World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:4, No:9, 2010

The Effect of the Tool Geometry and Cutting Conditions on the Tool Deflection and Cutting Forces

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***Abstract*—**In this paper by measuring the cutting forces the effect of the tool shape and qualifications (sharp and worn cutting tools of both vee and knife edge profile) and cutting conditions (depth of cut and cutting speed) in the turning operation on the tool deflection and cutting force is investigated. The workpiece material was mild steel and the cutting tool was made of high speed steel. Cutting forces were measured by a dynamometer (type P.E.I. serial No 154). The dynamometer essentially consisted of a cantilever structure which held the cutting tool. Deflection of the cantilever was measured by an L.V.D.T (Mercer 122) deflection indicator. No cutting fluid was used during the turning operations. A modern CNC lathe machine (Okuma LH35-N) was used for the tests. It was noted that worn vee profile tools tended to produce a greater increase in the vertical force component than the axial component, whereas knife tools tended to show a more pronounced increase in the axial component.

***Keywords*—**Cutting force, Tool deflection, Turning, Cutting conditions.

I. Introduction

ONE of the most promising techniques for detection of cutting condition involves the measurement of cutting forces. In turning operations, it is convenient to consider the forces as at here component system. These are the tangential component, the axial component and the radial component. The components of the cutting forces in metal cutting operations provide a wealth of information on the metal removal process. Changes in these forces indicate changes in machining parameters, such as depth of cut, feed rate, cutting speed and condition of tool. Thus the accuracy of machining operations could be improved through the cutting force feedback. Many attempts have been made to use cutting forces for tool wear monitoring. Even though some interesting results have been obtained using forces for tool wear monitoring, they are not universal and hence commercial systems have to be trained for given operations and components [1-4].

Since no exact and reliable mathematical models exist for the cutting process which are able to predict tool wear, tool breakage, cutting temperature and forces, the development of tool condition monitoring systems are highly request by industry, especially in recent years [5].

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Sikdar and Chen [6] showed that there is an increase in the three directional components of the cutting force with increase in flank wear area. Among the three cutting forces measured, the tangential force is the largest while the radial force is the smallest. However, when the tool insert begins to fail, all the three cutting forces increase sharply, especially so for the axial and radial cutting forces. The radial force was also found to be slightly larger than the axial force when tool begins to fail. Cakir and Isik [5] showed that when a tool wears or breaks, cutting forces increase slightly right after the tool breakage and then decrease sharply. The change of cutting forces can itself be a good indicator to detect the tool failure. Dimla [7] presented the cutting forces and vibrations signals are affected by variations in the cutting conditions, however, the effects of cutting speed and feed rate are more complex compared to a liner increment in depth of cut change. Isik [8] described that cutting speed is the most influential parameter on tool life, feed rate is the second most one, and cutting depth is the least influential parameter. The influence of cutting depth is negligible compared with those of the other cutting parameters. At the end of the tool life, considerable increases in cutting forces are observed, but the increase rate varies according to the cutting tool and the workpiece. The amount of flank wear and the cutting force are appropriate parameters to determine the tool life. Scheffer et al. [9] showed that the best method to monitor tool wear during hard turning would be by means of force-based monitoring with an Artificial Intelligence (AI) model. The novel formulation of the proposed AI model enables it to provide an accurate solution for monitoring crater and flank wear during hard turning. Chungchoo and Saini [10] showed that the energy of force signal can be reliably used to monitor tool flank and crater wear over a wide range of cutting conditions. However, the total entropy of forces does not appear to be sensitive to feed rate, rake angle and tool wear. The experimental results also indicate that crater wear causes an increase in the effective rake angle resulting in lower total energy of forces. For some particular shapes of worn tool, however, the crater wear results in a decreased rake angle which increases the total energy of forces. The influence of crater wear on forces and the root mean square of acoustic emission (AErms) signals are also observed in this research. Lee [11] investigated that using force ratios, flank wear can be predicted to within 8 and 11.9%, and also using force increment, flank wear can be predicted to within 10.3% of the actual wear for various turning conditions. Venkatesh et al. [12] indicated that in machining of low carbon steel (1018) at speeds of 450, 560, and 710 sfm at a depth of cut of 0.1 and a feed of 0.01 ipr, the tool with −5° side cutting edge angle performed better than 0°, and +15°. Ravindra et al. [13] showed that the ratio between force components is a better indicator of the wear process, compared with the estimate obtained using absolute values of the forces. It also eliminates variation in material properties, which was identified as a major noise source in signals measured during machining.

