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Cutting Tool Characteristics

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ABSTRACT [ENGLISH/ANGLAIS]

Cutting tool characteristics are examined with respect to the effects of the machine controlled parameters and tool geometry on cutting phenomenon. This subject has been a matter of prolonged interest to machine tool designers and users alike as it is the basis on which tool life and hence general metal cutting economics are evolved. Most previous research works concentrated on temperature generation usually without recourse to the combined effects of the machine controlled parameters and tool geometry. This missing link is supplied in this work. Basically, the findings in this work show that the cutting speed has great influence on the forces and temperature and hence on tool life as well as the machining economics. The feed has similar but less influence on these quantities. The cutting efficiency expressed as compression ratio is also influenced by both the speed and feed. However, the influence of speed and feed on the compression ratio is in opposing direction.

Keywords: Machine tool, cutting operation, tool life

RÉSUMÉ [FRANÇAIS/FRENCH]

Caractéristiques des outils de coupe sont examinés à l'égard des effets des paramètres de la machine contrôlée et géométrie de l'outil sur le phénomène de coupe. Ce sujet a été une question d'intérêt prolongée pour les concepteurs de la machine-outil et les utilisateurs car il est la base sur laquelle la vie d'outil et donc l'économie générale de coupe en métal sont évolué. La plupart des recherches antérieures travaille concentré sur la génération de température généralement sans recours à l'effet combiné des paramètres machine contrôlée et de la géométrie de l'outil. Ce chaînon manquant est fourni dans ce travail. Fondamentalement, les conclusions de ce travail montrent que la vitesse de coupe a une grande influence sur les forces et de la température et donc sur la vie de l'outil ainsi que l'économie de l'usinage. L'alimentation a une influence semblable, mais moins sur ces quantités. L'efficacité de coupe exprimée en taux de compression est également influencé par la vitesse et l'alimentation. Cependant, l'influence de la vitesse et l'alimentation sur le taux de compression est en s'opposant à la direction.

Mots-clés: Machines-outils, l'opération de découpe, la vie de l'outil

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INTRODUCTION

The study of cutting tool characteristics is by definition the examination of the ways the cutting phenomenon is affected by cutting speed, feed, depth of cut and tool geometry. Over the years, designers of machine tool and users alike have concerned themselves with ways of improving metal removal rate, long tool life and bringing down the general economics of metal cutting operations. To achievethese goals, a lot of research works are undertaken and volumes of literature now abound but the issues are far from being resolved. Notable amongst the well-researched areas in metal cutting is the study of temperature generation within the regions of plastic deformation. This aspect is utmost in terms of tool life economics. Boothroyd [1] has shown experimentally that the work-tool interface temperature increases with increasing cutting speed and feed. Other researchers like Chandiramani [2] employed different experimental approaches and found that the temperature rise during metal cutting sets the ultimate limit to the practical cutting speed and feed. This implies that for most economic cutting condition giving maximum metal removal rate with maximum tool life, the maximum practical feed rate should be employed.

The cutting forces on the tool are also found to decrease with increasing cutting speed [3]. He also established the dependence of cutting forces on basic cutting operation parameters. Rake angle effects and other tool geometric parameters are also examined. Tool wear and chip formation mechanism are extensively dealt with. Important contribution in this area is made by Viegelahn et al. [4] who used a single-coated tungsten carbide at 5^0

negative rake angle to machine steel railroad wheel axles at high speeds and feeds. They discovered the formation of crater wear and the conditions of its prevalence.

The cited works notwithstanding, extensive general understanding of the tool characteristics in the main remains inconclusive because of the dynamic nature of cutting operations. There is therefore the need to investigate further the ways the machine controlled parameters combine to affect the tool and its performance in service. This study therefore sets out to investigate the cutting tool characteristics in relation to the development of cutting forces, temperature generation, the effects of cutting speed variation on cutting forces and temperature as well as the general effects of temperature, cutting forces and speeds/feeds on tool life.

MATERIALS AND METHODS

The methodology involves an experimental process

Force Measurement

A Tec-equipment two component displacement gauge dynamometer is used to evaluate the forces (stress) acting on the cutting tool. The displacement gauge dynamometer is of the mechanical (cantilever) type. In this design, the cutting tool is supported at the end of the cantilever and the vertical and horizontal deflections of the cantilever are determined by displacement gauges. The readings registered by the displacement gauges are taken as the vertical and horizontal forces acting on the cutting tool. The main design features of this device are the high rigidity and high sensitivity it possesses. It is essential that the dynamometer should have high rigidity and high natural frequencies so that the dimensional accuracy of the cutting operation is maintained and the tendency for chatter or vibration occurring during cutting is minimized. To realize this objective, the base plate of the dynamometer is fastened to the cross-slide of the lathe by means of grub screws. For the experiment, the cutting tool is insulated from the dynamometer by means of fibre glass to minimize heat loss due to conduction. Secondly, the pointer on the dial gauge of the dynamometer is set to zero before any cutting operation to eliminate or reduce the zero error of the device.

