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ORIGINAL ARTICLE

Optimization of facing process by indigenously developed force dynamometer

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Abstract

Cutting forces in machining process provide useful information in understanding the mechanics of machining process, tool wear, tool/workpiece material selection, and quality of a machined surface. In addition, cutting force measurements has become a crucial activity for process enhancement and optimization. In this study, a strain gauges-based novel force dynamometer capable of measuring cutting forces in facing process has been designed and manufactured to measure optimal cutting parameters for the studied material, i.e., mild steel A1010. The selection of orientation of strain gauges was set in the developed dynamometer to have maximum sensitivity and minimum cross-sensitivity during facing process. The dynamometer was connected to a quarter bridge data acquisition system for signal capturing and processing to achieve cutting forces at selected cutting conditions. The rigidity and stiffness of the dynamometer were also analyzed by determining its natural frequency at the design stage. Finally, Taguchi method is deployed on experimental results at specified cutting parameters to get optimal parameters for selected material. The dynamometer was experimentally tested, and results obtained are found in good relation to the numerical data (simulated) that confirm its reliability to measure the cutting forces in all three components (*x*, *y*, and *z*) for facing process.

Keywords Force measurement · Strain gauge · Force dynamometer · Optimization · Facing process

1 Introduction

Machining process such as metal cutting is widely used metal shaping process in manufacturing industries to achieve desired shapes, close tolerances, and better surface finish difficult to obtain by any other metal shaping process. The common metal cutting process includes drilling, grinding, milling, and turning. According to Hanif et al. [6], these processes utilizes a sharp cutting tool to expel abundance of material from the surface of the work piece to obtain the desired shape. All sorts of materials including metals, composites, plastics, and wood can be machined, and a variety of features even complex contours can be formed on their surface by these processes.

In light of its economic significance, machining industries have prompted the need to optimize these processes to enhance productivity and get economic benefits. Hence, the knowledge of cutting parameters, e.g., cutting force, depth of cut, feed rate is of great significance for the stated issue. Additionally, estimation of cutting forces, not just aides in

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presuming all work done in material removal process but at the same time gives overall information about cutting process mechanics Sun et al. [20], which leads the researchers to build up a cutting force model or used the existing model to predict the required output parameters.

Furthermore, these obtained cutting forces also helps in choosing the appropriate tool material and geometry enhancement of cutting process [2], the workpiece machinability [18], cutting parameters upgradation [5], vibrations amid machining [12], better control over metal cutting process [22], and for complete cutting tool condition monitoring [16].

To date, different researchers considered the metal cutting (turning) process and measure cutting forces numerically, hypothetically, and experimentally with a specific end goal to accomplish optimized cutting conditions. However, according to Şeker et al. [17], measurement of cutting forces by numerical and hypothetical computation must be affirmed experimentally as most of the times, these estimations fail to attain precise outcomes due to complex tool designs and some unknown stresses.

Cutting forces can be measured tentatively by two methods: indirect or direct method. An indirect method of force measurement uses an approach of change in power rating of the machine tool to measure the cutting forces. This method is only used for process monitoring [14].

According to literature survey, Jeong and Cho [7] uses current (an indirect method) for cutting force measurements in milling process. Auchet et al. [4] also uses the same approach of an indirect method to measure dynamic cutting forces as a response of voltage of a magnetic bearing located at the spindle of five axes milling machine. Similarly, Albrecht et al. [1] uses an indirect force sensor (i.e., capacitance displacement sensor) to measure the cutting forces.

A direct force method in contrast utilizes an instant approach of force measurement by mounting a tool (in turning) or work piece (in milling, drilling, or grinding) on a force dynamometer, which measures the cutting force by making a corresponding electrical signal in response to that cutting forces. This technique is utilized for overall process examination and/or for process optimization where both the magnitude and direction of forces are required.

Literature also showed that wide variety of force dynamometers are available for measurement of cutting forces during metal cutting processes. Totis et al. [23] demonstrated that all force dynamometer works on a principle of measuring the effects of cutting forces during metal cutting (e.g., it may be either displacement, local, or central deformation and/or accelerations of a mechanical component of that machine tool upon which that dynamometer is mounted). Also, there is a tradeoff between stiffness and sensitivity while designing dynamometer as it reduces the stiffness of mechanical component and affect frequency, but frequency response should be wide enough to measure the rapidly changing cutting forces accurately during experimentations.

Furthermore, in force dynamometer, two different types of transducers are used for cutting force measurements: It may be either piezoelectric crystals/rings or strain gauges. The piezoelectric rings can further be installed either in spindle housing for cutting force measurements [9] or they can be clamped between a tool and spindle [12]. These piezoelectric crystals provide the best compromise between sensitivity and stiffness. However, their range is restricted to low and medium spindle speed, and also cutting force signals obtained by these sensors are disturbed by low-frequency resonance of spindle vibrations.

Another possible solution is to measure these cutting forces from the local deformations of flexible mechanical components by using strain gauges Yaldız et al. [25] which requires the weakening of mechanical component to increase its local sensitivity where strain gauges are attached. However, the dynamics of weakened mechanical structure do not alter the measured cutting forces signals that result in good frequency bandwidth. Strain gauge mounted force dynamometer can measure force components either by using octagonal-rings [24] or by a tool shank type [13].

According to literature survey of force dynamometer, Spiewak [19] uses three component accelerometer to measure the dynamic cutting forces. Yaldız and Ünsaçar [24] works on octagonal rings to develop a force dynamometer for cutting forces in turning. The prim impetus behind using octagonal rings type dynamometer was to estimate static as well as dynamic cutting forces that result in generating heat at tool-chip interface, tool damage, and ultimately affecting the quality of machined surface and was able to quantify force up to 3500 N. Korkut [11] and Yaldız and Ünsaçar [24] also use the same approach of octagonal rings mounted with strain gauges to measure cutting forces for milling process up to 4500 N and 5000 N, respectively; Karabay [10] utilizes the same approach of strain gauges on octagonal rings as a transducer to develop a dynamometer but for drilling application to measure drill force, thrust force, and torque. Oraby and Hayhurst [13] design tool shank type dynamometer with mounted strain gauges having two symmetric holes connected through a narrow opening at the center line. The main purpose of those holes was to empower strain gauges for measuring greatest nearby strain achieved. Similarly, Rizal et al. [15] proposed a dynamometer design and development for process optimization, tool condition monitoring, and tool design while measuring cutting forces in the wireless environment for milling and drilling processes.

