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DESIGN, FABRICATION AND PERFORMANCE TESTING OF A TWO COMPONENT CUTTING FORCE DYNAMOMETER FOR DRILLING

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ABSTRACT

In this work, a two component cutting force strain gauge dynamometer for drilling has been designed, produced and tested. The dynamometer was fabricated from mild steel in the form of a spoke wheel usually having four spokes. It has a stiff hub and outer rim with two precision dial gauges of at least 0.01mm resolution for deflection measurement. Two spokes houses two octagonal rings with strain gauges mounted on the inside and outside of each to make the dynamometer achieve high sensitivity for both the torque and the thrust. Using the constructed dynamometer, several drilling tests were successfully performed. The dynamometer has been designed primarily for drilling. It has been recommended that further work should be undertaken on milling and turning.

INTRODUCTION

In recent years, great demands for goods and services in societies have made it necessary for most manufacturing processes to be automated. One of these aspects which is in great demand for automation is the metal cutting processes (turning, milling, drilling and shaping, etc.). However, the demands for improved processing and higher cutting rates have necessitated the need for an accurate measurement of cutting forces involved in metal cutting towards the optimal utilization of machine tools.

Measurement of metal cutting forces during processing techniques is carried out from different points of view and hence different techniques are used. Generally, the interest is either in process control or process improvement (Beckwith and Buck, 1988). On this basis the study of tool work interaction forces is of great practical importance in all the chip forming operations, as this is the control variable for ensuring required accuracy.

Conceptual Frame Work

In metal cutting operations, certain observations are made before, during and after a cut. The most important of the observations that can be made during the cutting process is the measurement and determination of cutting force components. The importance of monitoring the cutting force in drilling, milling, shaping and turning, etc. has been well recognized in machine tool operations. Sukvittayawong and Inasaki (1991) pointed out that on-line and real time information of the normal cutting force is closely related to the tool wear prediction, breakage detection or other malfunction.

A considerable amount of investigations has been directed towards the prediction and measurement of cutting forces in metal cutting. That is because the cutting forces encountered during metal cutting have a direct influence on the generation of heat and thus tool wear, quality of machined surface and accuracy of the work piece. Due to the complex tool configurations/cutting conditions of metal cutting operations and some unknown factors and stresses, theoretical cutting force calculations failed to produce accurate results (Shaw, 1984). On this basis, Boothroyd (1985) opined that experimental measurement of the cutting forces becomes unavoidable. For this purpose, many dynamometers have been developed

A dynamometer has been defined by Karabay (2005) as an important and fundamental instrument to measure the cutting forces during metal cutting. Examples of metal cutting processes are: milling, turning, shaping and drilling, etc. designs differ considerably depending on whether the deflections of the structure are measured direct with displacement transducers or whether the strains induced on the structure are measured by strain gauges and their associated components (Boothroyd, 1985).

In order to ensure accuracy of measurement, it has been observed by Tani, Hatamura and Nagoa (1993) that certain geometric parameters must be selected in special ways. Primary requirements of any dynamometer are: compactness, high sensitivity and high stiffness (Graziosis and Jona, 1989).

In this work, a two component cutting force dynamometer for drilling was designed, produced and tested. The tube element originated by (Venkatraman and Lamble, 1980) was adopted as the basis of the design. This consist of a stiff hollow shaft, one end of which is rigidly fixed to the base plate while the top carries the platform needed for the clamping of the work material. Dynamometers of this type are characterized by high rigidity (particularly in the axial direction) and comparatively low sensitivity in the thrust direction.

For better performance (low rigidity and high sensitivity), a spoke wheel (usually four spokes) dynamometer having a stiff inner hub and outer rim was designed, this is because it is believed that the four spokes can make it achieve high sensitivity for both the torque and the thrust. Furthermore, low rigidity and natural frequency can also be achieved.

Although the study is restricted to drilling, most of the techniques can easily be applied to other metal cutting operations such as turning, milling and shaping, etc. The need to produce dynamometers which can be used in the laboratories and workshops of mechanical/production engineering departments in higher institutions of learning in Nigeria cannot be over-emphasized.

