Modeling and Analysis of Effect of Cutting Parameters on Product Quality in Dry Turning Operation of Mild Steel using Carbide & High Speed Steel Tool

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***Abstract*-Material removal plays an important role in finishing part/components. Information about cutting forces during machining can be considered as an index to evaluate the machinability of a material while considering the amount of heat in the cutting area, tool wear, quality of machined surface and accuracy of the part. In the present study, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces (feed force, thrust force) and surface roughness for turning of mild steel using high speed steel (HSS) and carbide tool. Experiments were conducted on a precision lathe (HMT) and the influence of cutting parameters was studied using analysis of variance (ANOVA) based on adjusted approach. The results showed that with increasing the depth of cut and feed for a given RPM, cutting force increases. With the same cutting speed and depth of cut, the force variation is significant in both high speed steel (HSS) and carbide tool. The minimum cutting force requirement for machining the component (theoretically) is almost same with that of experimental value obtained by dynamometer.**

Key words- Feed rate, depth of cut, cutting force, dynamometer, strain gauge.

I. INTRODUCTION

The process of metal removal has been a subject of research of many scientist and engineers. With the advent in technology, progress has been made for cutting force-measurements. The cutting forces developed in machining operations may be estimated indirectly by obtaining the power consumed or directly from metal cutting dynamometers (mechanical, hydraulic, and pneumatic or electro mechanical type) [1]. Due to the complexity of the metal cutting process, theoretical calculation of the forces necessitated for removing the chip from work piece. The accuracy of the empirical equations used to estimate cutting forces may be validated by the experiments [2]. Therefore, design criteria of the several machine tool dynamometers were considered to get some collected/compacted ideas. Knowledge of cutting forces is essential to machine tool builders in calculating power requirements and frame rigidity. At the design of tool that have sufficient strength capable to remove chip at the desired quantity from the work piece and to calculate power of tool driver system, cutting forces acting on the tool must be measured [3].

A. Cutting Force Components and their Significances

The single point cutting tools being used for turning, shaping, planing, slotting, boring etc. are characterized by having only one cutting force during machining. But that force is resolved into two or three components for ease of analysis and exploitation [4]. Figure 1 visualizes how the single cutting force in turning is resolved into three components along the three orthogonal directions; X, Y and Z.

These three components are:

Cutting force (Ft) acts in tangential direction. It is also called power component as it being acting along and being multiplied by cutting speed (VC) decides cutting power (PZ.VC) consumption.

Feed Force (Fa) acts in the direction of feed (axial direction). Generally, this force is small in magnitude but is responsible for causing dimensional inaccuracy and vibration.

Thrust Force (Fr) acts in radial direction. This force is least harmful and hence least significant.

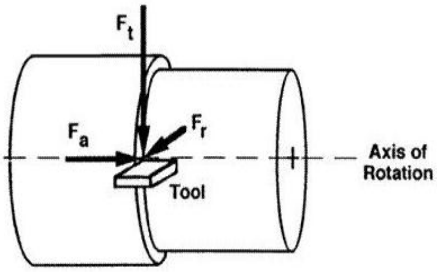

Fig. 1: Cutting forces during turning

B.Need for determination of the cutting forces

Cutting force determination is required for:

- Estimation of cutting power consumption, which also enables selection of the power source(s) during design of the machine tools
- Structural design of the machine-fixture- tool system

- Evaluation of role of the various machining parameters (Speed (VC), feed (f), depth of cut (t), tool-material and geometry, environment- cutting fluid) on cutting forces.
- Study of behavior and machinability characterization of the work materials.
- Condition monitoring of the cutting tools and machine tools.