Nevertheless, a lot of research is available on force measurement in numerous shaping processes, but still, there is a need to measure the cutting forces, especially in facing process as it is the only turning process in which the material removal rates suddenly increases from zero, i.e., center of workpiece to maximum value at the outer diameter. Additionally, there is a need to determine the optimal cutting parameters for such abruptly changing material removal rates even at the same cutting speeds.

The main purpose of this study is to design and develop low-cost compact strain gauge-based analog dynamometer for cutting force measurement to be used in process parameter optimization in turning application especially for facing process. The material selected in this study is mild steel A1010. The developed dynamometer is experimentally tested, and results obtained are found in good relation to the numerical data (simulated) that confirm its reliability for cutting force measurement in facing process. The accuracy is examined by comparing the results with the simulated results with the experimental findings. Furthermore, the newly developed force dynamometer was calibrated by known masses using a standard technique available in the literature and calibration curves along with the cross sensitivity obtain are depicted in concern manuscript. Also, dynamometer is checked for its rigidity and stiffness by determining its natural frequency at the design stage and found safe even at high cutting speeds of 1000 rpm.

2 Experimental setup

2.1 Dynamometer

Figure 1 depicts the schematic representation of the proposed force dynamometer. It consists of a main mechanical element having strain gauges mounted on it for measurements of all three component forces including feed Fz, thrust Fy, and main cutting forces Fx. The dynamometer is connected with data acquisition system and a computer for capturing and storing the obtained data.

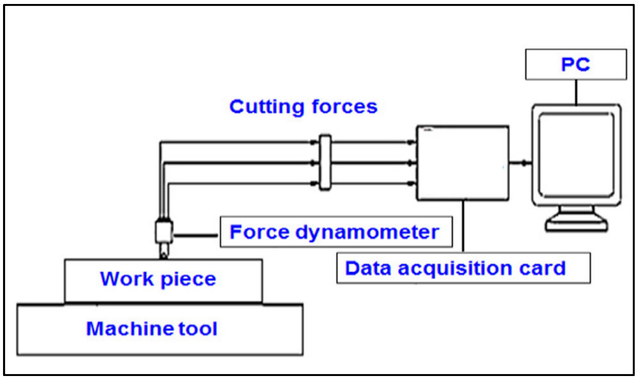


Fig. 1 Schematic representation of experimental setup

The newly designed force dynamometer in this study consists of a simple bend tool holder having three strain gauges mounted on selected surfaces for the measurement of all three component forces, it works on the principle of local deformations of flexible mechanical components by using strain gauges as a transducer. The working principle of this innovative dynamometer resembles the behavior of bend cantilever beam under three-dimensional loads depicted in Fig. 2. For this reason, dynamometer was treated as a bend cantilever and all the formulae of cantilever beam were applied to evaluate the stiffness in all three direction along with designed natural frequency to confirm its safety in use (Ref (Eqs. 4–8)). A computer connection has also been established for data obtained, as the output of the dynamometer is analog values and is difficult to deal manually. The obtained experimental results are used for process optimization for the local industry.

2.2 Data acquisition

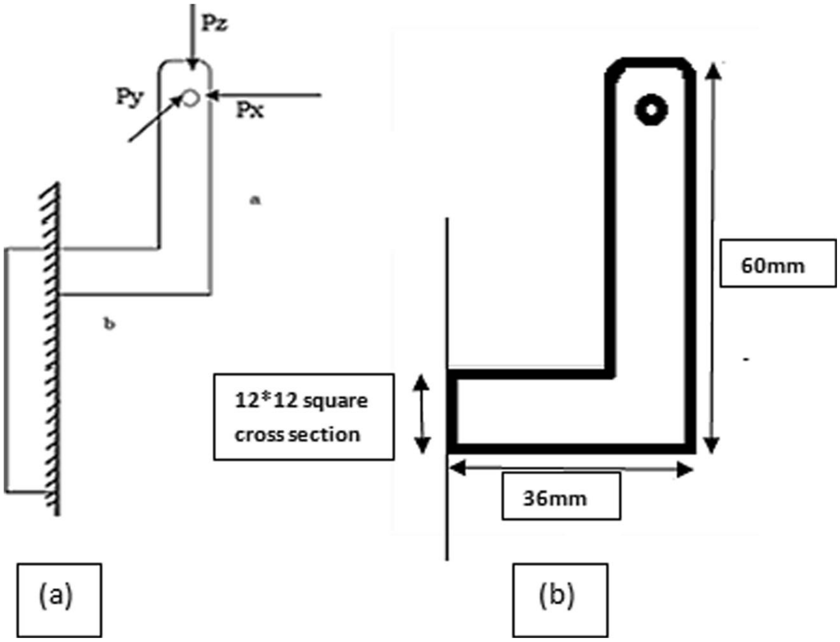
The digital strain quarter bridge data logger along with necessary connections, i.e., computer and programmable software, was connected to the force dynamometer to record and store data obtained during experimentation. Due to high stiffness of dynamometer, the output data obtained was first amplified and then converted into digital signals. The data obtained contains information about a change in resistance with time recorded for studied cutting conditions in facing process. In order to obtain correct data, the dynamometer was first statically calibrated prior to measure cutting forces by a spring balance. Calibration was done for all the components, and data obtained were averaged and compared to calibrated values. Table 1 shows specifications of equipment used in the current experiments.

3 Design and manufacturing of force dynamometer for facing process

3.1 Design criterions for dynamometer

For any dynamometer design, there are two basic but opposite requirements, i.e., sensitivity, and rigidity. The dynamometer should be sensitive to respond to the local deformation for measurement of cutting forces, and its rigidity is important against vibration during a metal cutting process for accurate force measurements. Other design requirements are concerned with the dynamometer structure, including wide frequency response, high natural frequency, and small cross sensitivity. Furthermore, the dynamometer material should have high heat conductivity. Mild steel AISI 1010 fulfills all the requirements and was selected for this study based on the availability and cost effectiveness.

