Mathematical Model to predict inter-relationship between cutting force and energy in machining

N Jain[1], P Mehra[2], N.Gupta[3]

[1,2,3-]MED, DTU, New Delhi
[3-]Corresponding author, Navritigupta@dce.ac.in

ABSTRACT

Manufacturing process comprises steps which are being followed to prepare a particular desired component, final product is obtained from some raw materials by using different manufacturing techniques. Machining process is meant to be a flexible process to get the required output of the work material. In the whole process, energy and cutting forces are output factors in the machining process. For manufacturing a product we first need to make a product design and select the material. In the paper a research method is proposed for the prediction and the modeling of cutting energy consumption, focusing on the relation between the energy consumption and various parameters of processes for cutting and optimization of these parameters such that we can cut down the energy required. Cutting force is the force required for dividing or removing a portion of a component or raw material to get the desired shape. In this paper, we are going to discuss these forces and energy inter-relationships. Various methods are suggested for increasing efficiency in machining processes which are taken into consideration and portrayed, Both the merits and demerits of old studies have been discussed and methods that can be useful are suggested in this paper for future research.

Keywords: Mathematics, Model, Machining, cutting force, energy, modeling, cutting parameters, optimization

1 Introduction

The demand of energy is increasing over the globe at an alarming rate causing several energy crises and environmental impacts. Industries have a huge contribution in energy consumption worldwide. According to the statistics 54% of the total energy delivered is consumed in industrial usage [1]. Machining operations are found to be important in the manufacturing sector because of the ability of manufacturing sharp tolerances and precise accuracy at the same time balancing costing in case of bulk production. Manufacturing industries are the major consumer among all the industries. They themselves consumes about 37.8 % of the total energy produced worldwide i.e. 70% of the energy consumed by all industries together [1]. The widely distributed and large energy consumption because of the low efficiency indicates that they have considerable energy saving potential [2]. It is found that the traditional processes of manufacturing consume more energy in comparison to the modern process like lasers and welding [3]. These processes are responsible for about 24% of the total emissions therefore along with the growth in the industries mandatory CO2 emissions reduction and energy efficiency policies should be implemented along with the encouraged use of renewable fuels and deployment of processes with low carbon routes [4]. Cutting forces are also responsible for the energy consumption. The use of cutting force more than the requirement results in poor surface finish, reduces the accuracy, leads to high power consumption and rise in temperature which overall results in lower efficiency of the whole process [5]. tools used for cutting are constantly subjected to thrust and stresses which act in opposite direction in the process although the edges involved in cutting are made sharp for processing the different kind of materials. Multiple efforts have been made in direction of optimizing the area of contact and angle of cutting to minimize the opposing force experienced by tool [6]. Specific cutting energy is also a crucial factor to lead manufacturing in a sustainable way. Specific cutting energy is the energy i.e. required to remove a unit volume of material, It also casts great impact on chip formation, cutting forces, tool wear and surface finish [7].

Therefore a need is there to implement the process and techniques that can be used to save energy and increase efficiency. by analysing the relation between force and energy and the relation of these factors individually with other cutting parameters like tool, speed etc. In this paper light all these suggestions, needs and possible benefits are discussed.

