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Measurement and Analysis of Forces During High Speed Milling of EN-30B Alloy Steel

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ABSTRACT

High speed machining (HSM) is one of the more useful and helpful technology. HSM is being adopted to increase the productivity, reducing manufacturing costs and for machining of hard materials. This research covers the steps taken to gain insight into the measurement and analysis of cutting forces during high speed milling so that these forces should have minimum effect on cutting tool and rapid tool wear can be controlled. In order to measure and record the cutting forces during high speed milling, a dynamometer is designed and developed. An accurate and reliable dynamometer is manufactured for measuring and recording the cutting force components. The calibration of the dynamometer is carried out and calibration factors for three axes and three force components are acquired. Based on these calibration factors three tests, cross-sensitivity, linearity, and performance tests were conducted. An alloy steel EN-30B is selected as work piece material. This material is high strength steel alloy and has good impact properties. A repeatable experimental setup and procedure is developed for measuring and recording the three components of cutting forces. A total of ten experiments are carried out and experimental setup is remained unchanged except for tool insert. The experiments involve same dry cutting cycle with face milling process. A sufficient set of experimental data is collected and three components of forces during high speed milling of EN-30B with coated carbide tool insert is measured, recorded and analyzed. Maximum high speeds of up to 500m/min are achieved during milling process. It is observed that the values of cutting forces increased with an increase in process parameters including, cutting speed, feed/ feed rate and depth of cut.

KEYWORDS: High speed machining, aerospace alloys, analysis of parameter, machinability.

INTRODUCTION

The machining of metals is being used in many industries, which include aerospace, heavy mechanical structures and automotive sectors, etc. Cutting tools are developed keeping in view their applications so that they can be used effectively. The design is carried out in such a way that forces should not deform cutting tools. Protecting the tool against wear can enhance the life of the cutting tool. In order to design and develop a cutting tool, its mechanical properties should be known and considered. The calculation of the stresses produced during metal plays a vital role in design of cutting tools. Therefore attention has already been given to the prediction and measurement of cutting forces during metal cutting.

In recent years, significant attention has been aimed at HSM. It is one of the more effective and efficient modern technology and is being adopted to increase the productivity, reducing manufacturing costs and for machining of difficult to machine materials. HSM has also been adopted in many industries due to short product cycle time and high material removal rate. The cutting speed of high speed machining is many times higher than the cutting speed of the conventional or traditional machines[1]. The latest research on HSM involves a wide range of materials ranging from easy to machine Aluminum alloys to difficult to cut hardened steels and advanced aerospace materials[2-3].Machining parameters like rotational speed, cutting speed ,feed rate and depth of cut are critical parameters which influence the cutting temperatures, tool life, surface quality and cutting forces .

Milling operations are the most common machining operations, which are used in aerospace and automobile industries. The milling process requires a milling machine, work piece, cutter and a fixture. The work piece is a pre-shaped and pre-processed material that is secured to a fixture that is itself attached to the platform in the milling machine. In order to analyze the metal cutting operation on a qualitative basis,

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certain observations must be made but one of the most important measurements is the determination of cutting forces. In this research work, the measurement and analysis of cutting forces in HSM is conducted and effects of cutting parameters are analyzed and monitored during HSM process. The measurement and analysis of these forces play an important role and is first step for optimization of cutting parameters for a particular machining process with a specific material and tool insert. With process optimization, the cutting tool insert life can be enhanced which results in reduction of machining cost and time. In order to measure the cutting forces, the work piece is mounted on 3-axis dynamometer.

