Design and Development of Low Cost Compact Force Dynamometer for Cutting Forces Measurements and Process Parameters Optimization in Turning Applications

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Abstract

Cutting forces plays a vital in machining process as they provide useful information not only for the work done but also for understanding the mechanics of machining process .On the other hand the heat generated during machining process has a direct influence on cutting forces therefore accurate measurement of cutting forces in turning is essential for tool material and geometry and selection of proper cutting parameters. Available commercial dynamometers cover a wide range of machining applications but there is a lack of force measuring devices capable for cutting forces in turning process with comparatively high spindle speeds under dry cutting conditions, In this work, the development and testing of an innovative tool shank type strain gauge based force dynamometer designed for high speed turning is discussed. The orientation of strain gauges was set to have maximum sensitivity and minimum cross sensitivity. The flexibility and stiffness of the dynamometer was also analyzed for determining its natural frequency. The developed dynamometer was experimentally tested by performing static calibrations and cutting tests and results obtained proved its reliability and effectiveness for measuring cutting forces in turning and allied applications. Furthermore optimize cutting parameters for cutting forces were obtained by applying simple steps of Taguchi method.

Keywords: *Force measurement; Strain gauge; Dynamometer, optimization.*

1. Introduction

Metal cutting processes are important manufacturing processes that are used to obtain the desired shapes, surface finishes and close tolerance difficult to achieve by other metal shaping processes. The common metal cutting processes are turning, grinding, milling and drilling in which a sharp cutting tool is used to remove metal from the work piece to produce the desired shape and features. The total work done by the cutting tool can be measured by knowing the component of cutting forces acting on the tool during machining process. These cutting forces are not only important for measuring the work done but it's an essential requirement for machining process as theses cutting forces are directly related to determine tool material, tool design, surface finish and also helps in predicting power consumption, vibration, toll chatter and machine part design etc. It is for this reason these cutting forces able us to understand the mechanics of cutting process such as it helps in developing force models [1], work piece material characterization and machinability [2] tool geometry optimization [3], proper selection of cutting parameters [4], chips formation [5], vibration detection and cutting process control etc [6].

These cutting forces in machining can be measure either theoretically, numerically or experimentally, many researchers have studied these cutting forces and found that forces obtained by engineering calculations i.e. theoretical and numerical methods even in steady state conditions have errors when compared to experimental values, as many parameters affect these cutting forces during machining process [7].

Experimentally cutting forces measurements can be accomplished either by direct or indirect method. An indirect method of force measurement is less accurate as it utilizes the power rating ratio of the machine tool to measure the cutting forces during machining process, while a force dynamometer is used in direct force measuring system in which either tool i.e. in turning or work piece i.e.in drilling, milling and grinding etc is mounted on the force dynamometer which measures the cutting forces generated during machining by producing proportional electrical signals (voltage) in response to elastic deformation. In theses force dynamometers, cutting forces are measured normally on the basis elastic deformation of the flexible mechanical component. Various design and developments of force dynamometers can be found in [8, 9].

Two types of force transducers are normally used in design and development of force dynamometers; it may be either strain gauge [10-14] or piezo-electric material [15-19]. Strain gauges are preferred as they provide good response to strain produces at suitable spots on flexible mechanical component [20]. On the other hand force dynamometer should have two opposing properties i.e. it should be sensitive to sense the cutting forces and also rigid at a same time to with stand the fluctuation during machining particularly during dynamic loads [21]. Ito et al. [11] suggested some design criteria for sensitivity and rigidity of force dynamometers based on strain gauges. Some other principles widely used for cutting force measurements in force dynamometers include parallel beam type discussed by [22, 23], circular hole [9-13] and piezo-electric type [24]. This current study outlines a strain gauges based tool shank type force dynamometer design and development capable of measuring three force components in turning of brass work piece under different cutting parameters.