2 Literature review

J. Ma, [27] reviewed 3 types of machining operation I.e. machining, turning and drilling on basis of the cutting energy and cutting force required and improvement in efficiency of machine on basis of different parameters. N.Liu [28] analyzed the relation of specific cutting energy and finishing of the surface and suggested some optimizations for having better surface finish along with better machine efficiency. R. Schlosser, F. Klocke, D. Lung [29] studied the increase of energy consumption over time in various machining process his study was mainly based on drilling and suggested ways of improvement. StefanVelchev [30] reviewed for the specific energy in computer numerical control process. They also empirically derived the relation between the life of the tool and speed along with various suggested optimization. Carmita Camposeco-Negrete [31] reviewed the relation of energy I.e. used In processes and also showed the optimization and feed rate link along with some numerical figures and experimentation. Zhaohui Deng [32] analyzed the energy used in machining process along with it's impact on environment with multiple parameters. Qianqian Zhong, Renzhong Tang [33] studied the methods to calculate and find cutting forces and energy in various machining process and supported it with experimental data. Mukherjee I, Ray PK [34] reviewed better machining alternative along with connection between the energy and cost of process. Mainly was based on input and output parameters W.Polini [35] Studied the generation of chips and its separation from the workpiece by diamond mill along with the numerical figures for proving the study. NaohikoSugita [36] analyzed cooling of the tool and workpiece for the better efficiency and finishing with the help of coolants and changing the speed of process. Vincent A.Balogun [37] evaluated the energy required per unit volume relation with the angle between the tool and workpiece along with the energy required. Z.M.Bi [38] analyzed the different machining process in industries using multi point cutting tool for having better efficiency finishing. I.N Tansel [41] reviewed the relation between the cutting force and tool wear in milling process (micro-end) which was considered for two different metals. Tae-Yong Kim [42] introduced a cutting force controller for the milling process which could practically benefit commercial CNC machining centers. K.V.B.S Kalyan Kumar [43] investigated the impact of cryogenic cooling on tool wear and high frequency dynamic cutting forces which were produced during machining of stainless steel. Kunxian Qiu [44] analyzed the machining characteristics of honey comb core and introduced a model to predict the millng force under different factors. G.Totis [45] designed a dynamometer for triaxial cutting force measurement and for implementation at a milling-turning CNC machine tool. Andreas Albrecht [46] presented a method to increase the bandwidth of the indirect force sensor for the spindle dynamics and to measure the cutting forces produced by rotation of spindle shafts. Zhengyou Xie [47] developed a tool holder for cutting force measurement for measuring four-component cutting force in milling and drilling processes. Gi D. Kim [48] reviewed the indirect cutting force measurement in machining centre using feed motor current. Tamas Szecsi [49] proposed an approach for modelling cutting forces via artificial neural network and how it can be used in stimulation purposes in cutting tool condition monitoring systems. Chandra Nath [50] presented the impact of machining parameters in ultrasonic vibration cutting. AR Mavliutov [51] reviewed the most effective methods in optimising the cutting parameters in turning process for non-linear constraints. M.Balazinski[52]implemented and idea of a fuzzy decision support system (FDDS) based on the composition rule of interference by taking cutting processes and other factors into account and modifying cutting parameters.

3 Cutting force

cutting force can be considered as the force that acts as a opposite to the hold or resistance applied by the work itself when the work is undergoing some cutting process. The direction in which they proceed and with how much strength depends on the process that is being followed. Which are carried out in manufacturing machines. Optimization of the cutting processes can be done after measuring and analysing these dynamic cutting forces[8].

Cutting Force can be broadly divided into two types[9]:-

- Primary Type- In this type of cutting force the force is induced because of the motion of the tool used for cutting relatively to the work which is being machined. The direction of force is same as that of the motion of tool for cutting.
- Secondary Type- This type of force are found to be induced with correlation to the primary type of cutting force,for example,vibrations during the machining.

Cutting forces originating at cutting points

When the machining is of continuous type the cutting force can be seen to act along the velocity vector however transverse forces are perpendicular to the main plane for example torque and thrust in many cases [10].

3.1 Measurement

Measuring cutting forces is one of the most crucial and primary task for finding and initiating the control the process and selecting components like the tool .These forces helps in determining the dimension of the tool and also allows to study and predict the formation of the chips while processing.

There are multiple kinds of technologies that are being used for the measurement of the force but dynamometers are the one who are the most considerable and efficient among them. Dynamometers themselves can be of many types. The most famous one are the one who works on the principle of piezoelectric effect. There are mainly 3 main types of these meters. Among these 2 are the stationary type with different count of the direction in which they measure. The remaining one is rotating type which can measure force along 4 directions.[8] with the help of the cutting force we can also find out the temperature of the operation, wear in the tools along with the power needed along with other properties throughout these resources and technologies which can be useful for optimizing the process.

3.2 Need

Force is part of many empirical formulas and hence the first step toward using them will be finding the force thus in cutting processes the cutting force is found so that the producer can have the maximum output with good quality and cost efficient manner.

While machining the tool can undergo multiple kinds of stresses. The stresses mainly are thermal and mechanical however there can be some chemical stress also in a few cases. They all together affect the running life of the tool and its ability to cut. During the development of the new tools it's crucial to analyse its behaviour in different situations for process stability and to make it quick and efficient and that's where the need for the measurement as accurate as it could be is required so that the best outputs could be obtained. In the case of machines like computer numerical control the increase in the force can be made up to get utilized properly because of the more effective and smart processing of them.