Temperature Measurement

The temperature measurement apparatus comprises Chromel-Alumel thermocouple wires of 0.4 mm diameter. A CROPICO microvolt meter is used to read out the signal from the thermocouple. The choice of Chromel-Alumel thermocouple wiresis influenced by its reliability at very high temperature. It has an accuracy of ±0.25 ^{0}c up to 1400 ^{0}c. Chromel-Alumel wires are also reputable for their high corrosion and oxidation resistances at high temperature. The small size of wires allows for high signal responses. The CROPICO microvolt meter also has a good readout accuracy of 0.1% on conversion to temperature scale. For calibration purpose the thermocouple is used to measure the temperature of a melting metal of known melting point in a melt-vat arrangement. A calibration curve is obtained. On the shop floor when the lathe machine is rigged-up for the tests, an electric furnace with adjustable temperature is used to check the calibration. The observed results are comparable to those of the calibration curve within allowable experimental error. The thermocouple at the region close to the cutting action is insulated using ceramic insulators to prevent radiation/conventional heat losses.

Due to the problems encountered with drilling the holes on the carbide tool, an alternative method of monitoring the cutting temperature during machining has to be sought. Opportunity occurred in the use of THERM 2210 Electronic Probe Thermocouple (EPT). The EPT has a temperature range of -200 to 1370 ^{0}C and the extended probe is very sensitive, registering the temperature of point of contact within seconds of touch. The EPT is also used on the High Speed Steel (HSS) and Low Carbon Steel (LCS) tools for comparative purposes with the readings of the wire thermocouple.

Cutting Tool Preparation

The intention is to drill a set of 0.8 mm holes on the rake face at predetermined distances from the cutting edge. This is not possible because of the hardness of the cutting tools and the unavailability of full carbide drill of the right size. However, using "stalite" drills which are carbide tipped, it is possible to drill one hole each on the HSS and LCS cutting tools. The carbide tool could not be drilled into. In drilling the holes on HSS and LCS tools, a high speed drill operating at a speed of 1800 rpm is used. Even at this high speed, breakages of the expensive carbide tipped drills are rampant. The thermocouple is secured in the drilled holes by using a heat resistant adhesive (IS 12 Cyanoacrylate adhesive).

Tool Geometry

The three cutters - the Low Carbon Steel (LCS), the High Speed Steel (HSS) and the carbide tools –are ground to

give the following tool geometry: - plan trail angle 13^0, plan approach angle 90^0, front clearance angle 16^0, side clearance angle 10^0, back rake angle 0^0 and side rake angle 13^0.
Holes are drilled as close as possible to the cutting edge of the LCS and HSS tools.

Workpiece Material

The workpiece material is mild steel (Hardness HV = 245) and has the following composition as supplied by the manufacturer:
C(0.45),Si(0.39),Mn(0.77),Ni(1.66),Cr(1.11),Mo(0.10),S(0.06),P(0.05)
Solid workpieces of outside diameter 15mm and 305mm in length are prepared from a bar stock. Prior to cutting operation, the diameter is reduced to 13mm by turning so as to remove the oxide layer on the metal and work on fresh and clean surfaces.

Other Equipment

Other equipment and facilities used in the experimental process include the lathe, stop watch, grinder, jigs, fixtures, hacksaw and micrometer screw gauge.
All the turning operations are performed on a COLCHESTER MASTIFF 1400 centre lathe with centre height of about 254mm (10 inches). The lathe is semi automotive and has a variable speed ranging from 18rpm to 1400rpm.
A Swiss MAYLAN stopwatch is used to time all the turning operations of this study. A time base of 100 seconds is adopted for the study.

Typical Test Run

The workpiece was positioned in the headstock chuck and properly centered using the tailstock. The lathe machine was then switched on. The cutting speed, feed and depth of cut are selected and recorded. The cutting tool is engaged and the instruments are read against time. For all cutting operations, no cutting fluid is used (Dry cutting conditions prevailed). The depth of cut is kept constant while the speed and feed are varied for subsequent turning passes.