MATERIAL AND METHODS

1.1. Dynamometer Design And Development

During the design of dynamometer various features such as sensitivity, elasticity, accuracy, rigidity and calibration should be considered as discussed in the previous section. Among these features the sensitivity and rigidity are the most critical factors in dynamometer design [4]. The structure must meet the requirements for high natural frequency as compared to operating frequency of machine and it must exhibit small cross-sensitivity [5]. The basic design of dynamometer includes four octagonal rings, top and bottom plates, sixteen strain gauges and a data acquisition system. The four octagonal rings are placed between top and bottom [6]. The strain gauges are installed on octagonal rings for measurement of cutting forces in three directions. The selection of material for octagonal rings and supporting plates is also important factor. The octagonal rings must be identically manufactured to prevent cross sensitivity. The factors like rigidity, high natural frequency, corrosion resistance and high heat conductivity are considered while selecting the material for the dynamometer components. Alloy Steel EN-30B is selected as material for development and manufacturing of dynamometer. The maximum expected force which the rings may face in each direction is 5000N in each direction. The radius, thickness and width of octagonal rings are the basic controllable parameters that can affect the rigidity and sensitivity [7]. The rings and the plates are manufactured at CNC machine in order to acquire precision and accuracy and to avoid cross sensitivity.

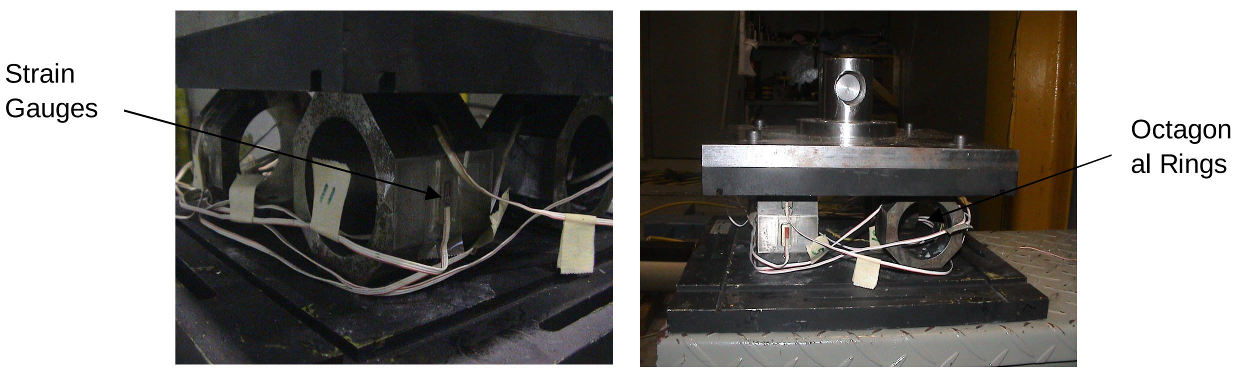

Figure 1. Different views of manufactured dynamometer

The TML, WFLA-3-11 type strain gauges are used for strain measurement. These strain gauges are recommended for use with steel and aluminum. In order to mount strain gauges, proper selection of points is very important for achieving high accuracy in wheat stone bridge [8].Totally, 16 numbers of strain gauges are mounted on four rings. The different views of dynamometer with stain gauges are given in Figure 1.

1.2. Calibration And Testing Of Dynamometer

The aim of the calibration is to determine elastic deflection of rings under the certain static load conditions. The elastic deflection is measured in terms of output voltages under the static load. The necessary hardware for calibration setup includes load cells, conditioner, data acquisition box and data acquisition system. The online and real time information of applied force and corresponding output (mv) is automatically recorded through data acquisition system. The calibration has been carried out in three directions F_x, F_y and F_z which are feed force, cutting force and thrust force respectively. The loads up to 5000N are applied and output voltages (mv) values are recorded. Based on recorded data, calibration factors for three axes and three force components are acquired. In order to verify and to establish consistency of the calibration values, each calibration step has been repeated for three times and very close values are obtained.

In order to test the performance and functionality of dynamometer, three tests of cross sensitivity, linearity and performance respectively are designed. The purpose of the tests is to determine the influence of a force component on other component of forces, accuracy in force measurement and performance of the system.

In cross sensitivity analysis of dynamometer, the effect of loading in one direction on other force components is examined and analyzed. It is observed that with an application of load in one direction results in minor fluctuations in other force components. The range of errors for cross sensitivity tests in three directions are measured from 2% to 4.27 %. In order to test the linearity and accuracy for measuring force in any direction, linearity test has been carried out. In the test, 50% of designed load is applied in x, y and z-direction respectively. The corresponding output (mv) in each direction is measured and recorded. It has been observed that the percentage error in force measurement is almost 4%. In order to test the performance of dynamometer, a load of 2000 N is applied at 45 degrees in x and y direction respectively. The purpose of the test is to verify the force components with an application of load in any given direction. It has been observed that the percentage error in measurement for force components is less than 10%.