Signals based on forces can also be introduced and used to have better and sustainable machining operations [39,40].

Results of high cutting force can lead to

Higher temperature in the cutting region along with the side effects like chips getting stuck to the work. The high force can lead to a great decrement in surface finish since the vibration also increases with cutting force . The tool life also gets affected by the speed of the and decreases if the force increases. Since the vibrations gets increased the noise and the difficulty in operation also increases. The increase in force can lead to failure of many components.

4 Energy Efficiency in Machining process

Energy which is required for machining operations is termed as the input, which is utilized a bit for useful work, while the remaining energy is transformed and gets wasted or radiated as heat. Machining processes utilize energy that is much lesser in ratio to the whole supplied energy by some external source, the major part is used for setting up the suitable conditions for performing the operation
Dividing the observations for energy utilized into multiple stages(level) can be very helpful. In this study, as shown in Fig(1)

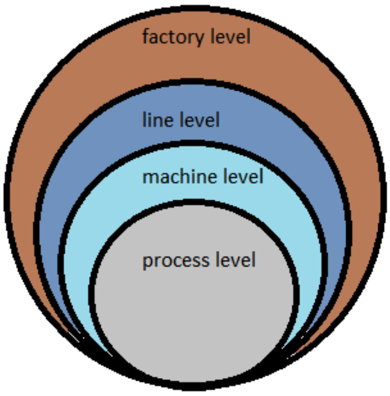

Figure 1: Energy Consumption at different levels

Although the recent studies [14] have indicated that the %age of energy spent at the processes themselves are small %age of the total spent energy.

Models based on analysis can help us to evaluate the result in both quantity and quality that can be analyzed and applied to a broad category. The energy that is going to be put in the processes is much smaller . The energy consumed at the peripherals can be easily reduced by the help of a proper and analysed selection of certain parameters which inturn is very high [11,12].
Hence the need arises for the selection of the process parameters more carefully as they are considered to be responsible for both the power that is being consumed and the output of the production unit.
In Conventional Processes Material removing processes is considered to be very important for the processes related to machining as most of the industries are meant to need high accuracy and precision along with some flexibility when undergoing multiple types of desired processes [13]. The turning and milling processes are presented for understanding. Definition for energy efficiency can be simply and appropriately considered as the ratio of the material removed to that of the energy supplied in total.

$$\mathbf{E_{fp}} = \frac{\mathbf{Volume}}{\mathbf{E_{supplied}}} \qquad \mathbf{(1)}$$

The index p in the Eqn(1)is for the process level. The relation between the energy efficiency and feed rate can be taken for understanding [14]. Certain types of material and keeping the parameters fixed except feed velocity and energy. We will find that they are directly proportional to each other the more and more fast the process is the more energy efficient it will be. As a general trend it is found to appear in many conventional processes.

Non conventional processes have gained a huge popularity over some years and most popular among them are lasers. Lasers can be used for many types of machining processes varying from welding and cutting to sintering also. There are many possible applications of laser [15]. Since lasers are not conventional energy efficiency will have to be changed according to the process. Whereas, in drilling use of laser can cut any shape slot and are not bound to circular slots only.

$$\mathbf{E_{fp}} = \frac{\mathbf{d_{cut}}}{\mathbf{E_{supplied}}} \qquad (2)$$

In the eqn(2) d_{cut} means the depth of the hole created . However in the case of lasers many times it becomes difficult to decide what will be the numerator of the empirical definition of efficiency. It can either be the depth of the cut or the volume that melted and so, it can be said that energy efficiency can be dependent on the process undergoing. Generally, multiple energy losses are found at the process levels because of the mechanism. The energy mainly gets lost due to reflection that can go upto 90 percent of the total energy supplied.
Defocusing of laser beams also occurs in many laser operations like drilling. The laser beam is focused with the help of an optical lens on the surface of the workpiece and when the surface advances because of melting the lens loses the focus and large amounts of energy get absorbed and waste on the adjoining surfaces. whereas in processes where the surface does not change its position no such kind of problem will be there.
Conduction of the energy in the work is also a factor for high energy losses as the most of the energy gets conducted in the form of thermal energy only small factors act for the purpose. These factors together permit a small amount of the laser energy to get used that is around 1 percent that of the energy supplied.

