A Method to Determine Cutting Force Coefficients in Turning Using Mechanistic Approach

T. C. Bera, H. Manikandan, A. Bansal, and D. Nema

***Abstract*—During performing turning operation, cutting force plays a significant role in metal cutting process affecting tool-workpiece deflection, machine tool vibration and eventually part quality. The present research work aims to develop a mechanistic cutting force model that will be used in development of tool-workpiece flexible system of thin-wall machining. It also concentrates to study the mechanistic constants used in the force model in case of turning operation. The proposed model can be used for the reliable and accurate estimation of the cutting forces establishing relationship of various force components (cutting force and feed force) with uncut chip thickness. The accurate estimation of cutting force is required to improve thin-walled part accuracy by controlling the tool-workpiece deflection induced surface errors and tool-workpiece vibration.**

***Keywords*—Turning, cutting forces, cutting constants, uncut chip thickness.**

I. INTRODUCTION

Turning is one of the most common and versatile manufacturing processes used for various industries such as automobile, aerospace, biomedical sectors etc. During performing turning operation, cutting force plays a major role in metal cutting process affecting tool-workpiece deflection, machine tool vibration and eventually part quality. Therefore, accurate estimation of cutting forces in turning becomes an important factor to process characterization, process optimization and above all to enhance machining performance. Moreover, there are many situations like machining of thin-walled components where reliable prediction of cutting forces is essential for workpiece dimensional as well as geometrical accuracy. The precise and reliable estimation of cutting force largely depends on cutting force coefficients, the determination of which is the foundation of cutting force model. The proper identification and determination of cutting force coefficients have great influence in modeling of cutting forces [1].

There are several research work have been done regarding modeling of cutting forces in turning. They can be categorized broadly into three different groups. The first one is analytical approach which facilitates to establish mathematical relationship between cutting forces and various mechanical aspects such as cutting tool geometry, friction, process parameters, mechanical behaviour of workpiece materials etc. Earlier Merchant, Shaffer and Oxley attempted on developing analytical model for orthogonal and oblique cutting of metals [2]-[4]. Recently, Jawahir *et al.* [5] concentrates on understanding of the basic characteristics of machining processes using universal slip-line model for restricted contact tools. This kind of analytical models along with the theory of slip-lines is able to predict directly the cutting forces, friction, stresses, strains, strain rates and temperatures in the local cutting zone. Another one analytical force model is developed by Elbestawi *et al.* [6] for oblique cutting of metals based on chip formation and chip morphology. Kishawy *et al.* [7] proposed one more analytical force model for metal matrix composites by considering the effect of particle sizes on machining forces. More recently, Altintas *et al.* [8] studied on a unified mathematical model for prediction of chatter stability for multiple machining operations such as turning, boring, drilling and milling with defined cutting edges. Although analytical models are more generic in nature, predicted forces are not very accurate in oblique cutting operation due to determination of cutting constants by orthogonal cutting parameters that limits the use of analytical models in various cutting processes.

The second one is numerical approach which deals with fundamental mechanics and physics of metal cutting concentrating tool tip contact zone and interaction of tool-workpiece pair [9], [10]. Recently, Altintas *et al.* [11] developed a simulation model of metal cutting process in a more generalized way using ALE (Arbitrary Lagrangian Eulerian) method. Later on Schermann *et al.* [12] studied on metal cutting process including coupling process and dynamic behaviour of the machine tool using finite element method (FEM). More recently, Ozel *et al.* [13] concentrated on 3D machining of Inconel 718 incorporating large elastic-plastic deformation, high temperature change and high strain rates. Although this type of model has lot of advantages, but they are limited to simple orthogonal and oblique cutting. Computational cost is also very high in case of numerical models.

The third one is mechanistic approach which is semi-analytical in nature dealing with a series of experiments between machining parameters and cutting forces. This approach takes into account the geometrical characteristic of metal cutting process and empirical cutting constants obtained from experiments for a specific tool-workpiece pair. Although mechanistic model is very specific for a tool-workpiece pair, the calibration time of cutting constant is very short and it incorporates complex tool geometry into metal cutting process. It has enough capability to predict accurate cutting forces for a wide range of cutting conditions subject to a tool-workpiece pair. Therefore, an attempt has

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been made in the present work to identify and determine the specific cutting constants for estimating accurate cutting forces for turning of Al 6351 T6 material.

Henceforth, this paper is organized as follows: In Section II, the process geometry model of turning is described. The Section III deals with the proposed mechanistic approach in turning. It is described to identify and determine the cutting constants for cutting force model of turning. Using the cutting constant, cutting force model is developed and described in detail. Section IV deals with experimental setup and machining conditions chosen for the present research work. Section V illustrates the results and discussions of the proposed model. Finally, conclusion based on the present study has been summarized in Section VI.