2. Experimental setup

2.1 Dynamometer

A three force component force dynamometer for cutting force measurement in turning application was designed and developed. The schematic representation of the dynamometer is shown in Figure 1. This tool shank type dynamometer consist of three strain gauges mounted on its outer surfaces capable of measuring feed force, main force and thrust force during turning process. The dynamometer was further connected to computer through data acquisition card and is statically calibrated to measure the resulting voltage from Wheatstone bridge.
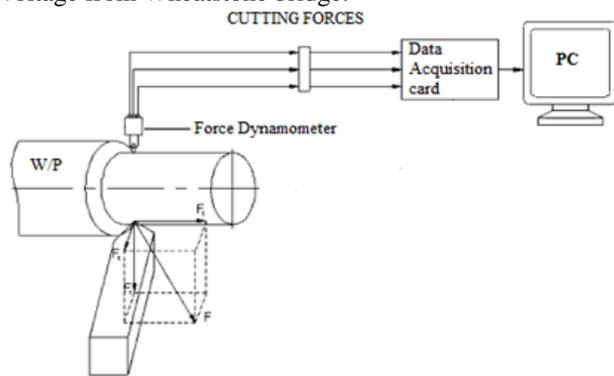

Figure 1 Schematic representation of experimental setup

2.2 Data acquisition

Data acquisition system along with computer and programmable software are used to obtain real time information about the cutting forces during metal cutting. It reads and store all the data concerned with cutting forces automatically from the wheat stone bridge circuit. As the output from the circuit is very low due to high stiffness of flexible mechanical element of dynamometer, data acquisition system not only amplifies but also converts the data into digital signals. Furthermore the DAQ programmable software is also capable of averaging and graphical simulation of the force signal obtained from the circuit during cutting process. All the specification of experimental equipments used are listed in Table 1.

Table 1 Specifications of experimental equipments, work piece and cutting tool used

lathe specifications	1.5KWatt, 2 Horse Power, Horizontal axis lathe machine tool
Dynamometer	Three perpendicular force component strain gauge force dynamometer
Strain gauge	Gauge type EA-060RZ-120 resistance in ohm
Data Acquisition Card	Norwood Instruments Ltd. Digital Quarter strain bridge Data Logger
Work Piece	Free cutting Brass
Cutting Tool	Carbide coated, positive basic shape Turning insert

3. Design and Construction of dynamometer for turning process

3.1 Design criterions for dynamometer

Two basic requirements concerned with the dynamometer design are rigidity and sensitivity. Sensitivity is important for dynamometer to sense the local deformation and rigidity is to with-stand fluctuations in cutting forces during metal cutting process. Other requirements are concerned with dynamometer structure; i.e. It should have minimum cross sensitivity in addition high natural frequency with wide frequency response is also desirable. Furthermore the material selected for dynamometer must have high heat of conductance and resistance to corrosion and should withstand vibration during machining. Moreover the local deformation under the load should be conforming to that of strain gauges mounted on dynamometer outer surface [18]. In this study mild steel AISI 1010 material meets the above requirements and was selected.

3.2 Dynamic properties of dynamometer

The vibration frequency at which the dynamometer is mounted in a machine tool should conform its natural frequency for cutting force measurements. Natural frequency of force dynamometer according to [21] must be at least four time to machine tool operating frequency. The machine tool frequency is related to the spindle speed and is given as.

$$f_m = \frac{n}{60} \qquad (1)$$

According to [21] the relation for natural frequency of force dynamometer will be

$$f_d > 4 * \left(\frac{n}{60}\right) \qquad (2)$$

shown in Figure 2. The dynamometer is assumed to be a bend cantilever beam subjected to three dimensional loading. To measure the stiffness for each direction of applied load fundamental equations for deflection in bend cantilever are applied.
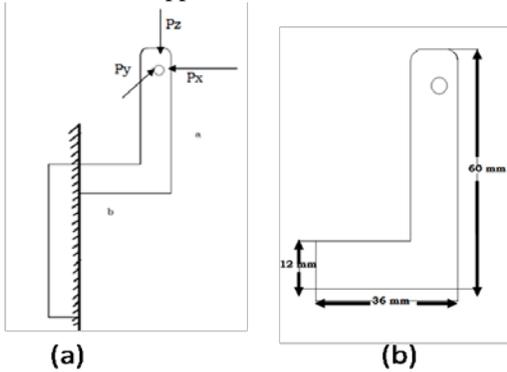

Figure 2 tool holder force dynamometer under three dimensional loads

Stiffness in x direction is given as

$$K_x = \frac{3EI}{a^2(3b+a)} \qquad (3)$$

$$K_x = 1800 \, N/mm$$

Stiffness in y direction is given as

$$K_y = \frac{3EI}{a^3} \qquad \text{(For member a)} \qquad (4)$$

$$K_y = 5040 \, N/mm$$

$$K_y = \frac{3EI}{b^3} \qquad \text{(For member b)} \qquad (5)$$

$$K_y = 23333.33 \, N/mm$$

Stiffness in z direction is given as

$$K_z = \frac{3EI}{b^3} \qquad (6)$$

$$K_z = 23333.33 \, N/mm$$

To measure natural frequency of force dynamometer the following relation is used by assuming dynamometer as s small mass attached to flexible element.