Cutting force dynamometer is very expensive, by producing it locally, the scarce foreign exchange of the country is saved. The apparatus can be used for experimental studies as the study of forces involved in any of the cutting forces could be useful in: fundamental studies for the understanding of metal cutting processes; efficient design and control of machining process.

Considerable amount of research work on the subject of cutting forces and tool life has already been carried out by various investigators in different countries. Since new materials are coming into use, more investigations have to be continued. Examples of force configuration in different machining processes are shown in figure 1.

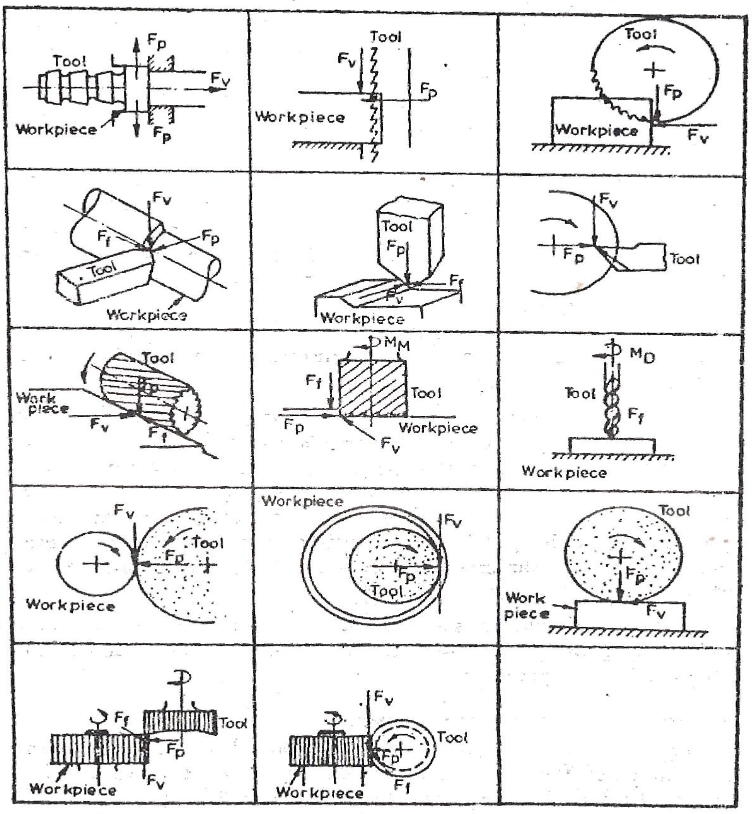


Fig. 1. Force configuration in different machining processes.

(Boothroyd, 1985)

Various types of dynamometers are available. They are generally; mechanical, electrical, pneumatic or hydraulic in their operations, but basically load cells with amplifiers are found in modern designs. The mechanical type relies on the deflection of a calibrated spring, which is measured with some level of accuracy and is displayed on a dial indicator, whilst the others rely on an electrical meter or a pressure gauge. In the latter case, the pressure gauge displays the pressure on a spring loaded piston and may take the form of column of liquid in a glass tube. In the majority of current force measuring techniques, the cutting force is applied to some elastic member of the dynamometer and the resulting deflection of the member is measured by using strain measuring equipment. Those dynamometers, where strains are measured, are known as strain- gauge dynamometers. Monitoring the cutting parameters in drilling operation can enable drill thrust, torque, gross and net power to be compared between different metals.

In measuring cutting force using a mechanical dynamometer, its effects on the tool is measured. Some of the effects of the cutting force are deflection and strains. Any of these parameters is measured and correlated to the cutting force causing it. Hence, two types of cutting force dynamometers are found viz: displacement gauge and strain gauge dynamometers.

(1) Displacement gauge Dynamometers

These types use displacement gauges to measure the deflection of the tool during machining. They are in the form of a cantilever, supporting the cutting tool. Chisholm (1982) has designed and produced a cantilever dynamometer. In these types slots are provided on the cantilever. The action of the cutting force is to bend the structure about the weakest point. Two displacement gauges are arranged to measure these distortions. The disadvantages of this dynamometer are that it is difficult to analyze the deflections of the structure and a lot of interaction between the force components. However, a practical design has resulted in an interaction of some 15 percent (Town and Moore, 1979).