Fig. 2 Mounted force dynamometer under three-dimensional loads



3.2 Dynamic properties of dynamometer

A higher natural frequency for force dynamometer is desirable to withstand vibrations in metal cutting. The vibration frequency at which the dynamometer is mounted in a machine tool should conform its natural frequency for cutting force measurements. According to Yaldız et al. [25], the natural frequency of dynamometer should be four times to that of a machine tool. The vibration frequency of machine tool is given as

$$f_m = \frac{n}{60} \tag{1}$$

Therefore, the natural frequency of dynamometer should be

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

To determine the frequency, the dynamometer was assumed to be a mass supported by flexible element and its relation is given as

$$fd = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{3}$$

where *k* and *m* are dynamometer stiffness and mass, respectively. To measure *k*, the dynamometer was treated as bend (*L shaped*) cantilever beam shown in Fig. 2, subjected to three force components loads denoted by Px, Py, and Pz, respectively. Using fundamental equations of bend cantilever beam individual component's stiffness can be calculated as follows:

Stiffness for load P_x

$$k_x \frac{3EI}{a^2(3b+a)} \tag{4}$$

Table 1 Specifications of experimental setup

Experimental setup	Specifications
Machine tool	1.5 kW, 2 hp, horizontal axis lathe machine
Dynamometer	Strain gauge based three force component 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	AISI 1010 mild steel
Cutting tool insert	Coated carbide Type: DCMT11T304-PS5, positive basic shape

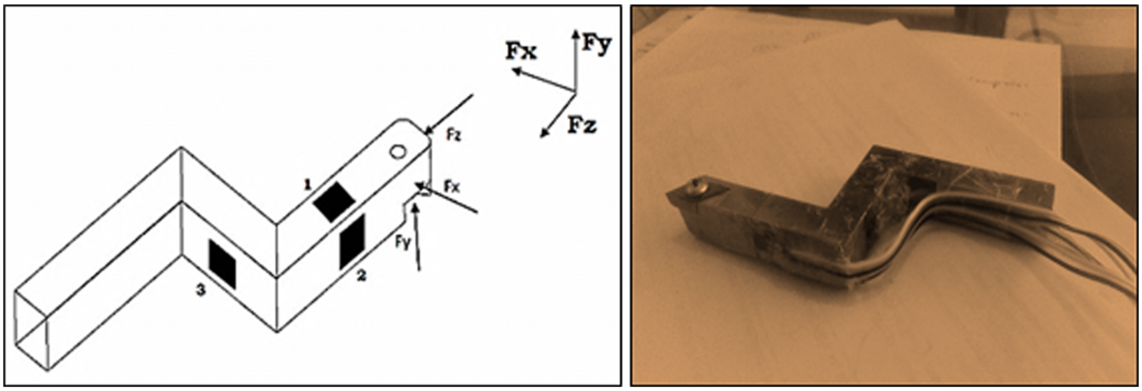


Fig. 3 Orientation of strain gauges on a dynamometer

For mild steel, $E = 210\text{GPa}$ and for square cross section beam $I = \frac{b^4}{12}$

$$k_x = 1800\ \mathrm{N/mm}$$

Stiffness for load P_y

$$k_y = \frac{3EI}{a^3}\ (\text{For member a}) \tag{5}$$

$$k_y = 5040\mathrm{N/mm}$$

$$k_y = \frac{3EI}{b^3}\ (\text{For member b}) \tag{6}$$

$$k_y = 23333.33\ \mathrm{N/mm}$$

Stiffness for load P_z

$$k_z = \frac{3EI}{b^3} \tag{7}$$

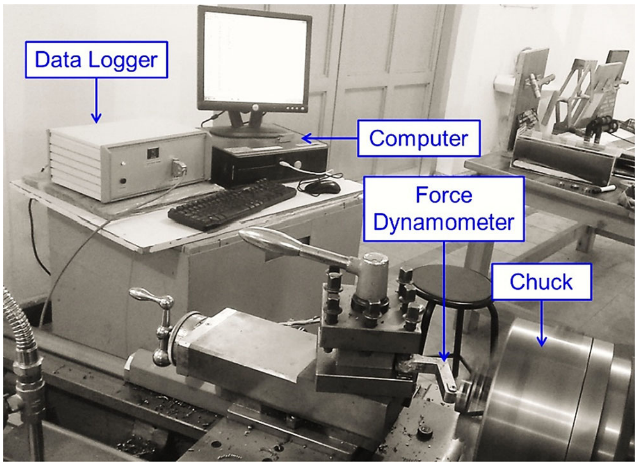


Fig. 4 CECOS University Lab view of force measurement system

$$k_z = 23333.33\ \mathrm{N/mm}$$

Putting the minimum stiffness value, i.e., K_x in Eq. (3) to measure the natural frequency of tool holder dynamometer.

$$f_d = \frac{1}{2\pi}\sqrt{\frac{1800}{0.18}} = 503.54\ \text{cycles/s} \tag{8}$$

The designed natural frequency of force dynamometer demonstrated that the designed natural frequency requirement is 66.66 Hz, which is safe in the current work.

3.3 The orientation of the strain gauges on the dynamometer

To achieve accurate measurements of the cutting forces, the exact orientation of strain gauges on the surface of dynamometer must be known. In this study, three strain gauges used are shown in Fig. 3, to measure all the three components of forces applied on dynamometer during the studied machining process.

Fz is applied on the tip of dynamometer shown in Fig. 3 and produces maximum deformation on dynamometer surface having strain gauge 3 mounted on it and subjected it under bending stress; the change in resistance of strain gauge 3 measures Fz. Similarly, Fy and Fx bring strain gauge 01 and 02 under compression, respectively.