$$fd = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (7)$$

Where m represents the mass of dynamometer and k is stiffness of dynamometer material used. In this study three values of stiffness are measured for all three perpendicular force components and the least value among them is selected for measurement of natural frequency. Shown below

$$f_d = \frac{1}{2\pi}\sqrt{\frac{1800}{0.18}} = 503.54 \, cycle/sec \qquad (8)$$

The natural frequency in the current study is 503.54 cycle/sec. According to [21] frequency requirement should be fd > 4*n/60= 4*1000/60=66.66 cycle/sec which is high enough even if the speed of the spindle is upto 1000rpm.

3.3 The orientation of the strain gauges on the dynamometer

For precision in cutting force values during turning process high accuracy is important in the wheat stone bridge circuit, therefore proper orientation is necessary for the strain gauges to be mounted on the outer surfaces of the force dynamometer. Shown in Figure 3 three strain gauges were mounted on the force dynamometer to measure all the three component of forces x, y and z respectively.

Strain gauge 02 mounted on dynamometer surface is subjected to tensile stress during metal cutting by the main cutting force denoted by Fx and is used to measure that force. Similarly strain gauge 01 is subjected to both compressive and tensile stress depends on spindle rotation direction either clock wise or a counter clock wise by the thrust force denoted by Fy and strain gauge 03 is subjected to tensile stress by feed force denoted by Fz and are used to measure these forces.
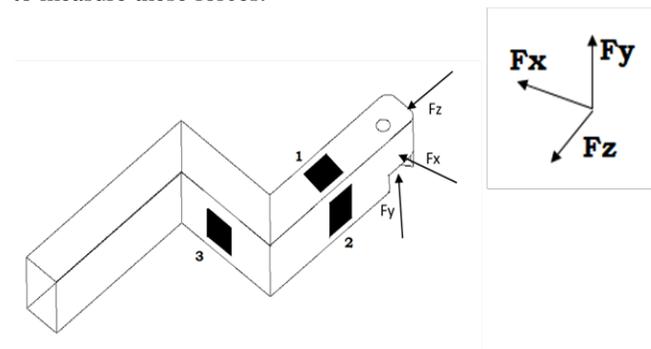

Figure 3 The strain gauges location on tool holder dynamometer

3.4 Dynamometer construction

3.4.1. Mounting of strain gauges and the dynamometer

After selecting proper orientation for the strain gauges on the dynamometer, next step is to mount theses strain gauges on the dynamometer. Super glue was used to mount them on selected surfaces of the force dynamometer shown in Figure 3 and were coated with clear silicone gel to protect them from hot metal chip come in contact during metal cutting process.

The tool holder type dynamometer was then mounted on tool post of horizontal axis lathe machine to measure the cutting forces as a response from a local deformation produced in tool holder during metal cutting in turning. Shown in Figure 4.
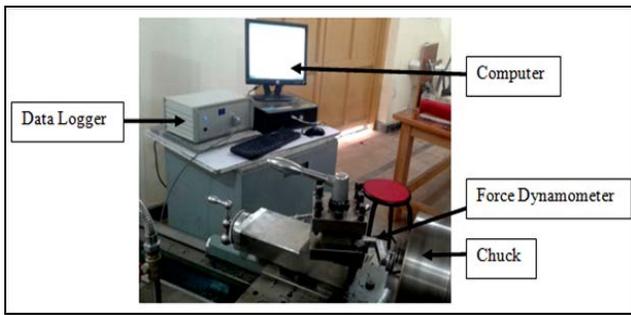

