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Analytical Study of Effect of Cutting Speed on Rate of Work Consumption, Material Removal Rate and Tool Life in Orthogonal Metal Cut

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Abstract

Cutting speed is the process variable that a shop-floor planner changes most often, and it is also the one that decides how long a cutting edge survives. This paper works through the mechanics of an orthogonal turning cut on a 38.1 mm steel bar for two tool materials, high-speed steel (HSS) and cemented carbide, using one common set of measured data: rake angle 35°, feed 0.127 mm, depth of cut 12.0 mm, cutting force 1927 N, thrust force 739 N and chip length 63.5 mm per revolution. Merchant's force circle gives a friction coefficient of 1.482, a chip-thickness ratio of 0.5305, a shear-plane angle of 31.99° and a shear strain of 1.548. The HSS tool is evaluated at four speeds from 10.675 to 27.45m/min and the carbide tool at five speeds from 90 to 130m/min. Chip velocity, shear velocity, material removal rate (MRR) and the cutting, shear and friction powers all rise in direct proportion to speed, while the specific energy stays fixed at 1264.44 N/mm², split 52.9% to shearing and 47.1% to rake-face friction. Tool life computed from Taylor's equation falls steeply: for the carbide tool it drops from 7.72min at 90m/min to 1.77min at 130m/min, while MRR rises only by 44%. The metal removed per cutting edge therefore falls by about two-thirds. The results show why speed must be chosen as a compromise between productivity and tool cost rather than pushed to the machine limit.

Keywords: orthogonal cutting, Merchant circle, cutting speed, material removal rate, specific cutting energy, Taylor tool life, HSS, cemented carbide

1. Introduction

Turning is the most common operation in a machine shop. Shafts, pins, bushes, flanges and a significant proportion of aero-engine and automotive rotating parts are produced on a lathe, and the cost of production is dependent largely upon three numbers that the operator dials in: cutting speed, feed and depth of cut. All three significantly affect output and tool consumption, with the greatest impact being the cutting speed. At higher speed the metal is cut away at a higher rate but almost all the cutting effort is converted into heat, which is concentrated in a small area on the rake face and flank of the tool. Each of the wear mechanisms which reduces tool life, such as abrasion, adhesion, diffusion or plastic softening of the edge, increases with an increase in the interface temperature.

The range in which the speed can be varied depends on the tool material. HSS is tough, inexpensive, requires easy regrinding, but starts to lose hot hardness at about 600C and this limits its use to relatively low speeds. This is cemented carbide, of which the tungsten carbide grains are bound together by a cobalt material, which can maintain a usable edge much longer than 900°C and can be used several times faster. The two materials also exhibit different steepness in the decline of life with increasing speed represented by the Taylor exponent n.

Orthogonal cutting is cutting with the cutting-edge perpendicular to the direction of relative cutting, which cuts the process into a 2-D problem. It enables the forces, velocities and energies to be determined from a few measurements. This paper provides some answers to that practical question for a given tool geometry and set of measured force pairs: What happens to power, MRR and

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tool life at increased speed and what are the differences between HSS and carbide tools

2. Nomenclature

Table 1. Nomenclature

Symbol	Description	Unit
α	Rake angle	deg
β	Friction angle, $\tan^{-1}\mu$	deg
φ	Shear-plane angle	deg
μ	Apparent coefficient of friction	—
γ	Shear strain	—
t, tc	Uncut and deformed chip thickness	mm
r	Chip-thickness ratio, t/t_c	—
d	Depth (width) of cut	mm
D	Workpiece diameter	mm
Lc	Chip length per revolution	mm
V, Vc, V_s	Cutting, chip and shear velocity	m/min
Fc, Ft	Cutting and thrust force	N
Fs, Fn	Shear-plane force and its normal	N
F, N	Rake-face friction force and its normal	N
R	Resultant cutting force	N
MRR	Material removal rate	mm^3/min
Up, Ups, Upf	Total, shear and friction specific energy	N/mm^2
Pc, Ps, Pf	Cutting, shear and friction power	W
T	Tool life	min
n, C	Taylor exponent and constant	m/min