(2) Strain Gauge Dynamometer

In these types the stress due to the cutting force are measured. The existence of strain nodes at certain sections of a loaded circular ring makes it possible to separate strains owing to vertical and horizontal loading.

One of the early successful applications of the strain gauge technique to dynamometry in cutting was reported by Merchant and Zlatin (1981). Two of the most successful spring elements for the conversion of forces into strain are the cantilever beam and the thin ring element. The simplest of these is the direct cantilever type used by Shaw (1984). Making successful use of the principle of dimensional analysis has given the empirical expression connecting the dimensions for the choice of the slot and hole sizes for practical design considerations.

Generally, with strain gauge dynamometers, it is necessary to choose between high stiffness and high sensitivity and between high cross-sensitivity and high quality workmanship. One such successful design for a two component turning dynamometer was produced by Boothroyd (1985). This dynamometer exhibits a maximum cross error of 4.4 percent and a natural frequency of the order of 7kHz and is claimed to be without hysteresis and sensitivity to reasonable variations in the positions of the applied force. The dynamometer works on the principles of two sets of vertical struts elements subjected to tension and compression (connected in a bridge circuit), measuring the main cutting force, while similar struts in the horizontal position measure the radial component.

The particular difficulty in the practical fabrication of this design is in the fixing of the strain gauges at the internal positions due to poor accessibility. Graziosi and Jona (1989) pointed out that two of the main problems encountered in building a strain gauge dynamometer for measuring tool forces in metal cutting are:

1. That of attaining combination of high stiffness and high sensitivity.
2. That of avoiding cross sensitivity or the sensitivity of the instrumentation designed to measure one component to the other components of the cutting force.

MATERIALS AND METHODS

A two-component drill dynamometer for the measurement of drill thrust and torque was designed and produced. Zinc was used in the fabrication of the dynamometer due to its good combination of elastic property, low cost, availability and high corrosion resistance under any condition. The dynamometer is in the form of a spoke wheel, usually having four spokes casted from a single block as it is difficult to produce it by machining. Mechanical parts of the dynamometer consist of five main parts. These are: inner hub, outer hub, three octagonal rings, work piece holder and four spokes. Two precision dial gauges of at least 0.01mm resolution were mounted on the dynamometer for deflection measurement.

The octagonal rings which were designed and produced has design loads and dimensions indicated in Table 1

Table 1: Design loads assumed on the ring and dimensions computed of the ring (Karabay, 2005)

Design thrust Force on ring T_v (N)	Design drill torque on ring M_d (Nm)	t_r (mm)	b_r (mm)	D_i (mm)	h_r (mm)	l_{sd} (mm)	t_b (mm)	R_m (mm)	R_o (mm)	Ring material (-)
3500	65	5	20	40	77.8±0.2	36±0.1	6	22.5	25	SAE/1040

Determination of Dimensions of the Thin Ring

The thickness t_r, radius R, and width b_r of the circular strain ring are the three basic controllable parameters that affect the rigidity and sensitivity. Since there is no effect of ring width b_r and modulus of elasticity E on the strain per unit deflection, b_r min can be taken as 20mm to set up the ring securely (Shaw, 1984).

Venkatraman and Lamble (1980) opined that octagonal ring is stiffer than circular ones of the same minimum section, the stiffness being found to be about 2.5 times more than the circular ones. Therefore, an octagonal rings (with circular holes) strain gauges 5,6,7 and 8 will be located on an axis 45° from the horizontal axis AA and strain gauges 1,2,3 and 4 will be located vertically on horizontal axis AA. This is shown in Figure 2a