This paper includes an empirical study that investigated the effect of tool and cutting condition in the turning operation on the tool deflection and cutting force.

II. Cutting Force and Tool Deflection

In metal cutting tool faces, including the rake face, major flank face and minor flank face are subjected to both shear and normal loads due to the pressure between the chip and the machined surfaces, friction between the tool face, chip and the machined surface. The resultant force F can be expressed by three orthogonal components, tangential force F_c, feed force F_a and radial force F_r as shown in Fig. 1.

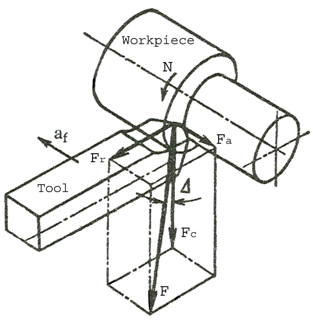

Fig. 1 Cutting force components in turning

After determining the individual components F_c, F_a and F_r, the resultant force, F, can be evaluated [14]:

$$F = \sqrt{F_c^{\,2} + F_a^{\,2} + F_r^{\,2}} \tag{1}$$

This three-dimensional force system can be reduced to a two-dimensional force system; for an Orthogonal system F_r is made zero, when the two-dimensional force system is [14]:

$$F = \sqrt{F_c^{\,2} + F_a^{\,2}} \tag{2}$$

The rate of energy consumption during turning operations is referred to as the product of the tangential or vertical cutting force and the cutting speed. Specific cutting force is defined as:

$$F_s = \frac{F_c}{a_p \times a_f} \tag{3}$$

where F_s is the specific cutting force; F_c, the tangential cutting force; a_p, the depth of cut and; a_f the feed per revolution.

Changes in specific cutting force is effected by cutting conditions and tool geometry that in nominal cutting speeds and feeds the specific cutting force remains fairly constant, however, for low cutting speeds and feeds there is a considerable increase in specific cutting force that can probably be attributed to the creation of built up edges on the tools and the imperfect formation of chips; these are also factors which are created by worn cutting tools.

The shank of a cutting tool is generally analyzed for strength and rigidity. The tool is assumed to be loaded as a cantilever by tool forces at the cutting edge as shown in Fig. 2.

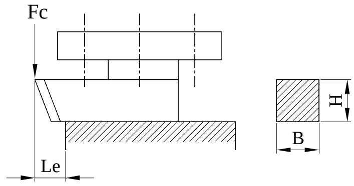

Fig. 2 Shank of cutting tool and tool overhung.

The main design criterion for shank size is rigidity. The deflection at the cutting edge is limited to a certain value depending on the size of the machine, cutting conditions and tool overhung. The tool overhung (L_e) is related also to the shank size as well as to end fixity conditions.

The permissible deflection of shanks ranges from 0.04 mm in finishing cuts to 0.1 mm in roughing cuts. Considering the shank to be a cantilever [14],

$$\Delta = \frac{F_c L_e^{\,3}}{3EJ} = \frac{4 F_c L_e^{\,3}}{EBH^3} \le 0.04 \tag{4}$$

where Δ is the tool deflection, B and H the tool dimensions (Fig. 2), E the modulus of elasticity of material, and J is the cross sectional moment of inertia.