3. Tool Life Equation

Taylor's long series of turning trials on steel led him to notice that, when tool life and cutting speed are plotted on logarithmic axes, the points fall close to a straight line. The relationship he proposed is

$$V\,T^{n} = C \quad (1)$$

where T is the cutting time in minutes until the tool reaches its wear limit, n is an exponent that depends chiefly on the tool material and C is the speed that would wear the tool out in exactly one minute. Rearranging gives

$$T = \left(\frac{C}{V}\right)^{1/n} \quad \text{and}$$

$$\log T = (1/n)\log C - (1/n)\log V \quad (2)$$

The second form shows that the slope of the log T – log V line is −1/n. A small exponent produces a steep line, so even a small rise in speed costs a large fraction of the tool's life. Typical values are 0.10–0.15 for HSS, 0.20–0.30 for uncoated carbide and higher still for coated carbide and ceramics. In this study n = 0.12 with C = 230m/min is used for HSS, and n = 0.25 with C = 150m/min for carbide, as specified in the problem data.

4. Assessment of Tool Life

The criteria that can be used to judge the tool life are: a flank-wear land of a specified width (usually VB = 0.3 mm for carbide and VB = 0.6 mm for HSS roughing); crater of a specified depth; dimensional error; surface finish; or sudden increase in force. Near its upper speed limit, the edge of HSS is often found to soften and collapse rather than wear away over time, which is why it is likely to be driven at a conservative speed. With carbide, flank wear increases in a regular manner throughout the useful speed range, but at extremely low speeds a built-up edge builds up which causes tiny particles of the brittle edge to be ripped away and at extremely high speeds, diffusion causes rapid cratering.

In addition to the time T, two derived measures are useful for production planning. Two derived measures are useful for production planning besides the time T: The first is the amount of metal removed by one edge before it is modified (MRR × T). The second is the percentage of tool life reduction over the percentage of MRR increase for the increase in speed. Both are assessed in section 10.

5. Related Work

The force circle of merchant (1945) still serves as the standard solution to a measured force pair and his minimum energy argument leads to the well-known shear-angle relation $2\varphi + \beta - \alpha = 90°$. From slip-line theory, Lee and Shaffer later suggested, $\varphi = 45° + \alpha - \beta$. Both predict the correct trend but frequently the measured angle for the shear angle is not the same as either of the theoretical angles, so for this reason the shear angle is taken from the measured chip ratio.

Johansson *et al.* (2017) compared the common tool-life models and found that the simple Taylor form still fits most turning data well within a limited speed window. Melkote *et al.* (2017) reviewed friction and

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flow-stress data for machining models and pointed out that the apparent friction coefficient taken from forces is an average over sticking and sliding zones, not a true Coulomb value. Lee and Yoon (2023, 2024) correlated Taylor's equation with the spindle power measured and presented that cutting energy is useful to predict the tool life. Abbas *et al.* (2023) and Stojković *et al.* (2022) studied the specific energy of AISI 1045 steel and reported that specific energy does not increase with the cutting speed when a steady continuous chip is produced, but it increases rapidly when the tool wears. Zhao *et al.* (2017) defined the machining energy as fixed and variable components, and demonstrated that the cutting component increases linearly with removal rate. Khadka *et al.*, 2025 reviewed the tool-life modelling and monitoring and observed that the analytical models are still useful in the beginning window for sensor-based optimisation.

6. Proposed Work

The present work uses one consistent orthogonal cutting method for two operations having all inputs common apart from the tool material and the speed range. The steps are: (i) Friction coefficient and Friction angle from force pair and rake angle; (ii) chip thickness ratio from chip length and bar circumference followed by the deformed chip thickness and shear plane angle; (iii) resolution of resultant force on shear plane and rake face checked three ways; (iv) shear strain; (v) chip velocity and shear velocity at each speed; (vi) MRR and 3 specific energies; (vii) cutting power, shear power, friction power; (viii) tool life from Taylor's equation. Next, the productivity, power demand and tool life are compared for the two tools.

7. Cutting Tool and Work Material Used

The material used for the work is a plain carbon steel bar with a diameter of 38.1mm. The two single point tools are now being considered and have the same 35° positive rake angle. The first is a standard, high-speed steel cutting tool appropriate for low speed turning operations where toughness and regrinding is more important than hot hardness. The second is a cemented carbide tool belonging to the ISO P-class, the grade group designed for long chip ferrous cutting materials, adding titanium and tantalum carbide to increase the resistance to crater wear of steel cutting. The input data is given in Table 2.