II. LITERATURE REVIEW

Rodrigues et al. [5] studied the effect of speed, feed and depth of cut on surface roughness (Ra) and cutting force (Fc) in turning mild steel using high speed steel cutting tool. Experiments were conducted on a precision center lathe and the influence of cutting parameters was studied using analysis of variance (ANOVA) based on adjusted approach. Linear regression equation of cutting force has revealed that feed, depth of cut, and the interaction of feed and depth of cut significantly influenced the variance. Senthil Kumar, et al. [6] found that Alumina-based ceramic cutting tools can be operated at higher cutting speeds than carbide and cermet tools. This results in increased metal removal rates and productivity. In this study, optimization of machining parameters on machining S.G. iron (ASTM A536 60-40-18) using alumina based ceramic cutting tools is presented. Yaldiz and Unsacar [7] researched about designing, developing and testing of a turning dynamometer for cutting force measurement. In his study, turning dynamometer that can measure static and dynamic cutting forces by using strain gauge and piezo-electric accelerometer respectively has been designed and developed. Hari Singh and Pradeep Kumar [8] determined optimizing feed force for turned parts through the Taguchi technique. The objective of the paper is to obtain an optimal setting of turning process parameters (cutting speed, feed rate and depth of cut) resulting in an optimal value of the feed force when machining EN24 steel with TiC-coated tungsten-carbide inserts. The effects of the selected turning process parameters on feed force and the subsequent optimal settings of the parameters have been accomplished using Taguchi’s parameter design approach. Sedat Karabay [9] analyzed and studied about electro-mechanical transducers and arrangement for measurement of strains due to metal cutting forces acting on dynamometers. In this paper, the elastic members which are the most important parts of dynamometers utilizing electric strain gages were analyzed to detect the suitable place to cement gages on them activated by compression and tension stresses due to cutting forces. Augustina, et al [10] have analyzed the influence of the cutting parameters (feed rate, spindle speed and depth of cut) and type of tool (nose radius on the cutting forces. They have affirmed the cutting component of the forces (Fm) is more sensible to the variations of the cutting conditions than the rest of components analyzed in this study. Furthermore, tools with nose radius of 0.4 and of 0.8 mm have similar behavior from the point of view of the forces generated during the machining at low feed rates. Rao et al, [11] have done the experiment to measured the cutting force and surface roughness while working with tool made of ceramic with an Al_2O_3+TiC matrix (KY1615)and the work material of AISI 1050 steel (hardness of 484 HV). Experiments were conducted using Johnford TC35 Industrial type of CNC lathe. The results have indicated that, feed rate which has significant influence both on cutting force as well as surface roughness. Depth of cut has a significant influence on cutting force, but has an insignificant influence on surface roughness.

III. EXPERIMENTAL SETUP

Figure 2 shows the schematic representation of the experimental setup used for cutting force measurement using a piezo-electric type dynamometer Experimental setup consists of precision lathe (HMT), workpiece, dynamometer (KISTLER 9272), charge amplifier (5070A), data acquisition system. Workpiece is mounted in the chuck of the lathe headstock. The tool dynamometer is mounted on the carriage at the place of tool holder. The tool holder is mounted on the dynamometer. Output of the dynamometer is amplified by charge amplifier and data are collected in the PC by using data acquisition system Dynoware.

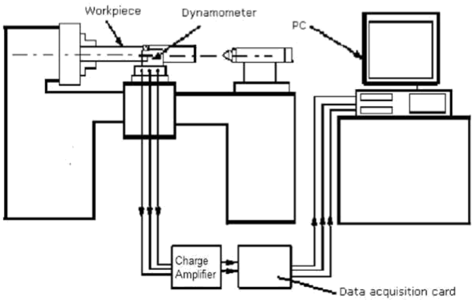

Fig. 2: Experimental setup

A. Experimental Observations

The Lathe Tool Dynamometer is initially set to zero reading. Three different types of tests were done to measure the cutting force on the cutting tool. The first test consisted of keeping the feed and depth of cut same and changing the velocity of the lathe. Three different speeds were used for this test. The second test consists of varying the feed and keeping the velocity and depth of cut the same. Three different feed rates are used for this test. The third test consists of varying the depth of cut while keeping the velocity and feed same. Three different depth of cut are used for this test. For each set data are acquired and documented (Table 1 and 2).

IV.RESULTS AND DISCUSSION

The present study contains the observations for both H.S.S. and carbide tool and the necessary calculations to compare cutting force with theoretical value. Graph was plotted to see the effect of cutting force on feed rate and depth of cut.

Table 1: Cutting force using carbide tool

Sl No	Rpm	Feed Rate in mm/rev	Depth of cut in mm	Cutting Force (Fz) in N	Theo. Cutting Force
1	68	0.52	1.0	837	735.73
2	88	0.52	1.0	841	
3	114	0.52	1.0	761	
4	68	0.72	1.0	1006	1018.706
5	88	0.72	1.0	969	
6	114	0.72	1.0	931	
7	68	0.92	1.0	1296	1301.68
8	88	0.92	1.0	1283	
9	114	0.92	1.0	1175	
10	68	0.52	1.5	1313	1103.598
11	88	0.52	1.5	1296	
12	114	0.52	1.5	1212	
13	68	0.72	1.5	1505	1528.06
14	88	0.72	1.5	1450	
15	114	0.72	1.5	1395	
16	68	0.92	1.5	1600	1952.52
17	88	0.92	1.5	1603	
18	114	0.92	1.5	1577	
19	68	0.52	2.0	1641	1471.465
20	88	0.52	2.0	1595	
21	114	0.52	2.0	1492	
22	68	0.72	2.0	1972	2037.413
23	88	0.72	2.0	1913	
24	114	0.72	2.0	1801	
25	68	0.92	2.0	2322	2603.361
26	88	0.92	2.0	2070	
27	114	0.92	2.0	2187	