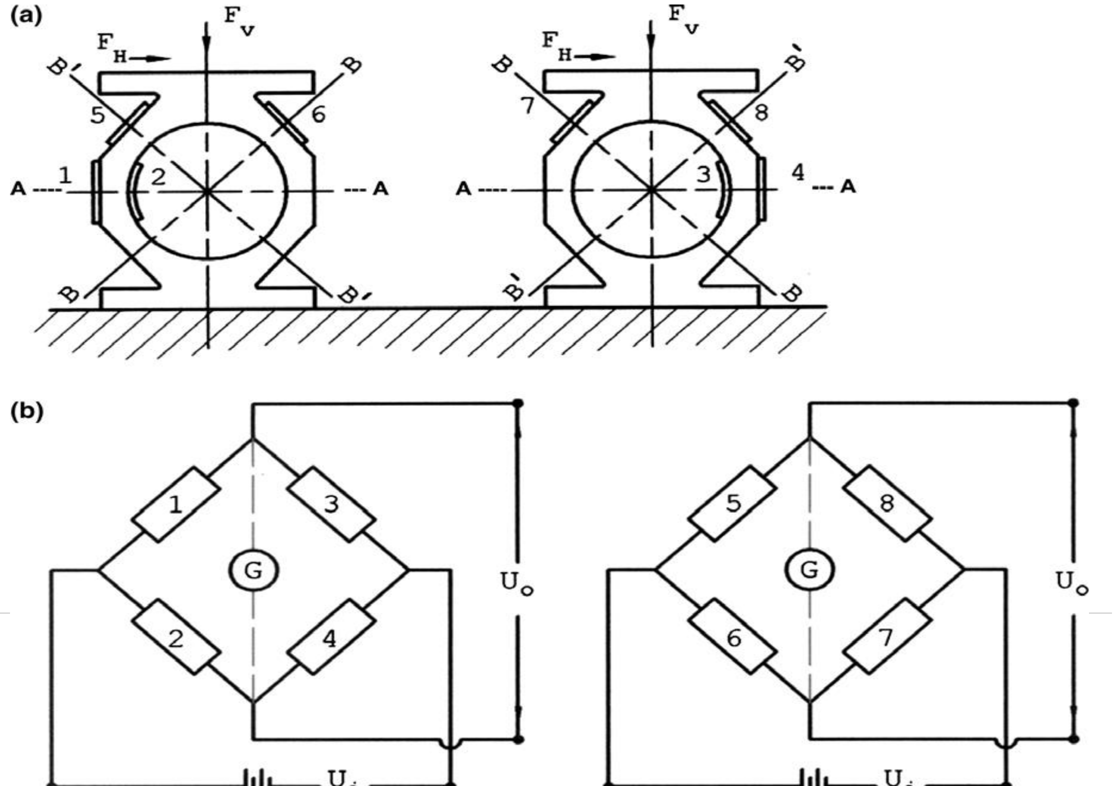


Fig. 2 (a) Octagonal rings with mounted strain gages. (b) Wheatstone bridge circuit of strain gages located on the octagonal rings for measuring drill thrust and torque. T_v: bridge circuit for measuring drill thrust; M_d: bridge circuit for measuring drill torque (Karabay, 1986).

The constructed dynamometer has a sensitivity of ±5N. After calibration, the cross-sensitivity of the dynamometer was determined as 0.05%. In dynamometer design, factors such as sensitivity, rigidity, accuracy and easy calibration should be taken into account (Karabay, 2005).

Dimensions shape and materials of dynamometer are considered to be effective factors of dynamic properties of the dynamometer (Yaldiz and Unsacar, 2000). In designing the octagonal rings, maximum thrust (T_{vs}) and drill torque (M_s) exerted by drill on the dynamometer were assumed as 10,500N and 1.95Nm, respectively. Thus, the dimensions of the rings were computed as indicated in Table 1 with the design formula of the ring by (Karabay 2005). Physical properties of the ring material have been summarized in Table 2 (Karabay, 2005).