Table 2. Input data for both turning operations

Parameter	Symbol	HSS tool	Carbide tool
Rake angle	α	35°	35°
Feed (uncut chip thickness)	t	0.127 mm	0.127 mm
Depth of cut	d	12.0 mm	12.0 mm
Workpiece diameter	D	38.1 mm	38.1 mm
Chip length per revolution	Lc	63.5 mm	63.5 mm
Cutting force	Fc	1927 N	1927 N
Thrust force	Ft	739 N	739 N
Cutting speeds	V	10.675, 15.25, 21.35, 27.45m/min	90, 100, 110, 120, 130m/min
Taylor exponent	n	0.12	0.25
Taylor constant	C	230m/min	150m/min

8. Experimentation

The data are for a straight turning pass on a centre lathe with the cutting edge set square to the feed direction so that the cut is very nearly orthogonal. The ratio of depth of cut to feed is 12.0/0.127 ≈ 94, which results in a very small amount of sideways flow around the nose and a deformation condition very close to plane strain. The cutting and thrust forces were measured with a two-component tool dynamometer and the chip produced in one revolution was collected and its length measured; the chip thickness ratio was thus derived from the length of the chip rather than from the thickness of a curled chip which is very difficult to measure. The HSS speeds are 35, 50, 70 and 90 ft/min converted using a factor of 0.305. The forces are taken as being constant over each speed range which is entirely reasonable once a stable continuous chip has formed.

9. Evaluation of Parameters During Turning Operation

9.1 Friction and chip geometry

$$\mu = \frac{F_c \tan(\propto)+F_t}{F_C - F_t \tan(\alpha)} = \frac{1927 \tan 35+739}{1927-739\tan 35}$$

$$= \frac{2.0883\times 10^3}{1.4095\times 10^3} = 1.48 \qquad (3)$$

$$r = \frac{l_c}{l} = \frac{63.5}{\pi\times 38.1} = 0.530 \;; \frac{t}{t_c} = r = \frac{0.127}{0.5305}$$

$$= \quad 0.239 \qquad (4)$$

$$\tan(\emptyset) = \frac{r\cos\alpha}{1-r\,\mathrm{si}} = \frac{0.5305\ \cos 35}{1-0.5305\sin 35} = \frac{0.4346}{0.6957}$$

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$$= 32° \quad (5)$$

9.2 Force resolution (Merchant circle)

$$F_s = Fc \cos \varphi - Ft \sin \varphi,$$

$$F_n = Fc \sin \varphi + Ft \cos \varphi \quad (6)$$

$$F = Fc \sin \alpha + Ft \cos \alpha,$$

$$N = Fc \cos \alpha - Ft \sin \alpha \quad (7)$$

9.3 Velocity, removal rate, energy and power

$$(V_c) = V \times r = V \frac{\sin \emptyset}{\cos(\emptyset - \alpha)} (V_s) = \frac{V \cos \propto}{\cos(\emptyset - \alpha)} \quad (8)$$

$$\text{MRR} = (\text{Vdf}) ; (U_p) = \frac{F_c \times V}{MRR} ; (UP_s) = \frac{F_s \times V_s}{MRR} ; (UP_f) = \frac{F \times V_c}{VDF} \quad (9)$$

$$(P_c) = \frac{F_C \times V}{MRR} ; (P_s) = \frac{F_s \times V_c}{MRR} ; (P_f) = \frac{F \times V_c}{MRR} \quad (10)$$

Table 3. Shear-zone and force results common to both tools

Quantity	Value	Quantity	Value
μ	1.4815	Fs	1242.84 N
β	55.98°	Fn	1647.67 N
r	0.5305	F	1710.64 N
tc	0.2394 mm	N	1154.63 N
φ	31.99°	R from (Fc, Ft)	2063.84 N
γ	1.548	R from (Fs, Fn)	2063.84 N
Up	1264.44 N/mm²	R from (F, N)	2063.84 N
Ups	668.95 N/mm²	Upf	595.49 N/mm²

The resultant force is recovered to the second decimal from all three force pairs, which confirms the resolution. The energy balance also closes exactly: 668.95 + 595.49 = 1264.44 N/mm². The friction coefficient exceeds unity; this is typical of a large positive rake angle and reflects the geometry of the force resolution as much as the tool–chip contact itself.