Figure 4: Photograph of the cutting force measurement system

3.5 Dynamometer calibration

3.4.2.   Static calibration of the dynamometer

Calibration of force dynamometer is necessary in order to achieve the accurate results from the wheat stone bridge as a response of change in resistance due to local deformation of force dynamometer during metal cutting process. This calibration was done for all the three perpendicular force components under static condition and the obtained strain was averaged for each direction. Figure 5 shown below shows calibration curves obtained for all the three components x, y and z along with cross sensitivity. The resulting effect of loading in one direction in response to the other was also measured but obtained values are small enough to be ignored. For consistency each of the calibration tests was repeated three times and the dynamometer was tested for 10 minutes idle before taking each reading.
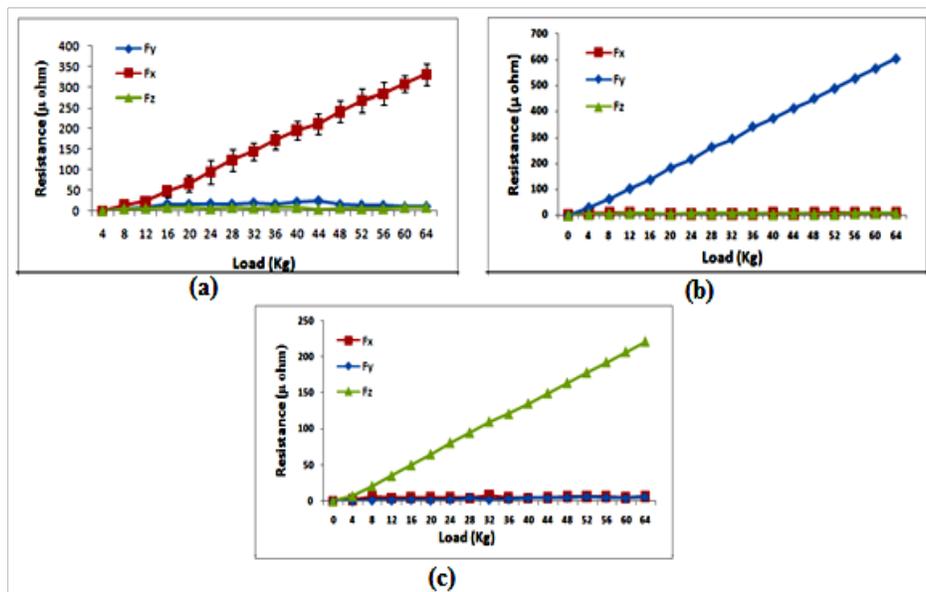

Figure 5 Calibration curve and cross-sensitivity for (a) Fx, (b) Fy and (c) Fz

3.6 Experimental results

3.6.1. Cutting force measurements

For measurements of cutting forces a strain gauge based force dynamometer was used (Figure 3). Horizontal axis lathe machine tool was used to perform all the experiments. Specification of all other equipments used in current experimental work is given in Table 1.

3.6.2. Chemical composition and Properties of Brass

The chemical composition and properties of work piece material (Brass) used for the cutting force measurements are given in the Table 2.

Table 2 Chemical composition and Properties of a Free-Cutting Brass, UNS C36000.

Chemical Composition		Properties	
Component	Weight %	Property	Magnitude
C	60 - 63	Tensile strength (Mpa), Ultimate	338 - 469 MPa
Fe	Max 0.35	Tensile strength (Mpa), Yield	124 - 310 MPa
Pb	2.5 - 3.7	Elongation at break (%)	53%
Zn	35.5	Shear Modulus	37 GPa

3.7 Experimental setup

Three force components strain gauge based force dynamometer with sensitivity of ±1% was mounted on horizontal axis lathe machine to measure the cutting forces in all three directions i.e. .x ,y and z respectively during turning of free cutting brass metal as shown in Figure 4.

It was further connected to digital quarter Strain Bridge in connection with computer and necessary software to record and analyse the data obtained from the force dynamometer in the form of change in voltage with time. For precision in force and respective voltage relation calibration of force dynamometer is necessary therefore dynamometer was statically calibrated prior to force measurements. All the cutting forces are measured and only the average values of the forces from experiments were selected

3.7.1. Experimental Procedure

The following Table 3 lists all the parameters that were used in cutting force measurements in turning of brass metal and machining is done for dry case only.