Thus, by improvising the methods whether conventional or not and the tools that are being used in process the wastage can be reduced and lots of energy can be saved increasing the efficiency[16].

5 Optimization in Cutting process

Optimization is a technique , process or method to optimize certain parameters like design,system or decision without violating some constraints.The major objective of optimization is to find maximum of a function by minimizing cost and maximizing output and efficiency.The idea of optimization helps in finding a solution of the problem or barrier from the model and validating it in real context
Machining is one of the most common , economical and feasible processes used in the sector of manufacturing industries. Optimization also holds some responsibility for the economic aspect and the ability to attain even higher standard of product finish. Energy that will be required to remove a certain volume of material is termed as the specific cutting energy. By which we can easily understand variables like energy utilized, machinability and optimized output[17].

5.1Types of cutting

• when the cutting edge is placed perpendicular to the direction of the cutting such type of cutting is considered orthogonal type and some of it's key features are stated below:
1. The edge of cutting is generally wider when compared to the width of the cut.
2. During its transformation into a chip, removal of no side spread layer is done.
3. Current cutting pass do not possess any influence on previous cutting pass rather it depends on various cutting parameters like ,the rotation speed ,axial feed etc.

• When the cutting edge is not placed perpendicular to the direction of the cutting such type of cutting is considered Oblique type

• Free cutting is also a type of the orthogonal/oblique cutting but involving only single cutting edge.

• Non- free cutting - In this cutting more than one cutting edges is found to be involved in cutting & promotes interaction of chip flows with the cutting edges[18].

The main feature of machining is to remove the chips from the work part with the help of cutting tools. Machining can be applied to a variety of work materials which includes solid metals, plastics and plastic composites, woods etc.

While performing cutting operation and removing material of the work part there is a need of relative motion between the cutting tools and work part. Conditions for cutting can be defined as a combination of the Speed,Feed and Depth of cut where primary motion known as the cutting speed ‘v’ secondary motion call the feed ‘f’ and Depth of cut below the main work surface of cutting tool is ‘d’.

5.2 Optimization Techniques

(i) Tool geometry

It has been found that due to an increase in metal cutting productivity there is an urge of more advancement in the cutting tools sector like new grades of the carbide , coatings and Polycrystalline cubic boron nitride. The advancement in this segment is an indisputably an important fact. Creation of new cutting materials is important but on other hand is a reactive task because it can end the progress.
Like, in case of heavy mechanical loads which cause tool breakage then we must select a suitable and tougher material for the tool and if tougher material doesn't exists, development comes to an end. Shape of deformed material can be changed in a positive way by changing the geometry of the tool. By customizing. Flake drizzle with a different tool geometry can change the amount and effect of chemical ,thermal ,and tribological loads in an active way.

(ii) Cutting Speed

When speed is increased ,forces doesn't changes on the other hand the power requirement rises , since the mathematical model for power utilized is stated as force times velocity. Research and practical experience have shown that the cutting force rises when cutting speed is less and decreases at higher cutting speed. When cutting force is increased at low speeds it results in the appearance of build-up edge which may be a sign of inappropriate cutting speed.
The fig (2) given below represents the expansion of tangential cutting force vs the cutting speed. The tangential cutting force component is nearly twice the other two. The cutting force first decreases then increases when we change speed from 35 to 450 meter/min.

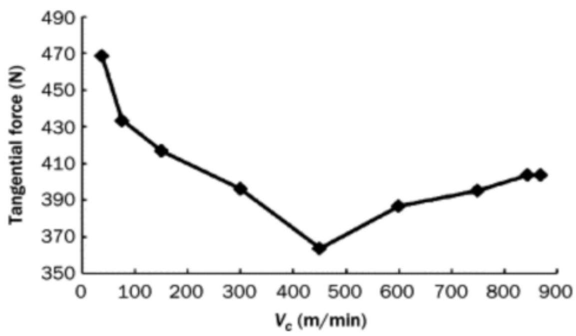

Fig. 2: Relation of tangential force and cutting speed

Johnson Cook’s eqn (3) which explains the relation of cutting forces with cutting speed by the balance between strain rate hardening and thermal softening.