A.Effect of depth of cut on the cutting force (for carbide tool)

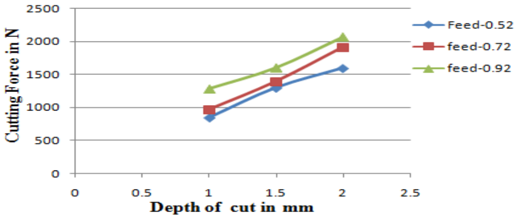

Fig. 5.2 Cutting Force Vs Depth of Cut for 88 RPM

At 68, 88 and 114 RPM the effect of depth of cut on cutting force is observed and at constant cutting speed and feed cutting force tends to increase (Fig. 5.2 shown, others similar). At higher depth of cut material removal rate is increased, which contributes to increase in the cutting force. With the same cutting speed and depth of cut in both HSS and carbide tool, it has been observed that the force variation is significant.

B.Effect of feed rate on the cutting force (for carbide tool)

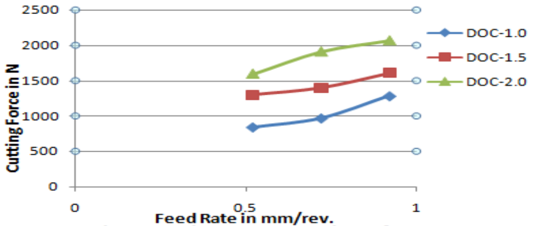

Fig. 5.5 Cutting Force Vs Feed Rate for 88 RPM

At 68, 88 and 114 RPM the effect of depth of cut on cutting force is that the cutting force increases linearly with increase of feed rate at constant cutting speed and depth of cut observed (Fig. 5.5 shown). The increasing trend of cutting force with respect to the feed rate is observed similar for HSS and carbide tool with turning of mild steel.

C.Effect of depth of cut on the cutting force (for HSS tool)

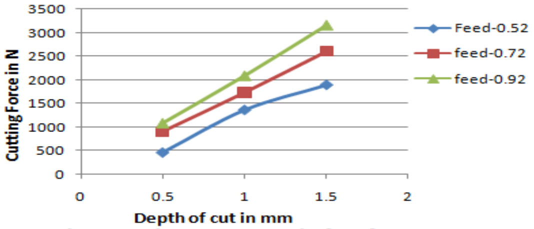

Fig. 5.8 Cutting Force Vs Depth of Cut for 88 RPM

At the above cutting speeds, when tool feed rate is increased, more resistance to tool is provided by the work material in the cutting direction which leads to higher machining force (Fig. 5.8 shown).

D.Effect of feed rate on the cutting force (for HSS tool)

Experimenting at the above speeds, when tool feed rate is increased, more resistance to tool is provided by the work material in the cutting direction which leads to higher machining force (Fig. 5.11 shown).

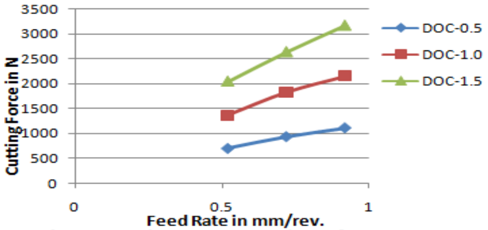

Fig. 5.11 Cutting Force Vs Feed Rate for 88 RPM

Table 2: Cutting force using HSS tool

Sl No	Rpm	Feed Rate in mm/rev	Depth of cut in mm	Cutting Force (Fz) in N	Theo. Cutting Force
1	68	0.52	0.5	722	355.32
2	88	0.52	0.5	696	
3	114	0.52	0.5	466	
4	68	0.72	0.5	914	491.992
5	88	0.72	0.5	936	
6	114	0.72	0.5	915	
7	68	0.92	0.5	1136	628.65
8	88	0.92	0.5	1115	
9	114	0.92	0.5	1084	
10	68	0.52	1.0	1453	710.656
11	88	0.52	1.0	1365	
12	114	0.52	1.0	1307	
13	68	0.72	1.0	1857	983.98
14	88	0.72	1.0	1830	
15	114	0.72	1.0	1733	
16	68	0.92	1.0	2233	1257.31
17	88	0.92	1.0	2153	
18	114	0.92	1.0	2087	
19	68	0.52	1.5	2102	1065.98
20	88	0.52	1.5	2045	
21	114	0.52	1.5	1896	
22	68	0.72	1.5	2681	1475.97
23	88	0.72	1.5	2638	
24	114	0.72	1.5	2595	
25	68	0.92	1.5	3199	1885.97
26	88	0.92	1.5	3170	
27	114	0.92	1.5	3156	