3.4 Dynamometer construction

3.4.1 Mounting of strain gauges and the dynamometer

After making all necessary connections for cutting force measurements, strain gauges were then mounted on the surface of force dynamometer as per orientation discussed Ref (Sect. 3.3). Furthermore, these strain gauges were coated with clear silicone gel to avoid direct contact with hot metal chips during facing process. The force dynamometer was then clamped on the tool post of horizontal axis lathe machine for cutting force measurements resulting from response to a local deformation

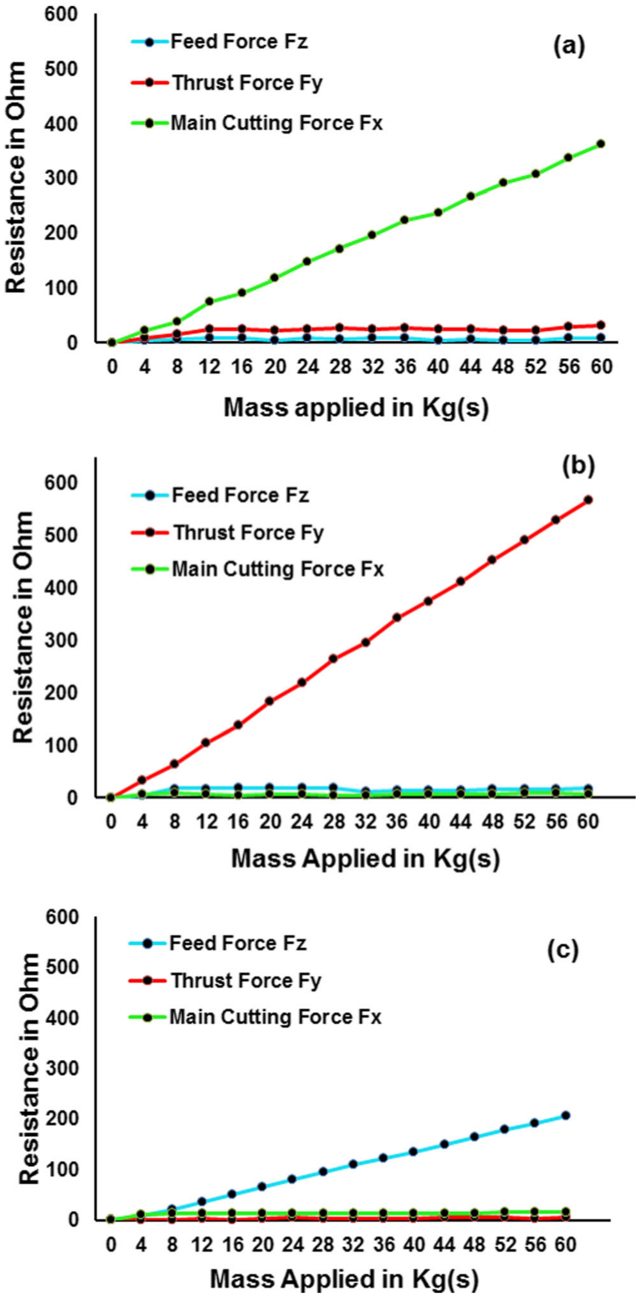


Fig. 5 Calibration curve and cross-sensitivity for **(a)** Fx, **(b)** Fy, and **(c)** Fz

Table 2 The results of cross-sensitivity test

Axes	Load (N)	Output (digital)			Average error %		
		X	*Y*	*Z*	*X*	*Y*	*Z*
Fx	60*9.8 = 588 N	331	22	9	–	0.066	0.027
Fy	60*9.8 = 588 N	7	567	17	0.012	–	0.029
Fz	60*9.8 = 588 N	16	6	207	0.077	0.028	–

Table 3 Cutting parameters used in current study

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

in dynamometer during the machining process as described in Fig. 4.

3.5 Dynamometer calibration

3.5.1 Static calibration of the dynamometer

Calibration of dynamometer is the prime steps in conducting experimentations in any machining process. The crucial aim of calibration is to determine the accurate values of change in resistance of a circuit as a voltage in response to the elastic deformation of the flexible component of force dynamometer and consequently for the output under static load. For this aim, static calibration was performed in three directions for all the force components using calibrated weights having known mass of 4 kg was applied up to 60 kg in a single direction at a time, as per standard procedure adopted by Jin et al. [8], and the output strain was recorded after application of individual load. The calibration curves were obtained by converting the output reading recorded into respective cutting forces as shown in Fig. 5.

All the measurements were repeated five times, and the output for each direction was also averaged to verify consistency in cutting forces. In addition, the overall effect of the load applied on one axis on the other two axes was also examined as shown in Table 2, but the response was too low and was ignored in the current study.

3.6 Experimental procedure

In the current work, three different parameters shown in Table 3 were used to measure all the three components of force as suggested by local manufacturers, and all the experiments were performed at dry cutting conditions. Further, each experiment was repeated at least five times to obtain good statistical data.

3.7 Experiment results

The measured cutting forces both experimentally and simulated in facing of AISI 1010 steel are presented in Table 4 below. As shown in Table 4, the measured and simulated values for the cutting forces are in a good relation except for some experiments, i.e., Exp nos. 1, 11, and 22 for Fy and Fz and Exp

Table 4 Experimental and simulated cutting forces

Exp no.	Feed rate (in/rev)	Depth of cut (in)	Spindle speed (rpm)	Experimental cutting force	Simulated cutting force	Parentage difference	Experimental thrust force	Simulated thrust force	Parentage difference	Experimental feed force	Simulated feed force	Parentage difference
				Fx	Fx	%	Fy	Fy	%	Fz	Fz	
1	0.01	0.01	400	130	128	1.54	37	34	8.11	59	55	6.78
2		0.02	400	169	161	4.73	78	73	6.41	84	81	3.57
3		0.03	400	245	249	− 1.61	90	94	− 4.26	87	88	− 1.14
4	0.02	0.01	400	169	162	4.14	78	79	− 1.27	84	79	5.95
5		0.02	400	280	273	2.50	160	156	2.50	157	149	5.10
6		0.03	400	423	437	− 3.20	193	187	3.11	180	177	1.67
7	0.029	0.01	400	197	192	2.54	142	139	2.11	115	110	− 4.35
8		0.02	400	292	287	1.71	170	167	1.76	216	217	− 0.46
9		0.03	400	453	446	1.55	243	244	− 0.41	241	249	− 3.21
10	0.01	0.01	660	165	162	1.82	60	57	5.00	69	62	10.14
11		0.02	660	185	178	3.78	85	79	7.06	92	88	4.35
12		0.03	660	317	322	− 1.55	109	112	− 2.68	98	93	5.10
13	0.02	0.01	660	195	187	4.10	111	109	1.80	90	88	2.22
14		0.02	660	314	312	0.64	176	169	3.98	170	163	4.12
15		0.03	660	434	428	1.38	241	246	− 2.03	197	188	4.57
16	0.029	0.01	660	200	195	2.50	158	155	1.90	167	169	− 1.18
17		0.02	660	328	322	1.83	187	182	2.67	225	221	1.78
18		0.03	660	476	487	− 2.26	271	279	− 2.87	272	266	2.21
19	0.01	0.01	1000	162	159	1.85	58	61	− 4.92	64	61	4.69
20		0.02	1000	182	178	2.20	82	85	− 3.53	89	87	2.25
21		0.03	1000	311	308	0.96	107	104	2.80	94	93	1.06
22	0.02	0.01	1000	182	174	4.40	82	79	3.66	89	84	5.62
23		0.02	1000	310	301	2.90	172	171	0.58	167	164	1.80
24		0.03	1000	429	437	− 1.83	238	233	2.10	195	192	1.54
25	0.029	0.01	1000	203	196	3.45	153	149	2.61	163	162	0.61
26		0.02	1000	323	322	0.31	182	177	2.75	219	217	0.91
27		0.03	1000	469	476	− 1.47	267	259	3.00	264	266	− 0.75