$$\boldsymbol{\theta} = \left(\mathbf{A} + \mathbf{B}\cdot\boldsymbol{\varepsilon}_{\mathbf{p}}^{\mathbf{N}}\right)\left(\mathbf{1} - \mathbf{T}_{\mathbf{H}}^{\mathbf{M}}\right)\left[\mathbf{1} + \mathbf{c}\cdot\ln\left(\frac{\boldsymbol{\varepsilon'}_{\mathbf{p}}}{\boldsymbol{\varepsilon'}_{\mathbf{0}}}\right)\right] \quad (3)$$

In the primary drop of the curve presented above upto the point of 400-450 meters/min, the cutting force decreases with increase in cutting speed. In this scenario the thermal softening factor→ ($\mathbf{1 - T_H^M}$) predominates the equation(3).The heat generated during machining cannot be dissipated rapidly.So , there is decrease in the cutting forces due to low thermal conductivity of AISI303 steel which results in rise of temperature in the chip deformation areas which leads to thermal softening of the work material. In the other part of the curve the cutting forces increase with increase in cutting speed.

Strain hardening factor → $\left(\mathbf{1} + \mathbf{c}\cdot\ln\left(\frac{\boldsymbol{\varepsilon'}_{\mathbf{p}}}{\boldsymbol{\varepsilon'}_{\mathbf{0}}}\right)\right)$ predominates over softening factor.Strain rate is high at these cutting speeds ,nearly of order 10 micron.Now, strain rate factor predominates over thermal softening which results in increase of cutting forces.

So, Material changes its behaviour at 450m/min (cutting speed) during the shearing process.

6 Cutting force and energy relation

the force acting on tool can simply be resolved in two components:

1. Cutting force acts in the primary direction. The cutting force nearly equal to 70-80% of the total force applied which can be used to evaluate the power that will be needed for the completion of the operation functionally.

$$\mathbf{P = v \cdot f_{cutting}} \quad (4)$$

2. Thrust force acts along with the feed motion of the process and from this it becomes clear that the work due to this force becomes zero but can be utilized to evaluate the power for the required movement. The force can also be resolved along the shearing plane into shearing force (fshearing). The shearing force is the one that gets expend in the shearing of the piece worked on. Normal force (fnormal) is responsible for exerting a stress on the shear plane that will be compressive in nature[20].

Shear energy is the energy i.e. required to introduce deformation(plastic) in the shear zone. Shear force can become the basis for calculation and calculation for finding the force needed for cutting [21].

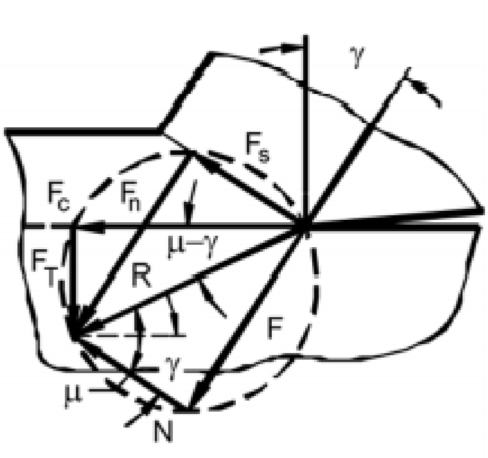

Figure 3: Force model proposed in 1941

Merchant and ernst in 1941 laid the eqn (5) that can be used to calculate the shear force [22].

$$F_{shearing} = \frac{Ty \cdot A_c}{\sin \varphi} \qquad (5)$$

where ty is the shear capacity of the work material, u is the angle of shear, Ac is shearing area.
Ernst and Merchant stated that the material (work-piece) gets deformed when the stress on that plane comes upto shear capacity of the material (work-piece). Then numbers of papers were published stating that they should be considered as shear stress (flow) i.e. higher than the yield capacity of the material (work-piece) that somehow depends on those condition of the process. However till now this can be considered relevant only to the nature and ability of material to oppose the cutting.

$$F_{cutting} = \frac{F_{shearing} \cos(\mu - \gamma)}{\cos(\varphi + \mu - \gamma)} \qquad (6)$$

By substituting $F_{shearing}$ from eqn(5) to eqn(6) we can get the value of $F_{cutting}$ which can be further used to determine the power/energy required.

$$F_{cutting} = \frac{Ty \cdot A_c \cos(\mu - \gamma)}{\sin \varphi \cos \varphi + \mu - \gamma} \qquad (7)$$

The regular practice has however shown that this model is no where even close to the reality. While determining Cutting force experimentally there are atleast two major kinds of problems faced.