2. Experimental Setup and Design of Experiments

The vertical milling machining center has been used for experiments. It is a 3-axis CNC milling center. The machine uses the rectangular box ways on Z-axis that dampen vibration. It has a jet lubrication system for effective lubrication during machining. The 22-HP spindle motor is engineered for heavy duty machining. The maximum spindle speed is 15000rpm. The machine tool used with clamped part is shown in figure 2. An alloy steel EN30B is selected as work piece material for experimentation. This material is high strength steel alloy and has good impact properties. This alloy steel is used where high tensile strength and toughness are required. It has many applications like automobile crank shaft assemblies, aircraft parts, heavy duty shafts and rolls, high strength gears and transmission components. The chemical and mechanical properties of EN-30B are given in Table 1 and table 2 [8].

Table 1. Chemical Composition of EN-30B

C	Mn	Cr	Mo	Si	S	Ni
0.20~0.34	0.45~0.70	1.1~1.4	0.20~0.35	0.1~0.35	0.025 Max	3.9~4.3

Table 2. Mechanical Properties of EN-30B

Material	Typical Ultimate Tensile Strength	Yield Strength	BHN Hardness
EN-30B	1540 N/mm2	1125N/mm2	444

Figure 2. Dynamometer and work piece installed on high speed milling machine

The major cutting parameters for experiments are selected as shown in Table 3.

Table 3. Cutting Parameters - Experiments

Cutting Speed	350,400,450,500 meters/min
Feed	0.1, 0.15,0.2 per tooth
Depth of Cut	1, 1.5,2.0 mm

APMT 1135 PDTR milling inserts are used for experiments. These are CVD/PVD coated inserts and have clearance angle of 11 degrees. The chemical vapor deposition (CVD) and physical vapor deposition (PVD) coatings are usually used for efficient and stable machining. These inserts are best for improving wear resistance and they are used for large range of applications. They are typically used for slotting, surfacing and face milling operations and stable machining is possible due to its crack resistance and high toughness properties. A total of ten experiments are designed and experimental setup remains unchanged except for the tool insert. The conventional face milling process is carried out in each experiment. The same cutting cycle is carried out for each experiment. All the cutting cycles are carried out without cutting fluid. The main cutting Force (Fc), Feed Force (Ff), and Thrust Force (Ft) are measured simultaneously for each cutting cycle. The insert is inspected after each cutting cycle for any damage. The summary of experiments is given in Table 4.

3. Limitations

The number of experimental tests performed is limited due to high cost of inserts, time and cost involved in machining process.

Table 4. Design of Experiments

Cutting speed meters /min	Feed (feed per tooth)	Depth of cut(DOC) (mm)
350	0.15	1.0
400	0.15	1.0
450	0.15	1.0
500	0.15	1.0
350	0.10	1.0
350	0.15	1.0
350	0.20	1.0
350	0.10	1.0
350	0.10	1.5
350	0.10	2.0

Despite the limitations restricting the number of experimental tests, a total of 10 experiments have been designed so that a sufficient set of data may be made available for analysis.

4. RESULTS AND DISCUSSIONS

The set of data for main cutting force (Fc), feed force (Ff), and thrust Force (Ft) are measured simultaneously for each cutting cycle with data acquisition system. The data is stored through data acquisition card in form of Microsoft Excel sheets. These Microsoft Excel sheets are then imported in MATLAB software. A software code has been developed in MATLAB for data analysis, data plotting and clear graphical representation. In order to collect data, the sampling rate in data acquisition system is selected as100Hz. The results trends are measured without losing any accuracy of maximum values. For comparison between experimental tests ultimate maximum values of recorded forces have been used.