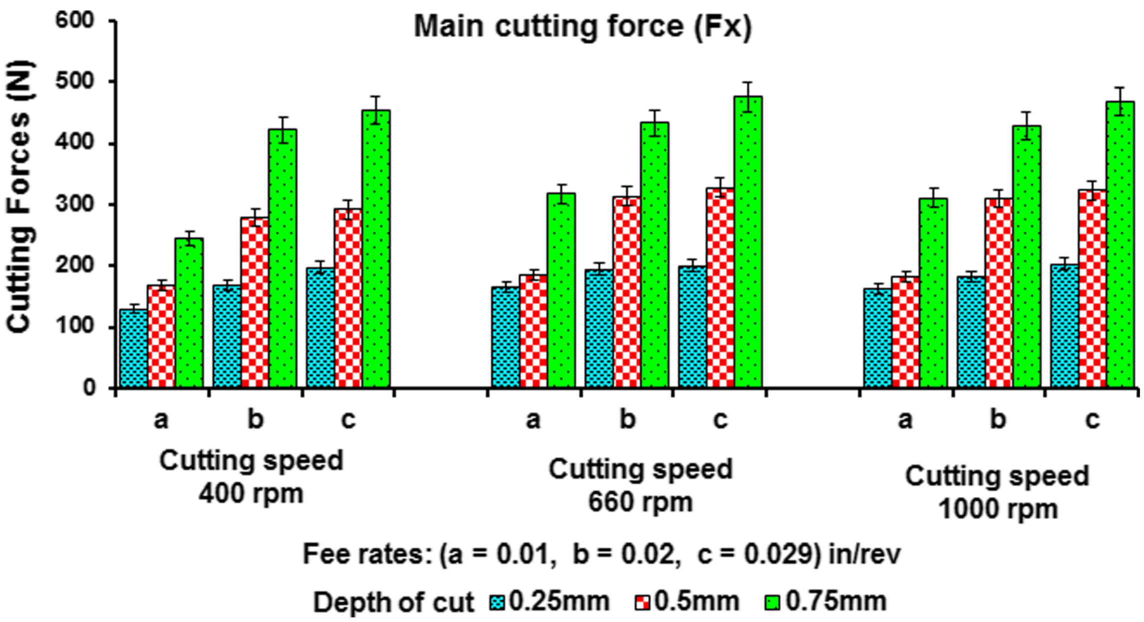


Fig. 6 F_x at specified cutting speeds, feed rates, and depth of cuts

no. 22 for all cutting forces are slightly more than other experiments in comparison. Furthermore, it has been observed experimentally that the cutting forces are affected by the feed rates and depth of cuts. As can be seen from Table 4,

As evident from Table 4, keeping other parameters, i.e., depth of cut *d*, and feed rate *f* constant an increase in cutting speed *v* for experiment nos. 1, 10, and 19 led to the reduction in all cutting forces including (main cutting Fx, thrust force Fy, and feed force Fz, respectively). The reason behind the first increase and then decrease increases in cutting forces is the high tendency of ductile material to form build up edge (BUE) chips at low and intermediate cutting speeds. While this tendency of (BUE) reduces at high cutting speeds because of flow zone created between cutting tool and chip, also (BUE) become less stable and brings off some cutting tool material with them as they brake off. Thus, increased formation of (BUE) reduces tool-chip contact and hence reduces the cutting forces. The increase in cutting forces with the feed rate also corresponds to the maximum undeformed chip thickness, hence chips cross-sectional area increases as a result cutting forces increases as the tool has to cut maximum materials from the workpiece. A gradual increase in the cutting forces was observed with an increase in the feed rates and depth of cut for Fx, Fy, and Fz as shown in Figs. 6, 7, and 8, respectively. Where *a*, *b*, and *c* in the figure represents three different feed rates for all specified cutting speed and depth of cuts.

For the selection of optimal cutting parameters, MRR was calculated using the following relation:

$$MRR = v \times d \times f \tag{9}$$

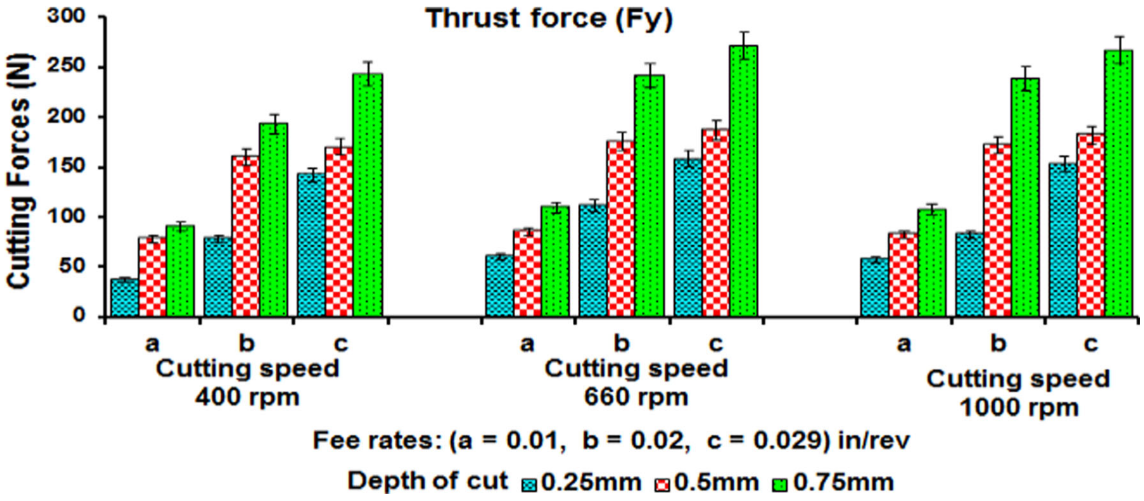


Fig. 7 Fy at specified cutting speeds, feed rates, and depth of cuts

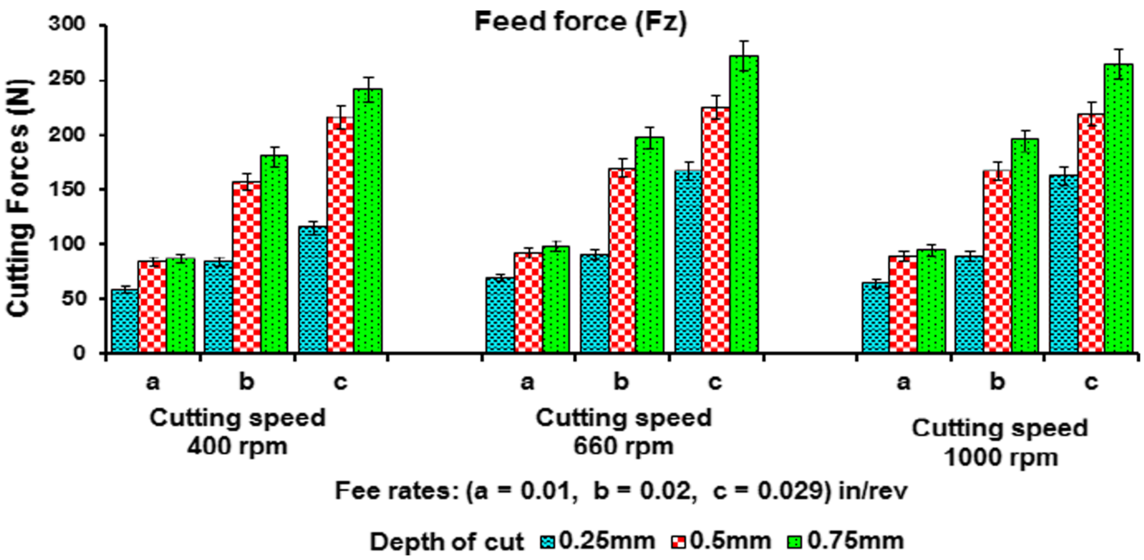


Fig. 8 Fz at specified cutting speeds, feed rates, and depth of cuts

Using Eq. (9), all the values for MRR were calculated for all specified cutting speeds, feed rates, and depth of cuts as presented in Table 5.

As the current study deals in measuring cutting forces in facing process in which tool moves radially from outer surface to the center of the workpiece, so during measuring material removal rates, velocity changes with diameter. For consistency in readings, a region of diameter ranges from 0.45 to 0.70 in. was selected to measure MRR and cutting forces for that region.

Stated in Eq. 9, the material removal rate has a direct relationship with all the three given parameters, i.e., cutting speed *v*, depth of cut *d*, and feed rate *f*, respectively, so with an increase in any one parameter, the percentage increase in MRR was recorded. This percentage increase was recorded up to 66%, while changing cutting speeds from slow to intermediate, i.e., 400 rpm to 660 rpm and further this percent increase in MRR reduces to 50% as cutting speeds moved from intermediate to high, i.e., from 660 to 1000 rpm, respectively.

The experimental data in Table 5 showed that the change in MRR has a direct influence on the cutting forces, since the percent change in MRR is high for intermediate cutting speeds and decreases comparatively for high cutting speed, so the intermediate speeds in the current study are critical for measuring cutting forces as the MRR values are maximum and started decreasing at high cutting speed. The reduction in MRR also reduces the cutting forces; hence, it satisfies the early finding of Şeker (2002) that a reduction in cutting forces with increasing cutting speed is common when cutting most metals and alloys.

To measure the optimal cutting parameters for cutting forces in facing process, all the calculated MRR are then plotted against the cutting forces at all specified cutting parameters, i.e., at depth of cut (a) 0.25 mm, (b) 0.50 mm, and (c) 0.75 mm at feed rate of (a) 0.01 in/rev, (b) 0.02 in/rev, and (c) 0.029 in/rev as shown in Fig. 9.

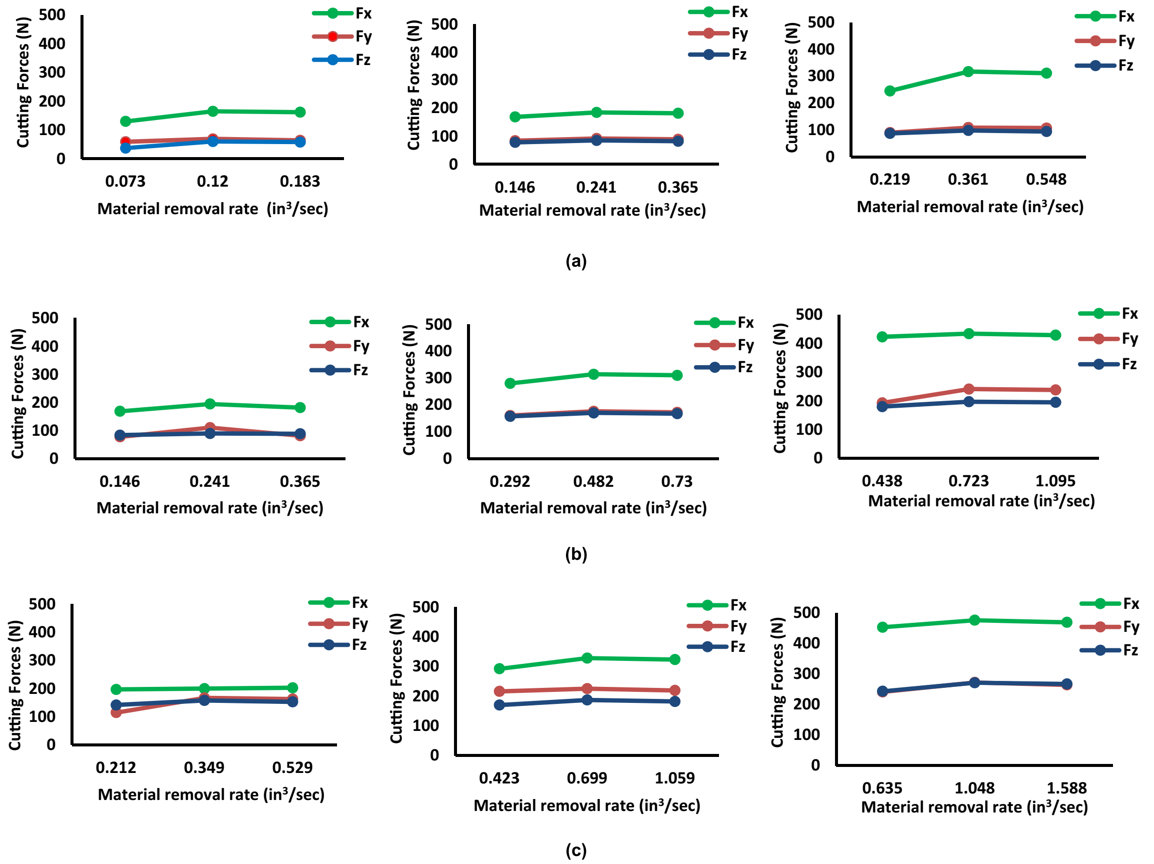
4 Process parameters optimization by Taguchi method