1. The cutting force is not being able to determined with precision and reliability however such a thing is never accepted to the specialist in the related areas. A significant variation was found at maximum of 50% in measuring cutting forces even when the appropriate care is taken. In the condition where no such care is taken the results could be even worse[23].
2. Incapability of some dynamometers as some of them do not have proper and accurate calibration because the known literature is somewhat insufficient and don't have proper methodology for using dynamometers for this[26].

Since, this modal was found insufficient for practical calculations and the aim of this paper was to present an appropriate model for relation between cutting force and energy we will be looking at another approach.

6.1 Preferred model

On the basis of the definition processes based on the cutting of metals. energy partition model in metal cutting system the power in the cutting machining system is represented in eqn(8) [24,25].

$$\mathbf{P_{cutting}} = \mathbf{F_{cutting}} \cdot \mathbf{v} = P_d + P_{fc} + P_{fw} + P_{ns} + P_{mc} \qquad (8)$$

where

1. $\mathbf{P_d}$ is power used for deforming the layer which is being removed and with the help of chip compression ratio along with other parameters of deformation can be easily calculated.
2. $\mathbf{P_{fc}}$ is the power that is used to overcome the friction experienced at the contact surface of the tool and the chips calculated by using the average of the shear stress at the chip and tool junction, ultimate tensile strength of material, length of contact .
3. $\mathbf{P_{fw}}$ is The power used to overcome friction at the interface of tool-workpiece and is calculated by using shear strength of material, radius of cutting edge, length of cutting part that is in use, and rake angle

4. $\mathbf{P_{ns}}$ is power for introduction of new surfaces. The power which got utilized for the formation of new surface and is empirically by multiplying the energy required for making a shear plane and the numbers of shear plane that are made per second. Chip formation frequency can be used for determining how many planes that are shear getting induced in a unit time. The frequency is mainly dependent on the speed of cutting and the material (work).
5. $\mathbf{P_{mc}}$ is power for aligned and correlated effect of the cutting edge the minor ones, they sometimes take the role of major edge used in cutting like in thread cutting[23].

The eqn(8) can be represented as eqn(9) and by finding all the power factors individually much more accurate value of cutting force can be found

$$\mathbf{F_{cutting}} = \frac{\mathbf{P_d+P_{fc}+P_{fw}+P_{ns}+P_{mc}}}{\mathbf{v}} \qquad \textbf{(9)}$$

However the power that will be required for operation will not only be the summation of these power factors because Power mainly gets dissipated on the face of rake in the shear zone. Actual power i.e. required also depends on the efficiency of the machine E(%) and in eqn(10) is empirically shown [20].

$$\textbf{Power Needed} = \frac{P_{cutting}}{Efficiency} \times \mathbf{100} \qquad \textbf{(10)}$$

7 conclusion

In this paper we came across various facts starting from the need of optimization along with the data which proved that most of the energy produced gets utilised in manufacturing industries and the efficiency of these machines are very low. The measurement of cutting force had been also a matter of great concern as most of the errors arises due to inappropriate measures of cutting force and the discussed one of the most accurate methods possible so far. The need of measuring cutting force is important so that a proper relationship between the force and other parameters can be laid down for having better efficiency. Energy efficiency in these processes is also discussed and while looking into the conventional and non conventional methods of machining we found some major energy losses in these methods which are needed to be improved so that the better efficiency can be achieved like we discussed about the defocusing of the laser in which the loss of energy occurs since the laser looses it's focus because of the formation of the new surface however this can be solved easily by making a setup that will continuously change the focus of the laser and thus making process much more efficient. Then some optimization techniques are discussed based on parameters such as tool geometry and cutting speed along with some empirical relations. Finally models that predict the relationship of cutting force and energy has been taken where two types of model are discussed first model is a very old model and have a large room for error more than twice the expected value and a modern model made by observing multiple energy consumption and later relating it to efficiency to find the cutting force and thus it's the most accurate model (upto 95%) possible so far.

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