4.1. Main Cutting Forces

The change in cutting force values with different cutting speeds is shown in Fig.4 (a), (b), (c) and (d). The data shows that cutting force increases with an increase in cutting speed. An increase of 42% in cutting speed from 350m/min to 500m/min has resulted in 33% increase in cutting force. At smaller speeds, the increase in cutting force is less than 10% but at larger speeds the increase is more than 20%. Similarly the results of variations of cutting forces with increase in feed and depth of cut are obtained.

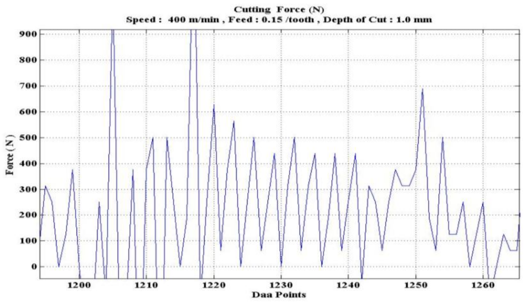

Figure .4(a). Cutting Forces
(Speed: 350m/min, Feed: 0.15/tooth, DOC: 1.0mm)

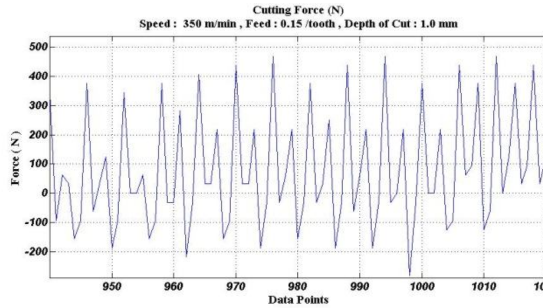

Figure 4 (b). Cutting Forces
(Speed: 400m/min, Feed: 0.15/tooth, DOC: 1.0mm)

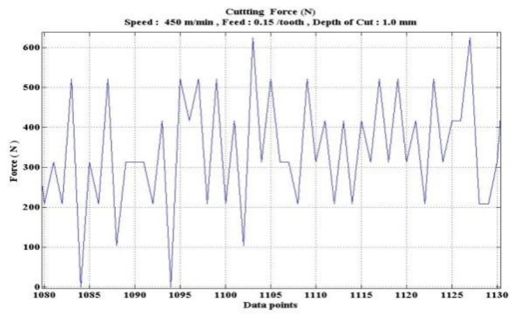

Figure 4 (c). Cutting Force
(Speed: 450m/min, Feed:0.15/tooth, DOC:1.0mm)

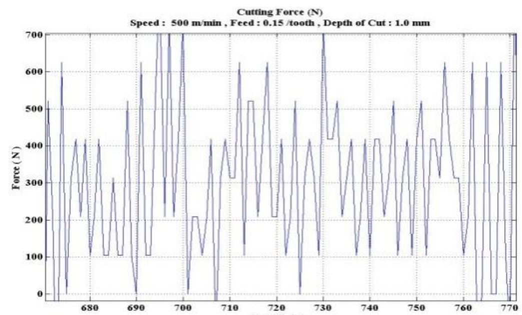

Figure 4 (d) Cutting Force
(Speed: 500m/min, Feed: 0.15/tooth, DOC:1.0mm)

Above plotted graphs *a,b,c* and *d* describes the behavior of cutting forces under different designed conditions.

4.2. Feed Force

The change in feed force with increase in cutting speed is shown in following Fig. 5 (a), (b), (c) and (d).

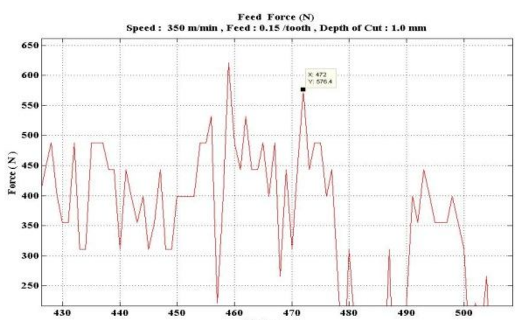

Figure 5. (a) Feed Force
(Speed: 350m/min, Feed: 0.15/tooth, DOC: 1.0mm)