III. Experimental Set-Up

The cutting experiments were carried out on a CNC lathe machine (Okuma LH35-N) and the workpiece material was mild steel. Machining was carried on standard high speed steel tools with a 20 mm square shank and 8 mm overhung. Experiments were done under different cutting speeds in the ranges of 30, 40, and 50 m/min, depths of cut employed were 0.5, 1.0, 1.5, and 2.0 mm and Feed rate was 0.084 mm/rev constant. Flank wear of the tool was measured using a surface texture instrument (Form Talysurf™ series). All tests carried out without the use of cutting fluid; and VB_{max} = 0.6 mm [1] for the flank wear as worn tool was selected. The dynamometer was used to determine the cutting forces (axial and tangential) exerted during the cutting operation. The nominal (starting) workpiece diameter was 100 mm and 500 mm long. Details of the tests, cutting conditions, tool material and workpiece material are listed in Table I.

The dynamometer used for this series of tests was a two force component (type P.E.I. serial No 154) dynamometer manufactured by Techquipment. The dynamometer essentially consisted of a cantilever structure which held the cutting tool. Deflection of the cantilever was measured by either a dial gauge or an L.V.D.T. Mercer 122 deflection indicator. Use of the Mercer indicator gave improved signal accuracy and also offered the facility of obtaining an output voltage signal which was relative to tool deflection. Schematic diagram of the experimental set-up is shown in Fig. 3.

TABLE I
DETAILS OF THE TESTS

Machine tool	Okuma LH35-N
Workpiece material	
Work material	BS 970
Hardness	Brinell 170
Composition	0.35% C, 0.05% Si, 0.6% Mg
Tooling material	
Tool type	HSS (AISI M10)
Tool material	0.85% C, 4% Cr, 8% Mo, and 2% V
Overhang length (mm)	8
Cutting conditions	
Cutting speed (m/min)	30, 40, and 50
Feed rate (mm/rev)	0.084 constant
Depth of cut (mm)	0.5, 1.0, 1.5, and 2.0
Cutting fluid	None

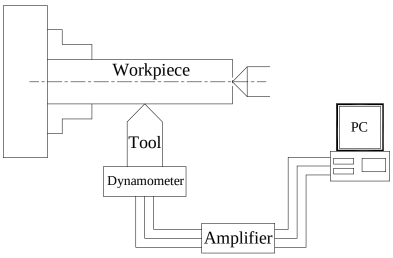

Fig. 3 Experimental Set-Up.

The Mercer 122 indicator offered a range of stepped deflection increments which extended the range of the instrument from ±5 µm to ±1500 µm full scale deflection. In general for light cuts the instrument could be set on the ±15 µm range whereas the ±50 µm range was required for tests on blunt tools.

During these tests two forms of cutting tools were used which produced: Orthogonal cutting conditions (knife edge tools) and Oblique cutting conditions (vee shaped tools) (Table II).

TABLE II
Specification of Tool Geometry

TOOL SHAPE AND GEOMETRY	TOOL ANGLES IN DEGREES			
	RAKE ANGLE	SIDE CLEARANCE	APPROACH ANGLE	TRAILING EDGE
KNIFE EDGE	14	7	90	30
VEE SHAPED	14	7	45	30

A sharp cutting tool was set-up in the dynamometer and after selecting the appropriate cutting speeds, feed and depth of cut, the feed was engaged and the relative vertical and axial deflection of the cutting tool was noted.

These tests were repeated over a range of cutting speeds and depths of cut for sharp and worn tools.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The cutting conditions for the experimental tests were as follows: cutting speed (V) range was 30-50 m/min, depth of cut range was 0.5-2 mm, and tool edge conditions were sharp (S) and worn (W), tool shape was knife (K) and vee (Ve).

Figs. 4-9 show the effect of sharp and blunt cutting tools of both vee and knife edge profile and depth of cuts on the both horizontal deflection (Hor.d) and vertical deflection (Ver.d).