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Special Precaution

After rig-up, the thermocouple is calibrated again using a portable electric furnace. This is to ascertain the effect of the increased resistance in the thermocouple circuit on the signal recovery.
The cutter is insulated from the rest of the lathe machine by means of glass fibre so that local temperature rises in the machine-tool structure will not affect the meter reading as well as prevent heat losses by conduction into the bulk of the machine-tool.
The thermocouple wires are insulated to prevent heat losses by radiation and convection and also to minimize heat losses by conduction.

Metallurgical Analysis

It is essential to link cutting mechanism with the structural changes that occur in the cutting zone of the workpiece. Essentially, this aspect is lacking in the literature. It is here attempted to give a complete overview of the metal cutting phenomenon. In this metallurgical analysis, microscopic cross-section of the cutting zone is done. The usual mounting of the selected elemental parts was done and thorough polishing through a battery of polishing drums is used. The surfaces are then etched using 5% nital in dilute acid. No significant structural changes in the area chosen areobserved at the best magnification. The undeformed area remained structurally stable.

RESULTS

The experimental results are presented in tables and relevant analyses are also done to derive the main parameters that affect machining economics.
For calculation purposes, the speed is assumed to be in the direction of cutting. Thus, V = ∏nD (m/min), where D is the diameter of workpiece and n is the revolutions per minute (rpm).
From merchant theory [5],

$\Phi = 45 - \frac{1}{2}(\beta - \alpha)$

$= 45 - \frac{1}{2}\beta$ since $\alpha = 0$

$$\beta = \tan^{-1}\left(\frac{Nt}{Ft}\right) \qquad \alpha = 0$$

Substituting values from the table

$$\beta = \tan^{-1}\left(\frac{518}{68}\right)$$

$= 82.52^0$

Compression ratio λ = Cot Φ
= Cot $(45 - \frac{1}{2}\beta)$
= Cot (45 – 41.26)
= 15.30

Where Φ is the shear plane angle, β is the angle of friction and α is the rake angle.

Sen and Bhattacharyya [6] worked on mild steel using HSS tool at Speed(10m/min) and feed(0.20mm) and found Taylor's constants[7],c = 100 and w = 0.4306. Taylor's equation [7] is $Vt^w = c$.

For a cutting speed of 2.88m/min,

$$\overline{log\ t} = \frac{1}{0.4306}(\log 100 - \log 2.88)$$

= 3.58

t = 3783 mins.

It was not possible to derive similar values for carbide and Low Carbon Steel (LCS) tools because the relevant Taylor's constants at known feed and depth of cut were not readily available in the literature.

In Table 1, the general trend shows an increase of cutting forces with increasing speed for the three cutters used in the experiment. However, there appears to be a threshold value at which the vertical force, N_t attains its maximum and thereafter decreases. This threshold value has a feed bias. Generally, the vertical forces N_t, are higher than the horizontal forces, F_t, for all speeds considered in the experiment. The cutting forces are greatest when the Carbide tool is used, followed by the High Speed Steel, (HSS) and then the Low Carbon Steel (LCS) tools.

The cutting forces increase with increasing feed for the HSS and LCS tools. No definite pattern could be established for the carbide tool. However, the increase in cutting forces due to an increase in feed is less than the increase recorded for a corresponding increase in cutting speed. This is true for the three cutters considered in the experiment. In Table 1, for instance, at feeds of 0.20mm and 0.40mm, and speeds of 55rpm and 100rpm, the increase in the cutting forces due to increase in speed is greater than that due to the corresponding increase in feed.

In Table 1, it can be seen that the cutting temperature increases with increasing cutting speed and feed for the three cutters considered in the experiment. The increase is greatest with the carbide tool followed by the HSS tool and lowest with LCS tool. For a given tool and feed, the increase in temperature is greater at lower speeds and tends to stabilize at higher speeds.

Only the compression ratios λ for the carbide and HSS tools are considered here because they are believed to be the most widely used tools in metal cutting. Table 2 shows the relationship between the cutting speeds with compression ratios, λ for carbide and HSS tools at feeds of 0.20mm and 0.40mm. Generally, the compression ratio decreases with increasing cutting speed for the two cutters. However, there exists a maximum value of λ for the two cutters. For a given feed, the values of λ are higher for the carbide tool than with the HSS tool. The decrease in λ with cutting speed is more gradual with the HSS tool than with the carbide tool.

Table 1: This table shows the vertical force, N_t (Newton, N), the horizontal force, F_t (N) and the temperature, T(^{0}c) developed when machining mild steel with carbide, HSS and LCS tools at various speeds V(rpm) and feed F(mm). The depth of cut, d, is kept constant at 0.5 mm.