II. Process Geometry of Turning

Turning is a continuous metal cutting process in which a non-rotary cutting tool moves linearly parallel to job axis while workpiece rotates about its own axis. Generally, this operation is carried out on lathe machine tool. The machined surface of workpiece in turning depends on three important factors namely tool geometry, workpiece geometry and relative motion and interaction between tool and workpiece. The rotational motion of job, linear motion of cutting tool and their complex interactions define the final shape of the machined components. It is well known that to perform turning operation basic input process parameters are cutting speed, nominal feed rate and nominal depth of cut. Final shape of machined surface will be produced based on relative motion and interaction of these input process parameters and geometry of complex cutting tool. Therefore, it is essential to study process geometry of turning and process geometry variables such as actual feed per revolution, actual depth of cut and peripheral cutting speed of workpiece.

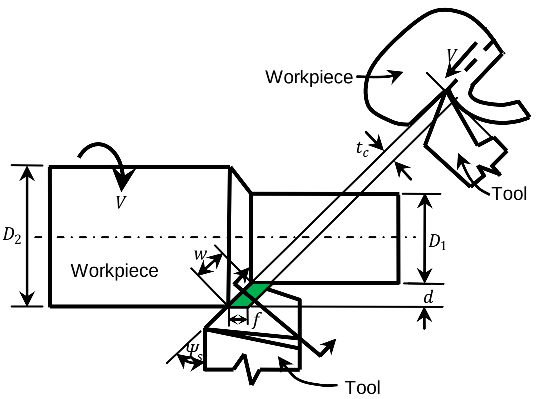

Fig. 1. Process geometry of turning.

The Fig. 1 shows a schematic representation of turning process describing various process geometry variables such as actual feed per revolution, actual depth of cut and peripheral cutting speed of workpiece.

The process geometry variables are actual or true feed per revolution, actual or true depth of cut and peripheral cutting speed. These variables are determined based on the cutting parameters used in machining process such as spindle rpm, nominal feed rate and nominal depth of cut. Cutting speed can be calculated using Eq. (1).

$$V = \pi D_1 N \tag{1}$$

where V is cutting speed in mm/min, D_1 is final diameter of the workpiece, N is spindle rpm. The nominal feed per revolution **(** f **)** can be computed using Eq. (2).

$$f = \frac{f_r}{N} \tag{2}$$

where f_r is nominal feed rate in mm/min. Nominal depth of cut **(**d**)** can be determined using Eq. (3).

$$d = \frac{(D_2 - D_1)}{2} \tag{3}$$

where D_2 and D_1 are initial and final diameter of the workpiece in mm respectively. From Fig. 2, it is seen that both nominal feed and nominal depth of cut are dependent on side cutting edge angle (Ψ_s) that can be known from the cutting tool nomenclature. Therefore, actual uncut chip thickness (t_c) can be calculated from the Eq. (4) as shown below.

$$t_c = f\cos(\psi_s) \tag{4}$$

In similar manner, actual depth of cut (w) can be determined using Eq. (5).

$$w = \frac{d}{\cos(\psi_s)} \tag{5}$$

Therefore, from the Fig. 2, it can be seen that effective cutting area (A_c) is the product of actual uncut chip thickness (t_c) and actual depth of cut (w). From the Fig. 2, it can also be seen that the effective cutting area is also product of nominal feed per revolution and nominal depth of cut and it can easily be calculated using Eq. (6).

$$A_c = t_c . w = f_d \tag{6}$$

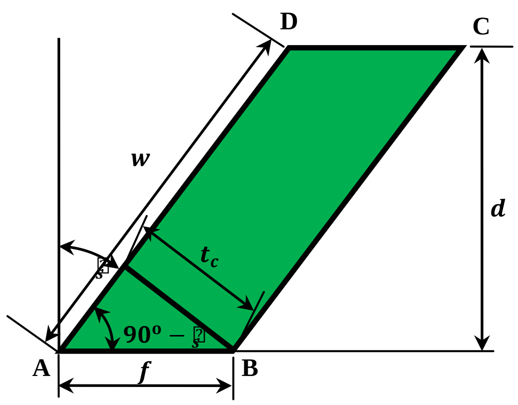

Fig. 2. Effective cutting area in turning.

III. Mechanistic Approach in Turning

The mechanistic approach can be defined as a combination of both analytical as well as experimental approaches. In mechanistic approach, instantaneous uncut chip thickness is determined analytically from the process geometry model considering the interactions of tool and workpiece. The cutting coefficients or cutting constants are determined experimentally for various values of uncut chip thickness keeping depth of cut same. Later on, empirical relationships are established among geometrical parameters obtained from the process geometry of turning.