Table 2: Properties of Ring Material SAE 1040 Steel

Source: (Karabay, 2005)

Tensile strength, D_r (N/mm^2)	Yield strength, d_y (N/mm^2)	Permissible stress, s.f: 1.5 d_{per} (N/mm^2)	Modules of elasticity, E (N/mm^2)	Poison ratio, r(-)	Carbon content % C(-)	Brinell hardness H_B (kg/mm^2)
550 – 570	280	186.66	210x10^3	0.3	0.35-0.44	172

Considering the data given Table 1, thin ring elastic theory show the strains at the inside and outside surfaces of the ring owing to F_V and F_H at A and B, respectively (Oraby,1990):

$$\varepsilon_{A} = 1.09F_{v}R \Big/ Eb_{r}t_{r}^{2} \qquad (1)$$

$$\varepsilon_{B} = 2.31F_{H}R \Big/ Eb_{r}t_{r}^{2} \qquad (2)$$

The stress occurring on rings caused by thrust and main cutting force can be calculated by placing elastic strain ratio values in equation (1) and (2) as follows:-

$$\delta_v = E\varepsilon_t = 190.8\text{N/mm}^2 \qquad (3)$$

$$\delta_H = E\varepsilon_H = 281.5\text{N/mm}^2 \qquad (4)$$

The calculated stress values δ_V and δ_H occurring on the rings are within safety limits for this material.

The Orientation of the Strain Gauges and the Rings on the Dynamometer

The proper selection of the points where the strain gauges are mounted is essential for achieving high accuracy in the wheatstone bridge circuits. The orientation of the strain gauges on the rings and the position of the rings on the dynamometer are as shown in figure 2 (a)

The thrust force F_v is supported by A and C rings of the dynamometer as shown in Figure 2 (a). The strain gauges 3, 4, 7, and 8 are affected by the thrust, force F_v. Among these strain gauges 3 and 7 are subjected to tensile stress while 4 and 8 are subjected to compressive stress. The strain gauges to measure the feed force F_f should be mounted on the outer surfaces of A and C rings with 45° inclination angles. As shown in figure 2 (a), the strain gauges 1, 2, 5 and 6 are affected by the feed force F_f. Among these strain gauge 1 and 5 are subjected to tensile stress while 2 and 6 are subjected to compressive stress (Oraby, 1990).

Mounting Of Strain Gauges on the Rings

The rings of the dynamometer were produced from S.A.E./1040 steel. The surfaces of the rings were ground for better strain gauge application. After cleaning, the strain gauges were mounted on two of the octagonal rings. Two strain gauges were mounted inclined at 45° on top of the two octagonal rings while four strain gauges were mounted vertically on the inside and outside of the two octagonal rings at 90° angle.

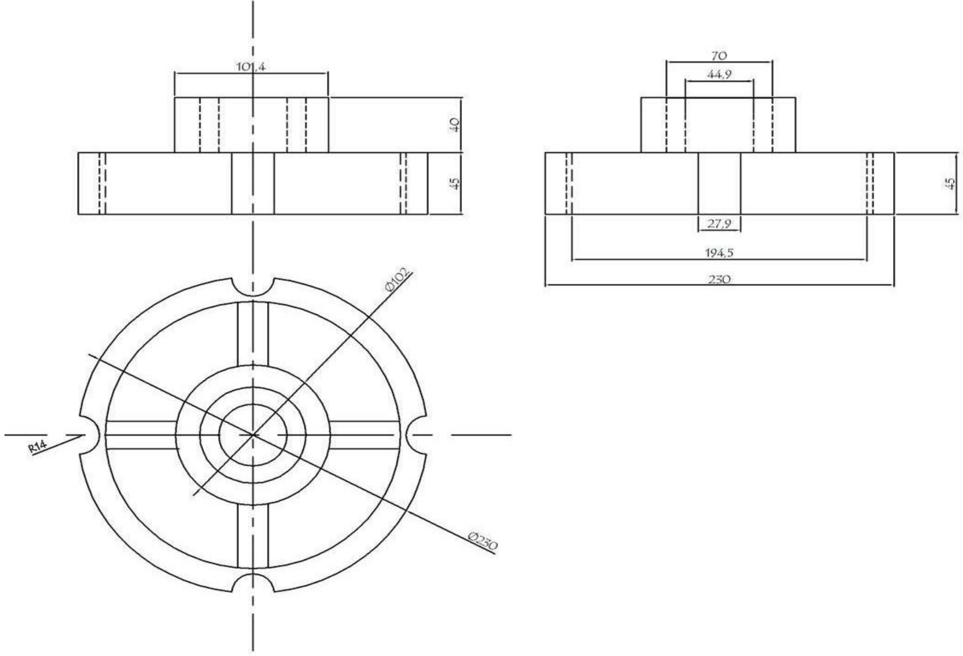
Mounting of the Dynamometer Rings

The rings of the dynamometer were mounted inside two of the four spokes of the dynamometer frame by using 4mm diameter pins and M5 screws. This is done to prevent the motion of the rings due to clearance which may cause cross-sensitivity during measurements.