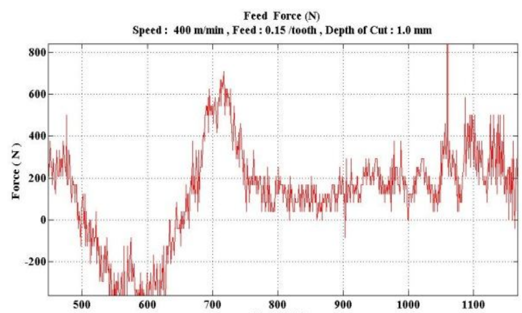

Figure 5. (b) Feed Force
(Speed: 400m/min, Feed:0.15/tooth, DOC:1.0mm)

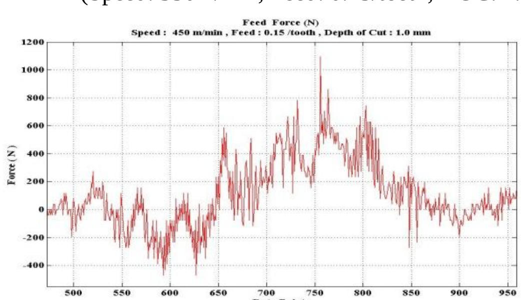

Figure 5. (c) Feed Force
(Speed: 450m/min, Feed:0.15/tooth, DOC:1.0mm)

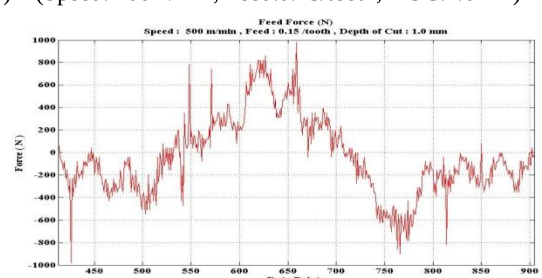

Figure 5. (d) Feed Force
(Speed: 450m/min, Feed:0.15/tooth, DOC:1.0mm)

The data shows that increase in cutting speed results in increase in feed force. At moderate cutting speeds from 350m/min to 450m/min, the increase in feed force is less than 12 % but increase in cutting speed from 450m/min to 500m/min has resulted in an increase of 25% increase in feed force. Similarly the variations of feed force with increase in feed and depth of cut is measured and recorded.

4.3. Thrust Force

The change of thrust force values with increase in cutting speed is shown in Figure 6 (a), (b), (c) and (d). The data that an increase of 42% in cutting speed from 350m/min to 500m/min results in about 40% increase in cutting force. This behavior is consistent as it has been observed in case of cutting force and feed force values. Similarly the variations of thrust force with increase in feed and depth of cut is measured and recorded.

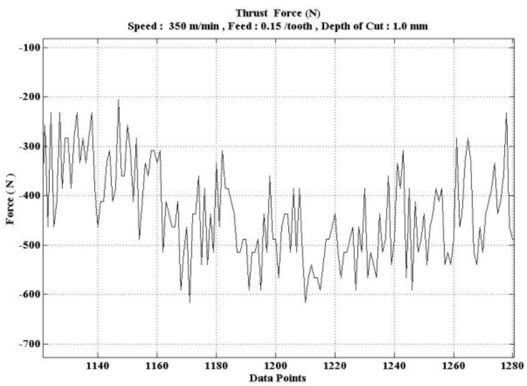

Figure 6. (a) Thrust Force
(Speed: 350m/min, Feed: 0.15/tooth, DOC:1.0 mm)

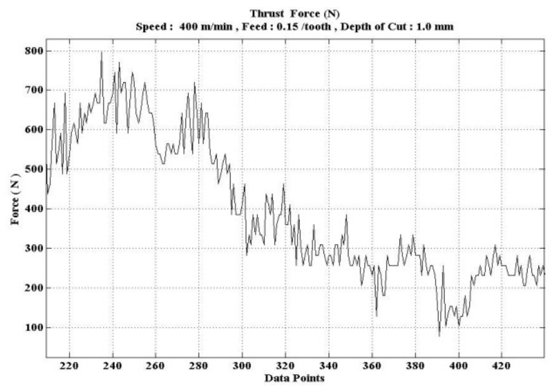

Figure 6. (b) Thrust Force
(Speed: 400m/min, Feed: 0.15/tooth, DOC:1.0mm)

