting force measurement and time, man power and material may be saved. This work is unique about developing and comparing two different prediction models.

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