The dimensions of the spokes were 50mm by 50mm by 50mm. A hole 50mm diameter was drilled at the centre to serve as the work holding device. The four spokes of the dynamometer are placed at 90° to each other. The outer diameter of the wheel is 230mm and the height of the wheel is 45mm, while the height of the work holder is 40mm. Four holes 40mm in diameter were drilled inside the wheel to house the three octagonal rings.

Calibration of the Dynamometer

In order to determine the elastic deflection of ring components and consequently the output voltage static load, the dynamometer was calibrated. The calibration has been performed using calibration ring. The dynamometer was calibrated in vertical direction for thrust forces and horizontal direction for horizontal forces created by drill moment. (Karabay, 2005)



Strain Gauge Circuits and Data

The electrical circuit of the dynamometer is basically Wheatstone bridge. This circuit consists of four gauges. The dynamometer has three octagonal rings; one of the rings is to be used as a support and the other two were cemented with eight strain gauges. Strain occurring in the strain gauges can be computed by the following relation (Karabay, 2005):

$$\frac{\Delta R}{R} = K\frac{\Delta L}{L_o} \tag{5}$$

Percentage elongation of the strain gauge is given as $\frac{\Delta L}{L_o} = \varepsilon$. Therefore, the above formula can be rewritten as $\frac{\Delta R}{R} = K\varepsilon$. The ratio of output voltage to input voltage of the bridge is given by (Karabay, 2005) as:

$$U_o/U_i = 1/4\left\{(\Delta R_{1,5}/R_{1,5}) - (\Delta R_{2,6}/R_{2,6}) + (\Delta R_{4,7}/R_{4,7}) - (\Delta R_{3,8}/R_{3,8})\right\} \tag{6}$$

On the other hand

$$\Delta R/R = K/4\left\{\varepsilon_{1,5} - \varepsilon_{2,6} + \varepsilon_{4,7} + \varepsilon_{4,7}\right\} \tag{7}$$

Where:

$\varepsilon_{1,5} = -\varepsilon_{2,6} = \varepsilon_{4,7} = -\varepsilon_{3,8} = \varepsilon$

$U_o/U_i = 1/4[K4\varepsilon]$ And strain gauge factor is given as K = 2.105 ± 1.5% of the output voltage which can be reduced to the below definition Karabay (2005):

$$U_o = 2.105 \pm 1.5\%\varepsilon U_i \tag{8}$$

The type of strain gauge used in the construction of the dynamometer is CAE-60-125UW-120 made by Micro- measurement. Its resistance and gauge factor are given as 120.0 ±0.3 and 2.105±1.5, respectively. Strain gauges mounted on the rings are shown in Figure 3.2a-b. To measure thrust and torque in drilling or similar cutting operations, strain gauges are connected to each other. Gauges 2 and 3 are sensitive to measure compressive strains whereas gauges 1 and 4 are sensitive to tensile strains when thrust is applied on the ring. When torque is applied on the dynamometer, gauges 5 and 7 are sensitive to measure tensile strains, whereas gauges 6 and 8 are sensitive to measure compressive strain