Table 3 Different parameters used for cutting force measurements

S. No	Parameters	Magnitudes
1.	Cutting Speeds (rpm)	400, 660, 1000
2.	Depth of cuts (mm)	0.25, 0.5, 0.75
3.	Feed rates (in/rev)	0.01, 0.02, 0.029
4.	Lubricants	Dry cutting

All the experiments were performed using the above cutting parameters and it was observed experimentally that the cutting forces increase with increase in depth of cut and feed rate values therefore they have direct influence on the cutting forces for all specified cutting speeds. Shown in Figure 6.To measure the optimal cutting forces it is important to select optimal cutting parameters, for this reason MRR was calculated shown in Tables 4 for all the cutting speeds
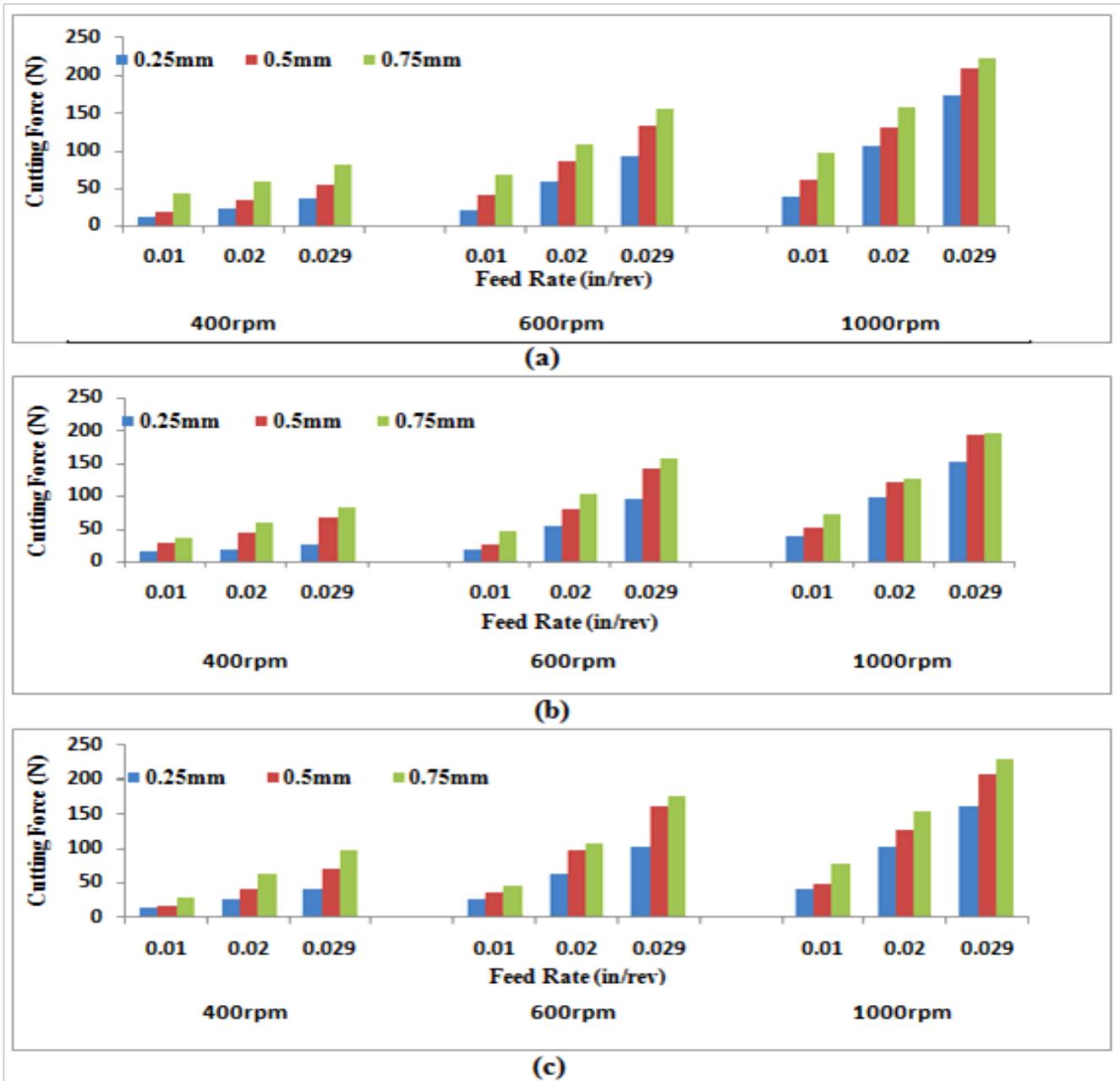
Figure 6. Cutting forces vs. feed rates for given depth of cuts & cutting speeds (a) Fx (b)Fy(c) Fz