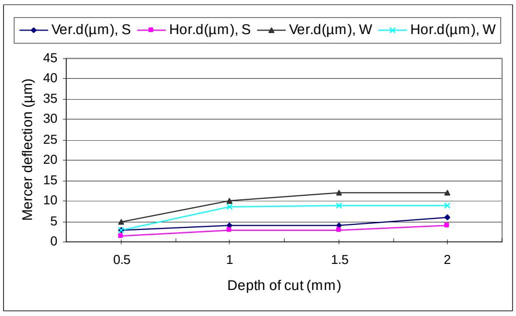

Fig. 4 Effect of depth of cut on the tool deflection (V = 30 m/min, tool shape = K).

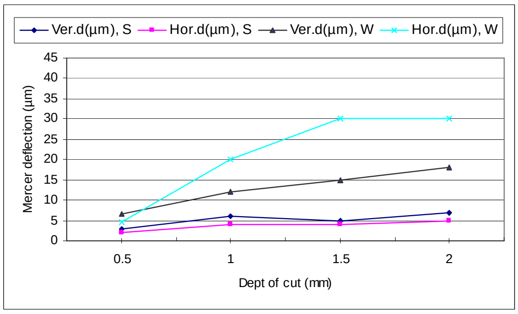

Fig. 5 Effect of depth of cut on the tool deflection (V = 40 m/min, tool shape = K).

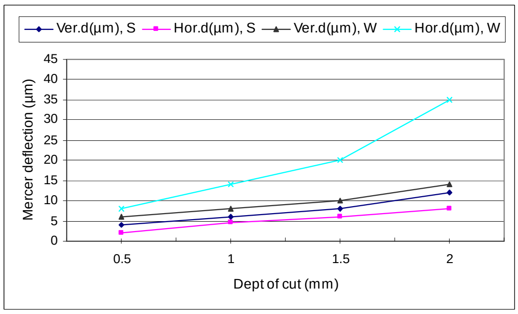

Fig. 6 Effect of depth of cut on the tool deflection (V = 50 m/min, tool shape = K).

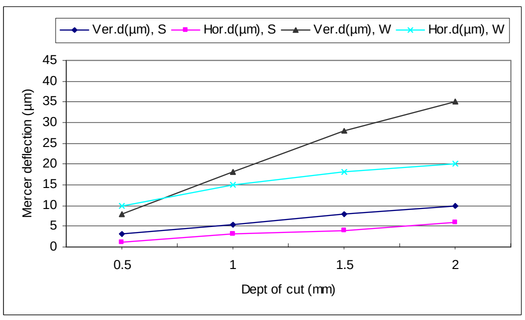

Fig. 7 Effect of depth of cut on the tool deflection (V = 30 m/min, tool shape = Ve).

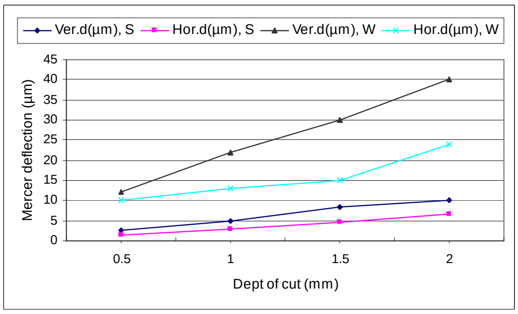

Fig. 8 Effect of depth of cut on the tool deflection (V = 40 m/min, tool shape = Ve).

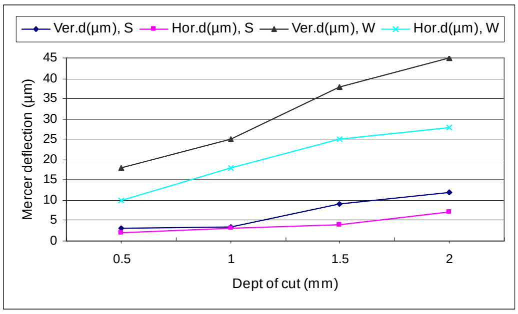

Fig. 9 Effect of depth of cut on the tool deflection (V = 50 m/min, tool shape = Ve).

The effect of the depth of cut on specific cutting force under axial loading (Axi.) and vertical loading (Ver.) is shown in Figs. 10-16.