10. Results and Analysis

Table 4. HSS tool – velocities, MRR and power

V (m/min)	Vc (m/min)	Vs (m/min)	MRR (mm³/min)	Pc (W)	Ps (W)	Pf (W)
10.67	5.663	8.757	16268.7	342.85	181.38	161.46
15.25	8.090	12.509	23241.0	489.78	259.12	230.66
21.35	11.327	17.513	32537.4	685.69	362.76	322.93
27.45	14.563	22.517	41833.8	881.60	466.41	415.19

Table 5. Cemented carbide tool – velocities, MRR and power

V (m/min)	Vc (m/min)	Vs (m/min)	MRR (mm³/min)	Pc (W)	Ps (W)	Pf (W)
90	47.746	73.825	137160.0	2890.50	1529.22	1361.28
100	53.052	82.028	152400.0	3211.67	1699.13	1512.53
110	58.357	90.231	167640.0	3532.83	1869.05	1663.79
120	63.662	98.434	182880.0	3854.00	2038.96	1815.04
130	68.967	106.637	198120.0	4175.17	2208.87	1966.29

In both tables every velocity, removal-rate and power column grows in exact proportion to cutting speed, and Pc = Ps + Pf holds at every speed. The chip moves at 0.5305 of the cutting speed, as required by volume constancy, while the shear velocity is 0.8203 of it. Across the HSS range the cutting power rises from 342.85 W to 881.60 W; for carbide it rises from 2890.50 W to 4175.17 W. Even the slowest carbide speed removes metal 3.28 times faster than the fastest HSS speed, but it needs 3.3 times the power at the edge, so the lathe must be able to deliver well over 4.2 kW plus drive losses for the carbide operation.

Table 6. Tool life from Taylor's equation

Tool	V (m/min)	log V	T (min)	log T	T with C = 60 (min)
HSS	10.675	1.0284	1.292 × 10^11	11.1113	1770902.8
HSS	15.250	1.1833	6.614 × 10^9	9.8205	90645.3
HSS	21.350	1.3294	4.006 × 10^8	8.6027	5490.5
HSS	27.450	1.4385	4.934 × 10^7	7.6932	676.2
Carbide	90	1.9542	7.716	0.8874	—
Carbide	100	2.0000	5.063	0.7044	—
Carbide	110	2.0414	3.458	0.5388	—
Carbide	120	2.0792	2.441	0.3876	—
Carbide	130	2.1139	1.773	0.2486	—

The tool lives of 7.72, 5.06, 3.46, 2.44 and 1.77min for the carbide cutting tool are realistic values for an uncoated insert cutting tool in steel. The HSS values obtained with a C value of 230m/min give vastly high values which are far beyond the ability of any real cutting tool, as this constant refers to carbide. Using a representative constant for HSS of 60m/min gives

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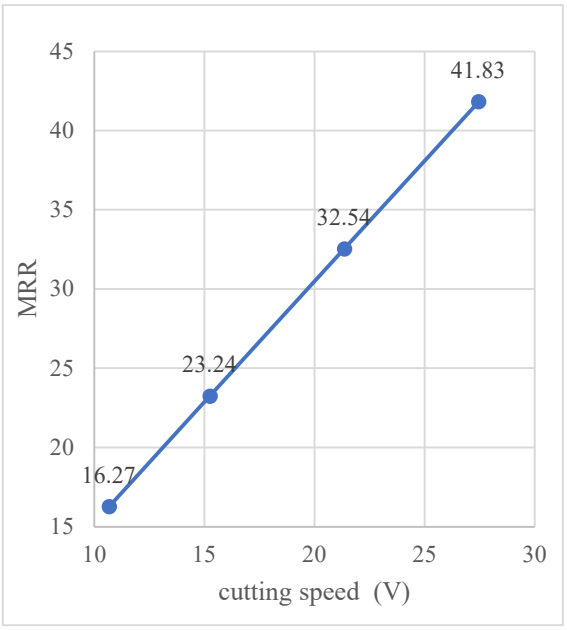
reasonable values for the tool life between 1.77×10^6 and 676min. The gradient of the log-log graph (-1/n) is unaffected by the C value so the sensitivity of the tool life is accurate, although the HSS tool lives are very dependent on the constant value chosen.

11. Effect of Tool Life and MRR

Doubling the HSS cutting speeds (from 10.675 to 27.45m/min) increases Material Removal Rate by 2.57 times but decreases tool life by around 2620 times. Increasing carbides cutting speed (from 90 to 130m/min) by 44% increases Material Removal Rate by 44% but reduces tool life by 77%. This gives a decrease inthe amount of metal being cut by each carbide edge from $1.058 \times 106mm^3$ to $3.51 \times 105mm^3$. This means each edge is only doing one third of the work at maximum cutting speed. All five speeds for cutting with carbides are above the speed required for achieving a 15-minute tool life (150/150.25 ≈ 76.2m/min). This means frequent indexing of inserts will be necessary during production.