There are many statistical methods developed and implemented over the last few years for process optimization in manufacturing processes [3]. Taguchi method is one of the statistical approaches developed by Taguchi and Konishi [21] for process parameters optimization to improve the quality of the product manufactured. Taguchi developed a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values. There are three categories of quality characteristics in the analysis of the S/N ratio, i.e., the lower the better, the higher the better, and the nominal the better. In this investigation, Taguchi method on facing process performed on lathe machine for process parameters optimization is considered. For performance characteristics, a suitable orthogonal array is selected based on three main factors including spindle speed, depth of cut, and feed rate, respectively, and experiments were conducted for three distinct levels. Cutting forces were measured, and S/N ratio was calculated using the following relation; the values are shown in Table 6.

$$\mathrm{S/N\ ratio} = 10\log_{10}\frac{(\mathrm{Mean})^2}{\mathrm{Variance}}\,(\text{for Nominal–the–best condition}) \tag{10}$$

Table 5 MRR at spindle speed 400, 660, and 1000 rpm

Feed rate (in/rev)	Depth of cut (in)	Spindle speed (rpm)	Min dia (in)	Max dia (in)	Min velocity (in/s)	Max velocity (in/s)	V_{avg} (in/s)	MRR = $d*f*V_{avg}$	Cutting force	Thrust force	Feed force	Surface texture		
									Fx	Fy	Fz	Rq	Ra	Rz
0.01	0.01	400	0.45	0.7	590	890	742	0.073	130	37	59	0.11	0.1	0.5
	0.02	400	0.45	0.7	590	890	742	0.146	169	78	84	0.11	0.09	0.5
	0.03	400	0.45	0.7	590	890	742	0.219	245	90	87	0.04	0.03	0.4
0.02	0.01	400	0.45	0.7	590	890	742	0.146	169	78	84	0.04	0.03	0.2
	0.02	400	0.45	0.7	590	890	742	0.292	280	160	157	0.07	0.06	0.5
	0.03	400	0.45	0.7	590	890	742	0.438	423	193	180	0.04	0.03	0.3
0.029	0.01	400	0.45	0.7	590	890	742	0.212	197	142	115	0.04	0.03	0.2
	0.02	400	0.45	0.7	590	890	742	0.423	292	170	216	0.04	0.03	0.2
	0.03	400	0.45	0.7	590	890	742	0.635	453	243	241	0.10	0.09	0.5
0.01	0.01	660	0.45	0.7	980	1470	1224	0.12	165	60	69	0.07	0.06	0.5
	0.02	660	0.45	0.7	980	1470	1224	0.241	185	85	92	0.13	0.09	1.0
	0.03	660	0.45	0.7	980	1470	1224	0.361	317	109	98	0.13	0.12	0.6
0.02	0.01	660	0.45	0.7	980	1470	1224	0.241	195	111	90	0.66	0.39	7.0
	0.02	660	0.45	0.7	980	1470	1224	0.482	314	176	170	0.16	0.12	1.1
	0.03	660	0.45	0.7	980	1470	1224	0.723	434	241	197	0.46	0.30	3.8
0.029	0.01	660	0.45	0.7	980	1470	1224	0.349	200	158	167	0.05	0.04	0.3
	0.02	660	0.45	0.7	980	1470	1224	0.699	328	187	225	0.05	0.04	0.4
	0.03	660	0.45	0.7	980	1470	1224	1.048	476	271	272	0.12	0.11	0.6
0.01	0.01	1000	0.45	0.7	1480	2225	1854	0.183	162	58	64	0.06	0.05	0.6
	0.02	1000	0.45	0.7	1480	2225	1854	0.365	182	82	89	0.63	0.27	0.8
	0.03	1000	0.45	0.7	1480	2225	1854	0.548	311	107	94	0.11	0.10	0.7
0.02	0.01	1000	0.45	0.7	1480	2225	1854	0.365	182	82	89	0.06	0.05	0.4
	0.02	1000	0.45	0.7	1480	2225	1854	0.73	310	172	167	0.07	0.05	0.7
	0.03	1000	0.45	0.7	1480	2225	1854	1.095	429	238	195	0.05	0.04	0.4
0.029	0.01	1000	0.45	0.7	1480	2225	1854	0.529	203	153	163	0.04	0.04	0.3
	0.02	1000	0.45	0.7	1480	2225	1854	1.059	323	182	219	0.04	0.04	0.3
	0.03	1000	0.45	0.7	1480	2225	1854	1.588	469	267	264	0.05	0.04	0.5



(a)

(b)

(c)

Fig. 9 Material removal rates Vs cutting forces for feed rates **(a)** 0.01, **(b)** 0.02, and **(c)** 0.029 rev/in