Fig 3.4 Working Drawing of the dynamometer

Scale 1:2

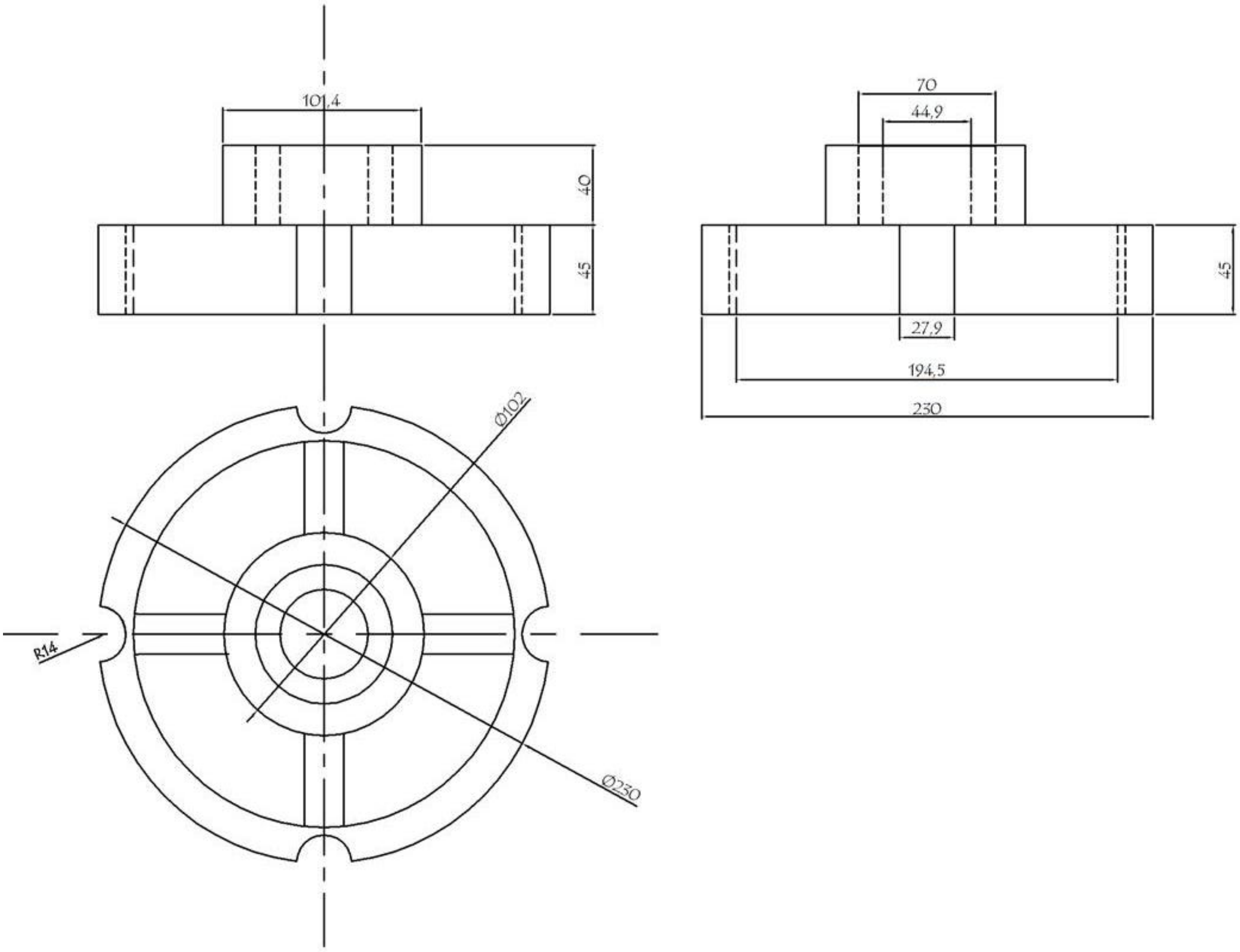


Fig. 3 Orthographic Drawing of the Dynamometer

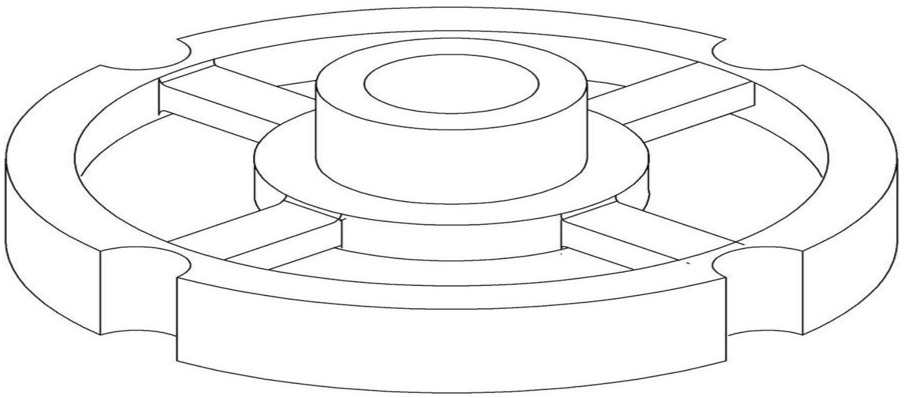


Fig. 4 Isometric Drawing of the Dynamometer

Performance testing of the constructed dynamometer

The constructed dynamometer was placed on the machine table with the work piece held on top of the work holder and clamped for drilling to commence. In order to determine the performance of the constructed dynamometer, series of drilling experiments on S.A.E. 1020 samples steel with Brinell hardness $H_B = 179$ was done. The drills used in the test ranged from 10mm to 15.5mm as shown in Table 3.

Table 3: Specifications of the drills used in tests

Drill diameter (mm)	10	12	14	15.5
Web thickness (mm)	1.8	2	2.45	2.75
Chisel edge angle $(^0)$	55^0	55^0	55^0	55^0
c/d	0.219	0.203	0.213	0.216

Those drills have point angle 118^o and helix angle 30^o. In this test, forces exerted by drills of diameters: 10, 12, 14 and 15.5mm on the work piece with feeds: 0.152, 0.178, 0.254, 0.304, and 0.356mm/rev were collated/recorded during machining. The tests were performed in the machine shop of the Department of Mechanical Engineering, Ramat Polytechnic, Maiduguri on a radial drilling machine.

Torque and thrust were measured on the constructed dynamometer. All tests were run dry without coolant at 370rpm of drill drive shaft of the machine with feed from 0.152 to 0.356mm/rev. This speed was low enough to prevent measurable wear of drills during the test. All the holes were drilled deep enough to obtain steady state values of torque and thrust. Average web thickness and average c/d ratio are given in Table 4

Table 4: Experimental results from the measurements of drill torque M_d (Nm) by dynamometer in drilling operation of the SAE 1020 steel