E.Effect of speed on the cutting force (for HSS and carbide tool)

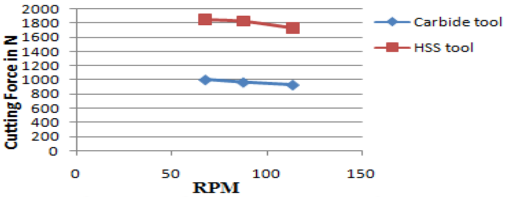

Fig. 5.14 Cutting Force Vs RPM Keeping Feed = 0.72mm/rev and DOC =1mm

It has been observed that with the same feed and depth of cut, the machining force requirement decreases with increase in RPM both in HSS and carbide tool. The effect of speed on cutting force is observed (Fig. 5.14 shown) that there is no considerable variation in cutting force at different speed.

F.Comparison of forces obtained from analytical method and experimental method for HSS tool

Tool used: Coated carbide
Tool signature:-7° - -6° - 7° - 7° - 5° - -5° - 1mm

1. Brinnel Hardness Number of material = 220.72kgf/mm^2
2. Dynamic Shear Stress of mild steel, τ_s= 0.186 X BHN kgf/mm^2
3. FOS for rough machining = 10
4. Shank of tool section is square.
5. Tool over hung is 30mm.
6. Chip reduction co-efficient is 2.5 for rough machining.

In ORS of nomenclature,
Φ = approach angle = 90° - Φ_s= 90°-(-5)=95°

Inclination angle (λ) :
tan λ = tan γ_y . sin Φ – tan γ_x. cos Φ = tan (-7). Sin 95 – tan (-7) . cos 95 = -0.131
Inclination angle, λ = tan^{-1} (-0.131) = -7.46°

Orthogonal Rake Angle :
tan γ_o = tan γ_y . cos Φ + tan γ_x. sin Φ = tan (-7). cos 95 – tan (-7) . sin 95 = 0.0214
Orthogonal Rake angle, γ_y = tan^{-1} (0.0214) =1.225°

Orthogonal Clearance Angle :
Cot α_o= cot α_x .sin Φ + cot α_y . cos Φ = cot 7. Sin 95 + cot 7. Cos 95 = 7.4035 Orthogonal clearance angle, α_o = cot^{-1} (7.4035) = 0.0121°
Tanγ_n = tan γ_o . cos λ=0.0214 . cos (-7.463) =0.0211

Effective rake angle :
Sin γ_e = cos^2 λ . Sin γ_n + Sin^2 λ = cos^2 (-7.463) . Sin (1.2144) + Sin^2(-7.463)=0.0375
Effective rake angle, γ_e = sin^{-1} (0.0375) = 2.149°

Effective shear angle :
tan β_e = (cos γ_e) / (ξ – sin γ_e) = (cos 2.149) / (2.5 – sin 2.149)=0.4057
Effective shear angle, β_e = 22.08°

Shear force :
τ_s= 0.74 x $\sigma u^{\varepsilon 0.6\Delta}$
τ_s = 0.186 x BHN kgf/mm^2 = 0.186 x 220.72 x 10 = 408.332N/mm^2

Sample calculation
Selecting depth of cut 2mm and feed 0.52 mm/rev, we have

1. Pz = τ_s S_o t (cot β_e+ 1) = 408.332 x0.52x2x(cot 22.08+1) = 1471.465N
2. Pxy = τ_s S_o t (cot β_e - 1) = 408.332 x0.52x2x(cot 22.08-1) = 622.134 N
3. Px = P_{xy} sin (Φ + λ) = 622.134 x sin (95-7.463) = 621.559 N (max)
4. Px = P_{xy} sin (Φ - λ) = 622.134 x sin (95+7.463) = 607.47 N (min)
5. Py = P_{xy} cos (Φ + λ) = 622.134 x cos (95-7.463) = 26.735 N (max)
6. Py = P_{xy} cos (Φ - λ) = 622.134 x cos (95+7.463) = -134.26 N (min)

Similarly, for all the other observations cutting force Pz was calculated theoretically and was noted down as shown in Table - 1.