Table 4 MRR at all specified spindle Speeds

Feed rate (in/rev)	Depth of cut (in)	Spindle speed n	Diameter (in)	Vavg (in/sec)	MRR=d*f*Vavg (in³/sec)	Fx (N)	Fy (N)	Fz (N)
0.01	0.01	400	1.5	31.4	0.0031	11	15	15
	0.02	400	1.5	31.4	0.0063	18	28	17
	0.03	400	1.5	31.4	0.0094	43	37	29
0.02	0.01	400	1.5	31.4	0.0063	22	19	27
	0.02	400	1.5	31.4	0.0126	34	45	42
	0.03	400	1.5	31.4	0.0188	60	61	65
0.029	0.01	400	1.5	31.4	0.0091	37	26	43
	0.02	400	1.5	31.4	0.0182	54	67	71
	0.03	400	1.5	31.4	0.0273	82	84	98
0.01	0.01	660	1.5	51.8	0.0052	20	18	26
	0.02	660	1.5	51.8	0.0104	42	26	37
	0.03	660	1.5	51.8	0.0155	68	48	47
0.02	0.01	660	1.5	51.8	0.0104	58	55	65
	0.02	660	1.5	51.8	0.0207	86	82	98
	0.03	660	1.5	51.8	0.0311	110	104	110
0.029	0.01	660	1.5	51.8	0.0150	93	96	104
	0.02	660	1.5	51.8	0.0300	135	142	163
	0.03	660	1.5	51.8	0.0451	157	159	178
0.01	0.01	1000	1.5	78.5	0.0079	38	39	42
	0.02	1000	1.5	78.5	0.0157	62	53	49
	0.03	1000	1.5	78.5	0.0236	98	72	78
0.02	0.01	1000	1.5	78.5	0.0157	107	98	104
	0.02	1000	1.5	78.5	0.0314	132	122	128
	0.03	1000	1.5	78.5	0.0471	159	128	155
0.029	0.01	1000	1.5	78.5	0.0228	176	153	164
	0.02	1000	1.5	78.5	0.0455	210	196	209
	0.03	1000	1.5	78.5	0.0683	224	198	231

After calculating the material removal rates the values are plotted against the respective cutting forces shown in Figure 7.
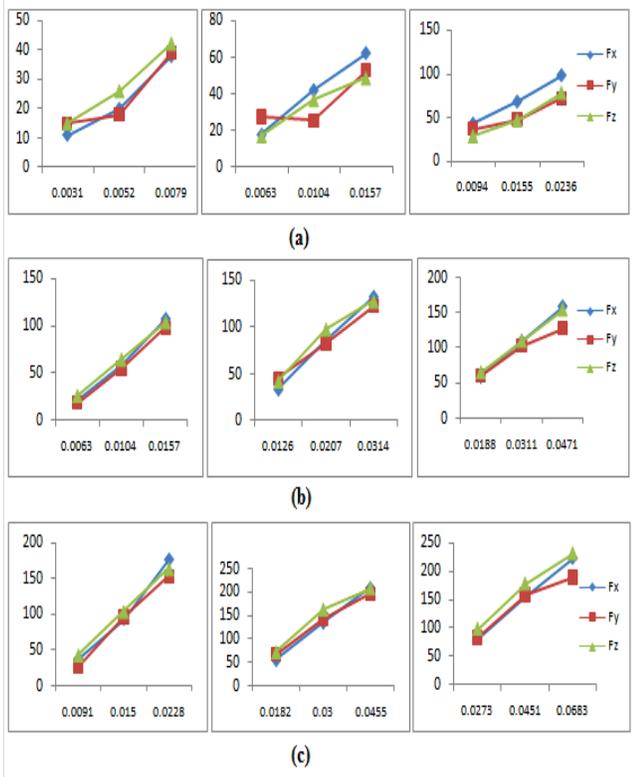

Figure 7 Material removal rates Vs cutting forces for feed rates (a) 0.01(b) 0.02 & (c) 0.029rev/in

It was found that the cutting forces increases with increase in MRR. To determine the optimal sets of parameter taguchi method was implemented.

3.8 Taguchi method for optimal process parameters

To optimize the process parameters in manufacturing process many statistical methods were developed and implemented. some of them are discussed by [25] Taguchi method is one of the statistical method developed by [26] to study the entire parameters space with relatively less number of experiments i.e. to overcome full factorial design method problems in which a large number of experiments were required. It consists of the following simple steps.