Mechanistic model considers that cutting force is proportional to actual effective cutting area. The constant of proportionality is known as cutting force coefficient or cutting constant or cutting pressure constant. The cutting force constant depends on several factors such as tool and workpiece material, tool geometry. Due to these significant factors, cutting force constant is difficult to quantify in many cases. Therefore, a reliable method is required to identify and determine the cutting pressure constant. A direct calibration method is used to determine the same. A series of machining tests are conducted to establish the cutting force coefficients over a range of cutting conditions. Mechanistic model considers that cutting force is proportional to the chip cross-sectional area or effective cutting area. The constant of proportionality is known as cutting force coefficient or cutting constant or cutting pressure constant. The cutting force constant depends on several factors such as tool and workpiece material, tool geometry. Due to these significant factors, cutting constant is difficult to quantify in many cases. Therefore, a reliable method is required to identify and determine the cutting constant. A direct calibration method is used to determine the same. A series of machining tests are conducted to establish the cutting force coefficients over a range of cutting conditions [14]. The cutting constant is directly related to the mechanics of metal cutting and tool-workpiece interaction which is shown in the Fig. 1. To obtain the magnitude of cutting force, the cutting constant is multiplied with effective area of cutting. This effective cutting area depends on actual radial depth of cut and actual uncut chip thickness. Cutting force component and feed force component can be obtained from the following equations.

$$F_C = K_c.A_c \quad (7)$$

$$F_F = K_f.A_c \quad (8)$$

where F_C is cutting force component and F_F is feed force component respectively. K_c and K_f are the cutting constants for cutting force and feed force components. These cutting constants are also known as cutting force coefficients or cutting pressure constants. Many researchers [1]-[3] are expressed the mechanistic constants as non-linear function of uncut chip thickness in more general form given below:

$$K_c = K_C(t_c)^p \quad (9)$$

$$K_f = K_F(t_c)^q \quad (10)$$

where K_C and K_F are specific constant for cutting force and feed force components. p and q are constants used in power function.

IV. Experimental Setup

All machining experiments are carried out on a conventional lathe equipped with piezoelectric dynamometer (Kistler) based cutting force measurement setup as shown in Fig. 3.

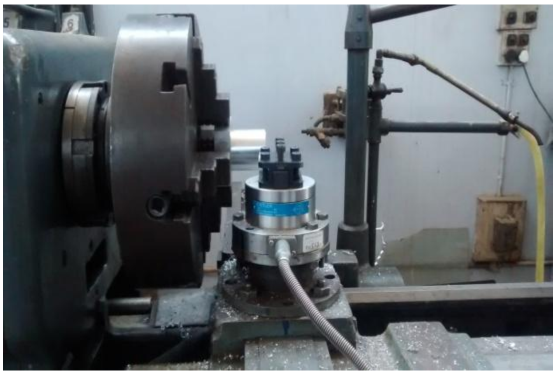

Fig. 3. Experimental setup.

The workpiece material and cutting tool selected during machining experiments are Aluminum 6351-T6 and carbide insert (TNMG 16 04 08 CQ) respectively. The pre-machined hollow cylindrical workpiece is produced from rectangular components using roughing and semi-finishing operation prior to final cut. The one end of cylindrical workpiece is attached to the square base mounted on four jaw chuck and other end is free as shown in Fig. 4.

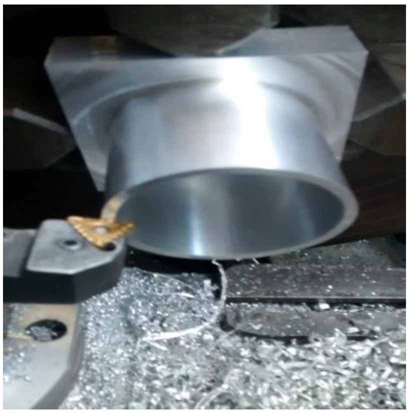

Fig. 4. The workpiece mounted on four jaw chuck.

The length of cylindrical workpiece is 75 mm from the to surface of the square base having dimensions of 75 mm × 75 mm × 25 mm. The outer and inner diameter of the workpiece is 55 mm and 49 mm respectively and thickness is 3 mm. Free orthogonal cutting is performed for each machining experiment for the duration of 20 seconds and cutting forces are measured by piezoelectric dynamometer and recorded the same using DAQ system. Later on, DYNOWARE software was used to process the recorded data to obtain average cutting force and feed force components. Other machining conditions are listed in the Table I.