Drill torque M_d measurements versus drill diameter and feed (Nm)

Drill d (mm)	Drill Feed, f (mm/rev) diameter,				
	0.152 mm/rev	0.178 mm/rev	0.254 mm/rev	0.304 mm/rev	0.356 mm/rev
10	9.12	13.68	15.96	18.24	22.80
12	13.68	15.96	22.80	25.08	26.94
14	18.24	23.37	29.64	33.06	37.62
15.5	22.80	26.22	35.34	41.06	45.60

The values of torque and thrust obtained in the tests along with averages for each drilling conditions are summarized in Tables 4 and 5 respectively.

Table 5: Experimental results from the measurements of drill thrust T_v by dynamometer in drilling operation of the SAE 1020 steel

Thrust T_v measurements versus to drill diameter and feed (N)

Drill d (mm)	Drill Feed, f (mm/rev) diameter,				
	0.152 mm/rev	0.178 mm/rev	0.254 mm/rev	0.304 mm/rev	0.356 mm/rev
10	2270	2707	3928	4685	5676
12	2550	3140	4283	5297	6243
14	2825	3419	4416	5400	6540
15.5	3040	3678	4637	5600	6776

Based on the results obtained during the tests, it has been found that the constructed dynamometer can be used efficiently to measure cutting forces in drilling.

CONCLUSION

In this work, a two component cutting force dynamometer has been designed, produced and tested for measuring cutting forces: thrust and torque on SAE 1020 steel. Zink was used for the production of the spoke wheel. The construction process is simple and the developed dynamometer is almost maintenance free.

RECOMMENDATIONS

1. The constructed dynamometer has been designed Primarily for drilling, as such, further work should be done on milling and turning.
2. Further research should be undertaken on the constructed dynamometer by processing the numerical values in a computer by data acquisition system.

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