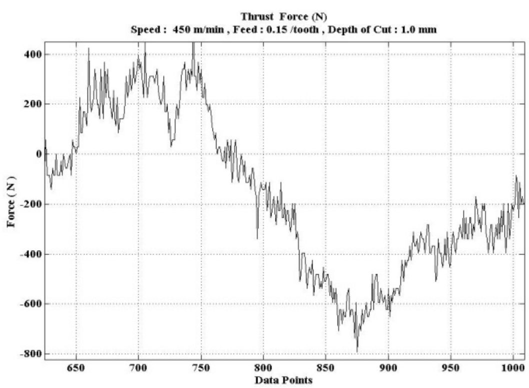

Figure 6. (a) Thrust Force
(Speed: 450m/min, Feed: 0.15/tooth, DOC: 1.0mm)

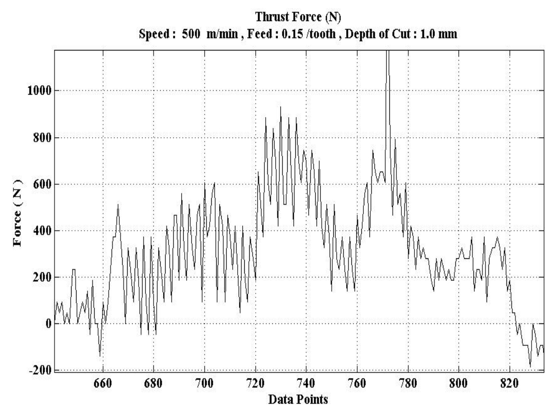

Figure 6. (b) Thrust Force
(Speed: 500m/min, Feed: 0.15/tooth, DOC: 1.0mm)

1. Comparison of Cutting Forces

The comparison of cutting forces achieved during experiments with variation in cutting speed, feed rate and depth of cut has shown in Figure.7 (a), (b) and (c).