Table 6 Tabulated S/N ratios

Experiment no.	Control levels			S/N ratio
	Cutting speed, *V* (rpm)	Depth of cut, *t* (mm)	Feed rate, *f* (in/rev)	
1.	1	1	1	18.52
2.	1	2	1	21.60
3.	1	3	1	25.80
4.	1	1	2	21.67
5.	1	2	2	38.50
6.	1	3	2	22.26
7.	1	1	3	27.90
8.	1	2	3	28.73
9.	1	3	3	18.03
10.	2	1	1	20.43
11.	2	2	1	22.87
12.	2	3	1	35.78
13.	2	1	2	24.41
14.	2	2	2	30.34
15.	2	3	2	19.73
16.	2	1	3	35.96
17	2	2	3	24.75
18.	2	3	3	16.27
19.	3	1	1	20.12
20.	3	2	1	22.50
21.	3	3	1	33.82
22.	3	1	2	22.50
23.	3	2	2	31.49
24.	3	3	2	20.02
25.	3	1	3	34.91
26.	3	2	3	25.62
27.	3	3	3	16.65

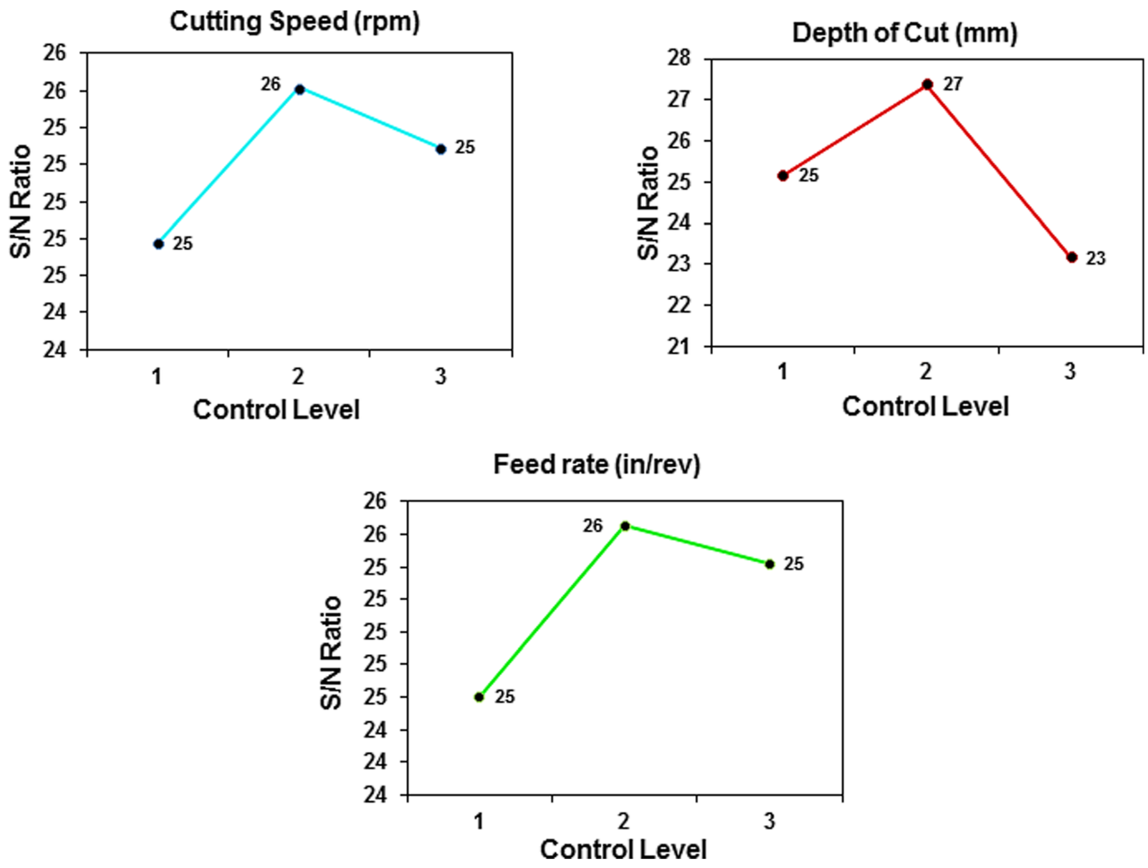


Fig. 10 Average S/N ratio verses control factors

To determine the optimal values of the cutting forces based upon S/N ratio, an average was taken for the corresponding S/N values and plotted against levels of each factor as shown in Fig. 10.

With the help of the above graph, optimum parameters were obtained for the cutting forces and surface texture and are listed in Table 7.

5 Conclusions

In this work, an indigenous force dynamometer is designed and developed for cutting force measurements in turning process. The dynamometer was experimentally tested, and results obtained are found in good relation to the numerical data that confirm its reliability for cutting force measurement in facing process. The process parameters such as cutting speed, feed, and depth of cut in turning (facing) of mild steel (A1010) obtained from the dynamometer are optimized using the application of Taguchi method. Experimental results reveal that:

- Cutting forces in *x*, *y*, and *z* are directly influenced by the change in MRR, the percentage increase is high from slow to intermediate speeds and reduces from intermediate to high speeds.
- Intermediate speeds are crucial for measuring cutting forces as their values are high and force values start reducing even though MRR increases when cutting speed increases, the reason behind the increase in cutting forces is the high tendency of ductile material to form Build up edge (BUE) chips at low and intermediate cutting speeds.

Table 7 Optimum parameters for cutting forces and surface texture

Parameter	Optimum levels	Optimum values	Fx (N)	Fy (N)	Fz (N)	Ra (μm)	Rq (μm)	Rz (μm)	MRR (in^3/s)
Cutting speed	3	1000 rpm	–	–	–	–	–	–	–
Feed rate	3	0.029 in/rev	203	153	163	0.04	0.04	0.3	0.529
Depth of cut	1	0.01 in.	–	–	–	–	–	–	–

While this tendency of (BUE) reduces at high cutting speeds because of flow zone created between cutting tool and chip. Furthermore, the use of Taguchi method provides an easy and efficient methodology to obtain optimized process parameters as compared to other statistical methods for process optimization. The following conclusions are drawn from this experimentation.

- Cutting speed of 1000 rpm, feed rate at 0.029 in/rev, and depth of cut 0.01 in. for all the cutting forces including thrust force Fy, feed force Fz, and main cutting force Fx are found to be optimum in this work for the specific work piece material used.

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