Cutter	Feed	Speed	N_t	F_t	T
	0.02	18	518	68	260
	0.02	24	570	78	270
	0.02	32	777	102	351
	0.02	43	803	105	486
	0.02	55	851	108	546
	0.02	75	1036	136	550
	0.02	100	1036	170	570
	0.02	185	1077	180	581
	0.02	245	1077	190	600
Carbide	0.02	330	948	185	615
	0.30	55	518	170	494
	0.30	100	648	204	544
	0.30	185	670	340	772
	0.30	245	777	347	800
	0.30	330	1036	681	1045
	0.40	55	907	115	805
	0.40	100	984	125	940
	0.40	185	1036	140	970
	0.40	245	1088	200	1000
	0.02	100	259	85	418
	0.02	185	285	155	430
	0.02	245	337	185	541
	0.02	330	363	202	577
	0.30	100	260	90	485
	0.30	185	290	160	512
HSS	0.30	245	347	192	530
	0.30	330	466	225	643
	0.40	100	725	170	615
	0.40	185	873	170	637
	0.40	245	807	185	650
	0.40	330	774	185	703
	0.40	450	763	180	720
	0.02	100	116	63	243
	0.02	185	181	85	371
	0.02	245	250	98	498
	0.02	330	302	102	511
	0.30	100	126	65	300
LCS	0.30	185	190	90	385
	0.30	245	260	99	500
	0.30	330	320	110	550
	0.40	100	140	85	385
	0.40	185	200	102	436
	0.40	245	295	115	500
	0.40	330	350	141	541

Table 2: This table shows the derived values of compression ratio, λ at various speeds and feeds when machining mild steel with carbide and HSS tools. Compression ratio is dimensionless.

Cutter	Feed	Speed	N_t	F_t	λ
	0.02	18	518	68	15.30
	0.02	24	570	78	14.68
	0.02	32	777	102	15.30
	0.02	43	803	105	15.36
	0.02	55	851	108	15.82
	0.02	75	1036	136	15.30
	0.02	100	1036	170	12.27
	0.02	185	1077	180	12.05
	0.02	245	1077	190	11.42
	0.02	330	948	185	10.73
Carbide	0.40	55	907	115	15.83
	0.40	100	984	125	15.81
	0.40	185	1036	140	14.87
	0.40	245	1088	200	10.97
	0.02	100	259	85	6.25
	0.02	185	285	155	3.93
	0.02	245	337	185	3.90
	0.02	330	363	202	3.85
	0.40	100	725	170	8.65
	0.40	185	873	170	10.37
HSS	0.40	245	807	185	8.84
	0.40	330	774	185	8.84
	0.40	450	763	180	8.49

Table 3: This table shows the derived values of tool life, t (min) at various speeds (m/min), temperatures, T (^{0}C) and a feed of 0.20 mm when machining mild steel with HSS tool.

Feed	Speed	Log V	T	Lot T	Lot t	t
0.20	2.88	0.46	418	2.62	3.58	3783
0.20	5.32	0.73	430	2.63	2.96	910
0.20	6.27	0.80	541	2.73	2.79	621
0.20	8.44	0.93	572	2.76	2.49	311

Table 3 shows the effect of cutting speed, V on tool life, t for HSS tool. The general trend is that tool life, t decreases with increasing speed, V for a given feed, f. The unavailability of relevant experimental data made it impossible for the calculation of tool life for the carbide and Low Carbon Steel (LCS) tools.

Table 3 also shows the effect of temperature, T on tool life, t for HSS tool. The trend is similar to that of cutting speed V, on tool life, t. Generally tool life decreases with increasing temperature.

DISCUSSION

Cutting Forces

The experimental results show that cutting forces increase with increasing speed and feed for the three cutters and speed range considered in this work. In metal cutting, the forces necessary to overcome friction between the workpiece and the cutting edge are driven through the cutting tool. There is a tremendous pressure (stress) build-up at the chip-tool interface because the point of contact is of small area. The coefficient of friction, μ, and hence the angle of friction β, vary considerably and are affected by cutting speed, V, the feed, f, and the rake angle α[8]. This variance is due mainly to the very high pressure (stress) that exists at the chip-tool interface during chip formation. For a zero value of the rake angle α, the variance in the angle of friction β is only influenced by the speed and feed. Increasing the speed causes an increase in the angle of friction, β which leads to a decrease in the shear plane angle Φ with a corresponding increase in the area of the shear plane, As. The force required to form the chip will be increased since the mean shear strength, ◎s of the workpiece remains constant [1]. Similarly, the feed, f exerts a great influence on the cutting forces. This is true because the cross sectional area of the uncut chip, Ac is directly dependent on the feed. Thus greater feed implies greater force required to plastically deform a layer of the workpiece. Therefore cutting forces increase with increasing speed and feed for the speed range considered in this work.