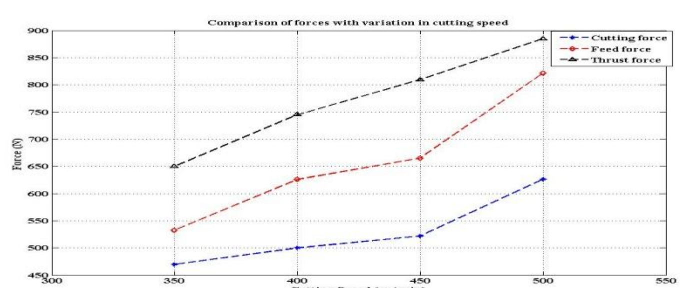

Figure .7 (a) Comparison of forces with variation in cutting speed

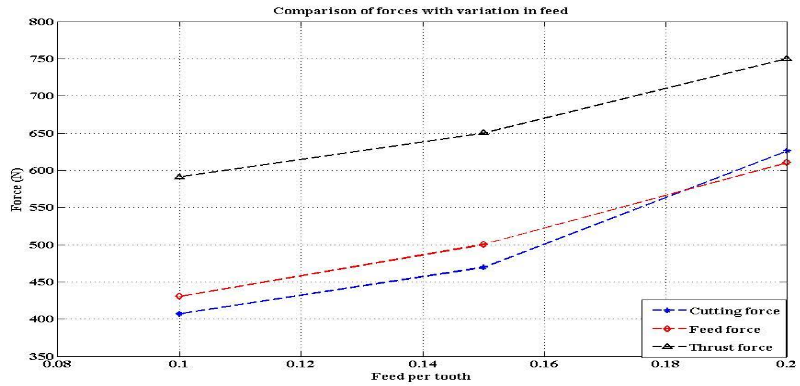

Figure. 7 (b) Comparison of forces with variation in cutting Feed

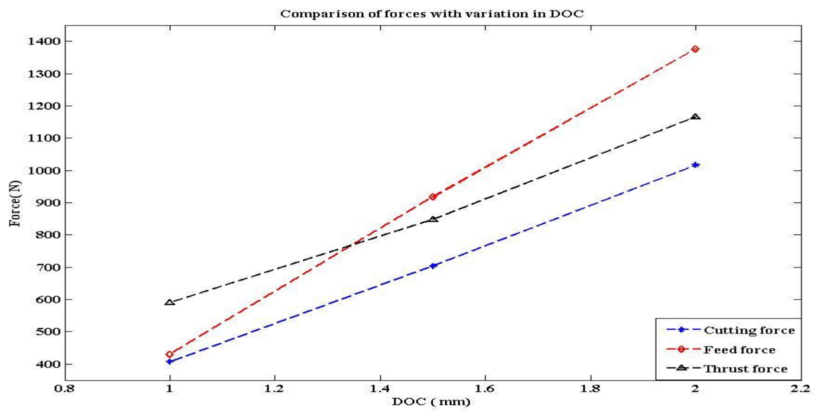

Figure.7 (c) Comparison of forces with variation in depth of cut

2. Conclusion

During the data analysis it was observed that the value of cutting forces increase with an increase in cutting speed, depth of cut and feed rate which is in agreement with available literature [9]. A 33% increase in cutting force values is observed with an increase of 42% in cutting speed. The increase in main cutting force values was less at smaller cutting speeds but at larger speed the increase in force values was large. Similarly at smaller feeds, the increase in cutting force is less than 10% but the increase of feed from 0.15 to 0.20 results an increase of 55% in feed force values. The variation in DOC was found to be the main influential factor for increasing in cutting force values. For DOC 1.0 mm to 1.5 mm, the increase in cutting force value was about 75% but for DOC 1.5 to 2.0 the percentage increase was less than 45%.

For feed force analysis it was observed that values of feed force were increased with increase in cutting speed. The behavior of increase of feed force with increase in cutting speed was found consistent as it was observed for cutting force values. At smaller speeds, the increase in feed force is less but higher increase was observed at higher speeds. The increase in feed force is about 45% with an increase of 100% in feed or feed rate. Again the increase in DOC was main factor for variation in feed force values. It was noted that for DOC change from 1.0 mm to 1.5 mm, the increase in feed force was more than 100 % but for DOC change from 1.5mm to 2.0mm, the percentage increase for feed force was 50% which was again consistent with the behavior of cutting forces values with increase in depth of cut [10].

The data analysis for thrust force values revealed that the thrust force increases with increase in cutting speed. An increase of 42% in cutting speed has resulted an increase of about 40% in thrust force values. This behavior was again consistent as it was observed in case of cutting force and feed force analysis. It was also observed that thrust force increase with an increase in feed or feed rate. The variation in thrust force is about 30 % with the variation of 100% in feed or feed rate. The variation in depth of cut resulted larger increase in thrust force values. It was noted that for change of depth of cut from 1.0mm to 2.0mm caused an increase of about 97% in thrust force values. The steep increase in component of forces at large depth of cut (1.5mm and 2.0 mm) is assumed to be due to excessive tool wear. This need to be further investigated, but exceeds the scope of this work. The trends observed corresponds well to the literature [11-12], which predicted an increase in component forces with increase in process parameters values of cutting speeds, feed and depth of cut.

Table 5 Summary of Results

S No.	CS m /min	Feed (f)	DOC (mm)	Cutting force (Fc) N	Feed Force (Ff) N	Thrust Force (Ft) N
1	350	0.15	1.0	469.5	532.4	650
2	400	0.15	1.0	500	625.9	745.3
3	450	0.15	1.0	521.7	665.1	809.5
4	500	0.15	1.0	626.1	821.6	884.9
5	350	0.10	1.0	406.8	430.4	591
6	350	0.15	1.0	469.5	500.4	650
7	350	0.20	1.0	626	610.3	750
8	350	0.10	1.0	406.8	430.4	591
9	350	0.10	1.5	704.2	918	847.9
10	350	0.10	2.0	1017	1377	1166

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