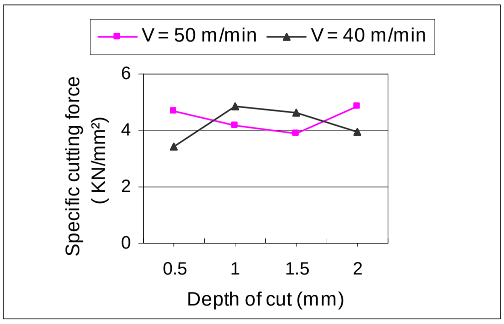

Fig. 10 Influence of depth of cut on specific cutting force (axial loading, tool shape = K, tool condition = W).

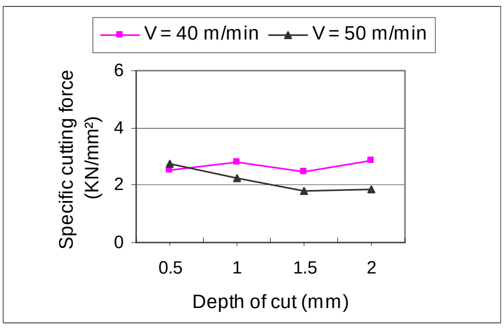

Fig. 11 Influence of depth of cut on specific cutting force (vertical loading, tool shape = K, tool condition = W).

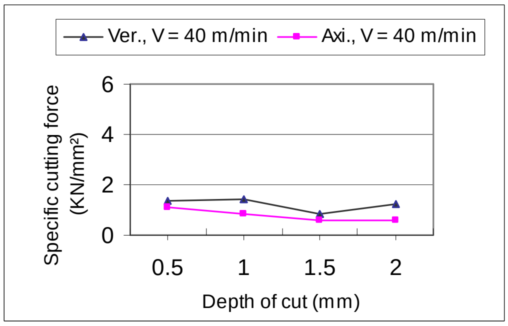

Fig. 12 Influence of depth of cut on specific cutting force (tool shape = K, tool condition = S).

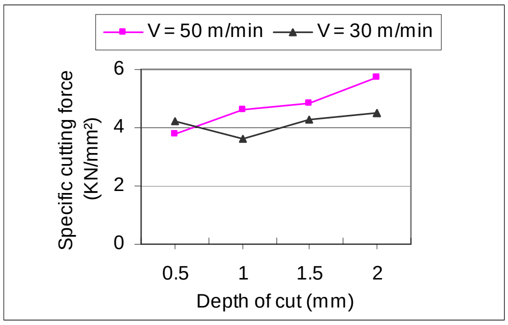

Fig. 13 Influence of depth of cut on specific cutting force (vertical loading, tool shape = Ve, tool condition = W).

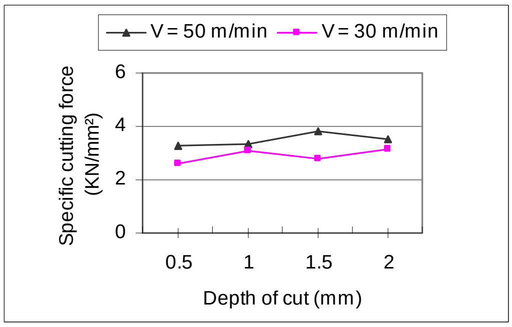

Fig. 14 Influence of depth of cut on specific cutting force (axial loading, tool shape = Ve, tool condition = W).

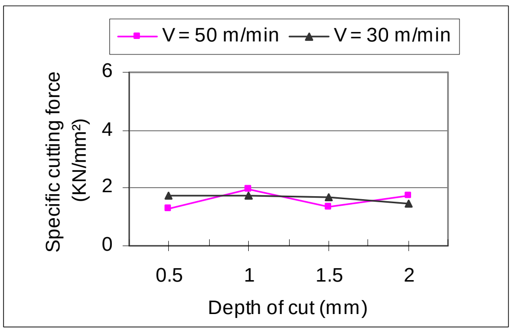

Fig. 15 Influence of depth of cut on specific cutting force (vertical loading, tool shape = Ve, tool condition = S).