Temperature

The high forces resulting from increases in speed and feed imply high energy requirement to plastically deform a substantial layer of the workpiece adjacent to the cutting tool. Almost all the energy consumed during the chip formation process is converted nearly instantaneously into thermal energy which greatly increases the temperature throughout the entire cutting zone. At low speed, the chip has time to take away much of these sensible heat and pass same on to the tool as it slides on the rake face. This action leads to a tremendous rise in temperature at the chip-tool interface. But at very high speed, the chip has little or no time to conduct the heat away from the deformation zone. The chip-tool interface temperature then tends to stabilize with time. The deep-blue coloured chips observed at high speed may be due to the high temperature developed by the additional plastic work required because of the zero value of the rake angle [4]. The temperature generated during metal cutting is influenced by the forces developed, speed, feed, tool geometry and the thermal properties of the tool and work piece [8]. Wear mechanisms such as diffusion, adhesion, abrasion and oxidation which are strongly temperature dependent become very active at high values of forces, speed and feed [9]. The more active these wear mechanisms are, the shorter the life of the tool. Sen/Bhattacharyya [6] and Boothroyd [1] established the domineering influence of cutting temperature on tool life and had shown that the temperature generated during chip formation process is more sensitive to an increase in speed than the same increase in feed. It therefore follows from the results of this experiment that for most economic cutting conditions giving a maximum material removal rate with maximum tool life, the maximum practical feed should be employed. This is true because an increase in feed results in a smaller increase in temperature than a corresponding increase in cutting speed.

Compression Ratio

The process of plastic deformation occurring along the shear plane elongates the individual crystals of the workpiece in the general direction indicated by the shear plane angle Φ. This action tends to produce a chip that is thicker than the parent material from which it came[1]. Hence the chip thickness, df, is always greater than the depth of cut, d (Thickness of the undeformed chip). It follows therefore that the compression ratio, λ which is the reciprocal of the chip thickness ratio, r is always greater than unity. The compression ratio λ is a measure of the efficiency of the cutting operation. The smaller the compression ratio, the more efficient is the cutting operation. Thus for any given cutting situation, the parameters selected should be geared towards reducing the compression ratio. Reduction of the compression ratio can be achieved by reducing the friction on the rake force through the use of cutting fluid.

The experimental results show that compression ratio decreases with increasing speed. Since no cutting fluid was used, the decrease in the compression ratio as the cutting speed increases may be attributed to the reduction in the area of the shear plane, As, as the speed increases. The thinner chip that results from the reduction in the shear plane area, As is easier to remove at faster rate. Thus small compression ratio is ideal for low metal removal cost. Apart from the initial increase in the compression ratio at low cutting speed, the experimental results indicate an efficient cutting operation when using the carbide and HSS tools at speed higher than 3m/min because the forces required to produce the chip become smaller. Thus the energy requirement of the cutting operation is reduced as the speed increases. On the other hand, the compression ratio increases with increasing feed. High feed implies thicker chip because of the elongation of the crystals of the work piece during the chip-formation process. The resulting thicker chip leads to high value of compression ratio as the feed increases. More energy is therefore required with increasing feed to plastically deform a substantial layer of the work piece. Thus the efficiency of the cutting operation decreases as the feed increases. As mentioned earlier, the influence of speed on tool life is more harmful than that of feed in any cutting operation. It is therefore highly beneficial to any cutting operation that cutting efficiency increases with speed and that the maximum practical feed should be employed because the latter has less harmful effect than the former on tool life. The maximum value of the compression ratio exhibited by the carbide and HSS tools at low speed may be an indication of the disappearance of the build-up edge (bue) while the minimum value of the compression ratio exhibited by the carbide tool at low speed may indicate the presence of maximum built-up edge [10].

CONCLUSION

The following conclusions can be drawn from the experimental results and the discussion of the result.

The cutting speed has great influence on the cutting forces and temperature and hence the tool life. The feed has similar but less influence on the cutting forces and temperature as well as tool life.

The cutting speed increase causes decrease in the compression ratio which is a measure of cutting efficiency. The feed influences the compression ratio in the opposite direction as the speed.

For most economic cutting conditions giving a maximum metal removal rate with a maximum tool life, the maximum practical feed should be employed because an increase in feed is less harmful to tool life through temperature increase than a corresponding increase in cutting speed.

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CONFLICT OF INTEREST

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