3.8.1. Identifying main function and its effects

Main function   : Turning of free cutting brass on horizontal axis lathe machine

Side effects   : Cutting forces variation in metal cutting

After selecting main function and side effects it is also important to list all factors that affect turning process and categories them into control and noise factors shown in table 5

Table 5 Factors affecting turning process

Control Factors	Noise Factors
Depth of cut	Material variation
Feed rate	Machine condition
Cutting speed	Chattering and vibration

3.8.2. Identification of noise factors and quality characteristics

Quality Characteristic	Cutting Force measurements
Work piece material	Free cutting Brass
Cutting tool	Coated Carbide Cutting Insert
Operating machine	horizontal axis Lathe machine
Testing equipment	Force dynamometer

3.8.3. Identification of objective function to be optimized

The objective function selected for the current case was nominal-the-best.

3.8.4. Identification of control factors with levels

The factors and their levels are shown in table 5.3 below.

Table 6 Selected Factors and Their Levels

Factors	Levels		
	1	2	3
Cutting Speeds (rpm)	400	660	1000
Depth Of Cut (mm)	0.25	0.50	0.75
Feed Rate (in/rev)	0.01	0.02	0.029

3.8.5. Orthogonal array selection and matrix construction

To select an appropriate orthogonal array for conducting the experiments the degree of freedom are to be computed. The same is given below

Table 7 Orthogonal array (OA) L9

Experiment No	Control Factors		
	1	2	3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

3.8.6. Conduction of the matrix experiment

All the above 9 experiments were conducted according to the orthogonal array mention and the cutting forces were measured using force dynamometer and are listed below in Table 8.

Table 8 Measured values of Cutting forces

Experiments No	Cutting forces		
	Fx	Fy	Fz
1	11	15	15
2	34	45	42
3	82	84	98
4	93	96	104
5	42	26	37
6	110	104	110
7	107	98	104
8	210	196	209
9	98	72	78

3.8.7. Data examination for predicting optimum control factor levels and its performance

(a) Result processing

As the objective function In current study is nominal-the-best for all the cutting forces measured during turning of brass metal so the following relation was used to measure the S/N ratio and the values are listed in the Table 9 below.

$$\text{S/N ratio} = 10 \ \log_{10} \frac{(Mean)^2}{Variance} \tag{9}$$

Table 9 Measured tabulated S/N ratios

Experiment No	Control Factors			S/N ratio
	V (rpm) levels	t (mm) levels	F(in/rev) levels	
1	1	1	1	10.54
2	1	2	2	14.54
3	1	3	3	41.38
4	2	1	3	26.32
5	2	2	1	13.57
6	2	3	2	20.84
7	3	1	2	23.07
8	3	2	3	6.20
9	3	3	1	37.45

The factor levels corresponding to the average S/N ratio values are selected to optimize the condition. From the figure 9 above, the average i.e. the optimum values of the factors and their levels obtained are listed in the Table 10.

Table 10 Optimum values of factors and their levels for process optimization

Parameter	Levels	Optimum values
Speed (rpm)	Level 02	660
Depth of cut(mm)	Level 03	0.75
Feed rate (in/rev)	Level 02	0.02

3.8.8. Verification of experiments.

The following Table 11 shows confirmation experiments conducted using 660rpm. 0.75mm depth of cut and 0.02 in/rev feed rate.

Table 11 Verification of Experiments

Parameter	Optimum Value	Fx (N)	Fy (N)	Fz (N)
Speed (rpm)	660			
Depth of cut(mm)	0.75	110	104	110
Feed rate (in/rev)	0.02			

4. Conclusion

This paper outlines the strain gauge based force dynamometer design and manufacturing for cutting force measurements and optimization of process parameters

using taguchi method for turning process. Based upon the experimental results discussed the following conclusions can be drawn.

- This force dynamometer is capable of measuring three perpendicular components of force simultaneously and the numerical values can be stored in computer through data acquisition card.
- Cutting forces in x, y and z are directly influenced by the change in MRR the percentage increase is low at slow to intermediate but increase when cutting forces changes from intermediates to high speeds
- The use of Taguchi method provides an ease and efficient methodology to obtain optimized process parameters as compared to other statistical methods for process optimization.

Acknowledgments

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