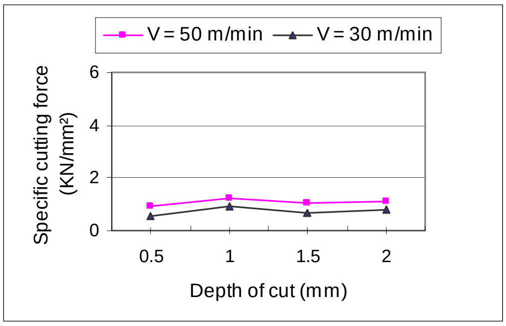

Fig. 16 Influence of depth of cut on specific cutting force (axial loading, tool shape = Ve, tool condition = S).

With both tool types examination of the cutting performance of the cutting tools in their worn state, showed that a built up edge tended to be formed quite quickly on the tool edge: when this built up edge reached a certain size this then broke away, causing tearing of the surface of the workpiece, considerable rubbing of the tool flank then occurred until a new built up edge was formed. This procedure occurred repeatedly until eventually the frictional heat generated by the rubbing action of the tool flank caused complete failure of the tool. Both tool types tested exhibited the same characteristic failure conditions, however, if the relative displacements of the dynamometer are examined the tool forces exerted on the knife and vee tool appear different. To understand why this is so the differences between Orthogonal and Oblique cutting actions must again be noted.

In Orthogonal cutting, which is essentially what occurs with knife edge tools, on force is directed along the plane of the cutting tool, only two force components are created: vertical and axial. Oblique cutting action, introduce three force components: vertical, axial and also a force which tends to push the cutting tool away from the workpiece against the action of the cross slide lead screw.

In engineering practice this backward force on the tool tends to reduce backlash in the cross slide and tends to reduce chatter. The approach angle on the vee tool has evidently caused a shift in the tool forces and apparently reduces the actual thrust on the tool. It was unfortunate in this series of the tests that the use of a two component dynamometer did not allow the measurement of the back thrust on the tool. Measurement of the tool back thrust in the case of worn cutting tools could possibly have yielded interesting results for both vee and knife profile tools.

By comparing the results obtained from the sharp and worn cutting tools it can be seen that the axial deflection of the knife edge tools in the worn state increase far more than the vertical deflection, whereas in the case of the vee tools the situation appears opposite. In both cases tests of the worn cutting tools produced considerable chatter which caused fluctuation particularly in the vertical readings which was particularly bad for depths of cut greater than 1.5 mm.

The plane of maximum deflection increase for the knife edge tool was the axial plane, whereas the vee shaped tools produce a maximum deflection increase in the vertical plane. Applying this deflection to the results obtained from the wear tests indicated that, when the cutting force in the plane of maximum increase reached, on average a value of 3 × the initial sharp tools, the cutting tool had reached the end of its serviceable life and required to be reground or changed. It is realized that the establishment of a relative cutting force of 3 × sharp values. For worn tools is somewhat tentative, and very many tests need to be run before the exact value can be established.

V. Conclusions

1) The tests indicated that it was possible to relate changes in tool loading, under identical cut and feed conditions, directly with tool wear conditions. It was found that for tools where the flank wear approached 0.6 mm depending on the cut conditions, the resulting tool loading was found to increase by 2 or 4 times the initial loading figures obtained when sharp cutting tools were used.

2) It was noted that worn vee profile tools tended to produce a greater increase in the vertical force component than the axial component, whereas knife tools tended to show a more pronounced increase in the axial component. To take into account variations in depth of cut, feed and cutting speed it was thought that wear condition should be related to changes in the specific cutting force in the direction of the plane of maximum cutting force. It was found that for the tools under test a general increase in the specific cutting force in the plane of maximum force was 3 × sharp values, which corresponded to a flank wear state of approximately 0.6 mm on high speed steel cutting tools.

3) Use of a three component cutting tool dynamometer would have enabled the back thrust on the tool to have been determined, which it was felt in the case of worn cutting tools, would have identified wear states more easily.

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