G.Comparison of forces obtained from analytical method and experimental method for HSS tool

Tool used - High Speed Steel (H.S.S.)
Tool signature - 7° - 10° - 7° - 7° - 9° - 15° - 1mm

1. Brinnel Hardness Number of material = 220.72 kgf/mm^2
2. Dynamic Shear Stress of mild steel, τ_s = 0.186 X BHN kgf/mm^2

3. FOS for rough machining = 10
4. Shank of tool section is square.
5. Tool over hung is 30mm.
6. Chip reduction co-efficient is 2.5 for rough machining

In ORS of nomenclature,
Φ = approach angle = $90° - \Phi_s = 90° - (15) = 75°$

Inclination angle (λ) :
$\tan\lambda = \tan\gamma_y \cdot \sin\Phi - \tan\gamma_x \cdot \cos\Phi = \tan(7) \cdot \text{Sin } 75 - \tan(10) \cdot \cos 75 = 0.073$
Inclination angle, $\lambda = \tan^{-1}(0.073) = 4.175°$

Orthogonal Rake Angle :
$\tan\gamma_0 = \tan\gamma_y \cdot \cos\Phi + \tan\gamma_x \cdot \sin\Phi = \tan(7) \cdot \cos 75 - \tan(10) \cdot \sin 75 = 0.202$
Orthogonal Rake angle, $\gamma_0 = \tan^{-1}(0.202) = 11.42°$

Orthogonal Clearance Angle :
$\text{Cot } \alpha_0 = \cot\alpha_x \cdot \sin\Phi + \cot\alpha_y \cdot \cos\Phi = \cot 7 \cdot \text{Sin } 75 + \cot 7 \cdot \text{Cos } 75 = 9.9747$
Orthogonal clearance angle, $\alpha_0 = \cot^{-1}(9.9747) = 0.01186°$
$\tan\gamma_n = \tan\gamma_0 \cdot \cos\lambda = 0.0214 \cdot \cos(4.175) = 11.387°$

Effective rake angle :
$\text{Sin } \gamma_e = \cos^2\lambda \cdot \text{Sin } \gamma_n + \text{Sin}^2 \lambda = \cos^2(4.175) \cdot \text{Sin }(11.387) + \text{Sin}^2(4.175) = 0.2016$
Effective rake angle, $\gamma_e = \sin^{-1}(0.2016) = 11.63°$

Effective shear angle :
$\tan\beta_e = (\cos\gamma_e) / (\xi - \sin\gamma_e) = (\cos 11.63) / (2.5 - \sin 11.63) = 0.4261$
Effective shear angle, $\beta_e = 23.078°$

Shear force :
$\tau_s = 0.74 \text{ x } \sigma u^{\varepsilon 0.6\Delta}$
$\tau_s = 0.186 \text{ x BHN kgf/mm}^2 = 0.186 \text{ x } 220.72 \text{ x } 10 = 408.332 \text{ N/mm}^2$

Sample calculation
Selecting depth of cut 0.5mm and feed 0.52 mm/rev, we have

1. $P_z = \tau_s S_o t (\cot\beta_e + 1) = 408.332 \text{ x } 0.52 \text{ x } 0.5 \text{ x } (\cot 23.078 + 1) = 491.992$N
2. $P_{xy} = \tau_s S_o t (\cot\beta_e - 1) = 408.332 \text{ x } 0.52 \text{ x } 0.5 \text{ x } (\cot 23.078 - 1) = 142.995$ N
3. $P_x = P_{xy} \sin(\Phi + \lambda) = 142.995 \text{ x } \sin(75 + 4.175) = 140.45$ N (max)
4. $P_x = P_{xy} \sin(\Phi - \lambda) = 142.995 \text{ x } \sin(75 - 4.175) = 135.061$ N (min)
5. $P_y = P_{xy} \cos(\Phi + \lambda) = 142.995 \text{ x } \cos(75 + 4.175) = 26.855$ N (min)
6. $P_y = P_{xy} \cos(\Phi - \lambda) = 142.995 \text{ x } \cos(75 - 4.175) = 46.967$ N (max)

Similarly, for all other observations cutting force Pz was calculated theoretically and was noted down as shown in table - 2.

V.CONCLUSION

From the above results we have concluded the following points:

i) It has been observed both theoretically and experimentally that with increasing the depth of cut for a given RPM, cutting force increases.
ii) In the same experiment, it has been observed that the cutting force increases with increasing feed.
iii) With the same cutting speed and depth of cut in both HSS and carbide tool, it has been observed that the force variation is significant.
iv) It has been observed the minimum cutting force requirement for machining the component obtained theoretically is almost same as the force requirement for machining the component experimentally which is obtained by dynamometer.
v) Cutting forces measured experimentally are good in agreement with the theoretical value.
vi) It has been observed that with the same feed and depth of cut, the machining force requirement decreases with increase in RPM both in HSS and carbide tool.

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