TABLE I: Cutting Conditions

Workpiece geometry	Hollow cylinder
Outer diameter (mm)	55
Inner diameter (mm)	49
Wall thickness (mm)	3
Nominal depth of cut (mm)	3
Feed per revolution (mm/rev.)	0.04, 0.08, 0.12, 0.16
Feed rate (mm/min)	6, 15, 30, 51
Spindle rpm	147, 190, 247, 320
Cutting speed (m/min)	25.39, 32.83, 42.68, 55.29
Cutting tool type	Carbide insert
Cutting type	Orthogonal cutting without coolant

Each experiment is performed on the same experimental setup by varying feed rate keeping depth of cut and cutting speed constant. According to mechanistic approach, empirical relationships are established among geometrical parameters obtained from the process geometry of turning. Depending on the machining conditions, effective cutting area has been calculated based on actual uncut chip thickness and actual depth of cut. The magnitudes of cutting forces are collected from the recorded data obtained from DYNOWARE commercial package for the given machining condition. Later on, cutting constants are computed for given machining conditions for a specific tool-workpiece pair. The detailed discussions about cutting constants and their dependency on process geometry variables have been presented in the following section.

V. Results and Discussions

This section analyzes the behavioral characteristics of cutting constants for given tool-workpiece pair and their dependency on uncut chip thickness. The values of cutting constants considered as dependent variables have been plotted against the uncut chip thickness as independent variable. The Fig. 5 represents the graph for cutting constant (K_c) for cutting force component versus uncut chip thickness.

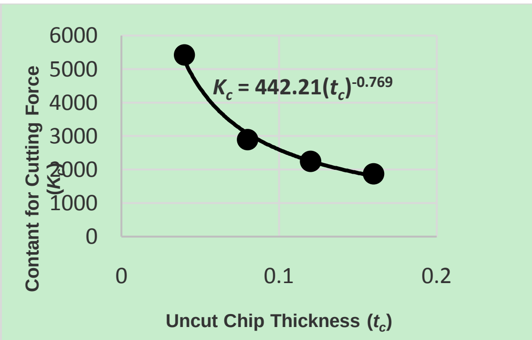

Fig. 5. Graph for K_c versus uncut chip thickness at 147 rpm.

From the Fig. 5, it is clearly observed that the magnitude of the cutting constant (K_c) decreases with increase of uncut chip thickness. As uncut chip thickness is function of feed rate, cutting constant (K_c) is also dependent on feed rate. When feed per revolution increases the sheared uncut chip thickness increases because the metal resists the rupture more and requires larger efforts for chip removal. Hence, the cutting force component also increases as the feed rate increases.

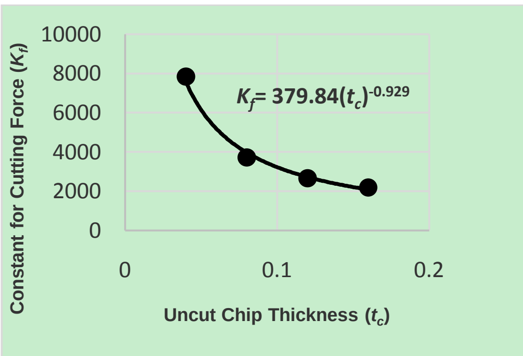

Fig. 6. Graph for K_f versus uncut chip thickness at 147 rpm.

From the Fig. 6, it can clearly be examined that the nature of the graph for cutting constant of feed force component versus uncut chip thickness is almost same although its magnitude is different. The magnitude of the cutting constant (K_f) decreases with increase of uncut chip thickness. It can be justified that uncut chip thickness is function of feed rate. Therefore, cutting constant (K_f) is also dependent on feed rate. When feed rate is more the uncut chip thickness will be more because the metal resists the more rupture of shear zone which requires larger efforts to remove chip from the cutting zone. Hence, the feed force also increases because of larger effective cutting area. The calculated values of specific constants (K_C, K_F) are given in the Table II.

TABLE II: The Values of Specific Constants

SL No.	RPM	K_C	p	K_F	q
1	147	442.21	-0.769	379.84	-0.929
2	190	389.65	-0.777	377.34	-0.879
3	247	395.20	-0.677	381.26	-0.808
4	320	366.74	-0.650	355.73	-0.773

VI. Conclusions

In the present study, mechanistic cutting constants are identified and determined for given pair of tool-workpiece combination. The relationship between cutting constants and uncut chip thickness is successfully established to develop cutting force model. A more generic relationship between mechanistic constant and uncut chip thickness has been established in non-linear form within an acceptable range of error for the specific range of cutting speeds. The accurate value of cutting constants are essential for precise and reliable estimation of cutting force. Later on, these cutting force values will be used to process control, process characterization and to enhance machining performance for machining of thin-walled components by developing tool-workpiece flexible system.

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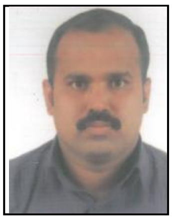

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