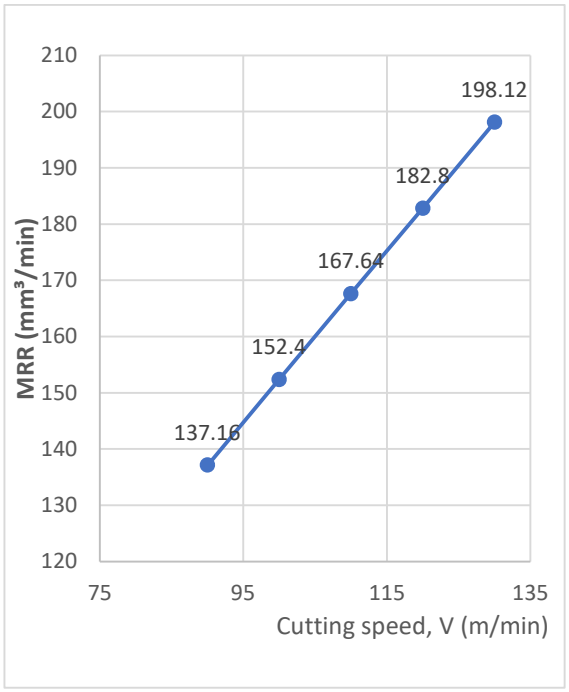
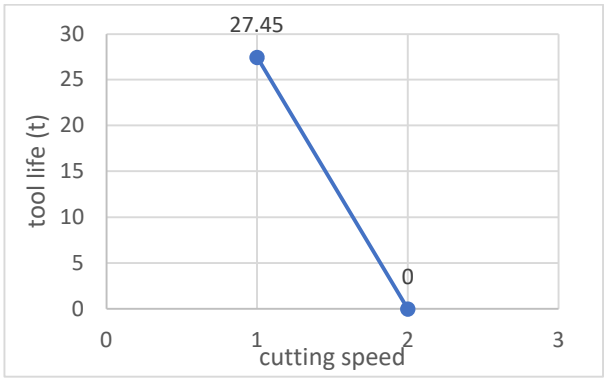


Fig. 1. MRR and tool life against cutting speed for the carbide tool



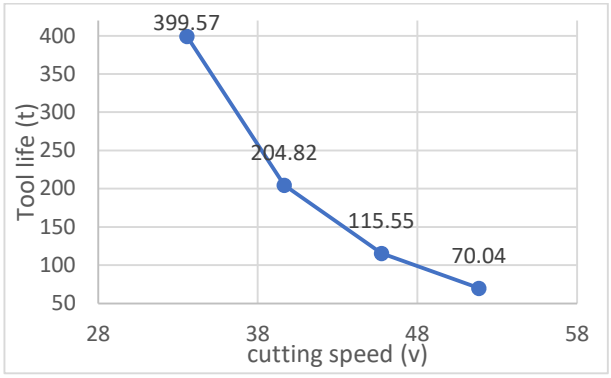


Fig. 2. Predicted tool life against cutting speed (log scale)

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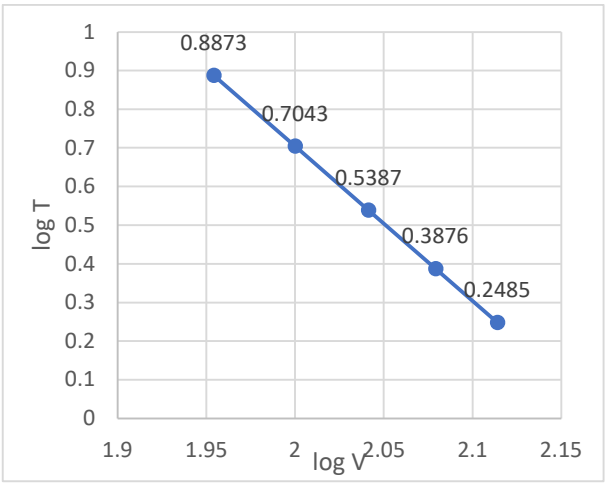
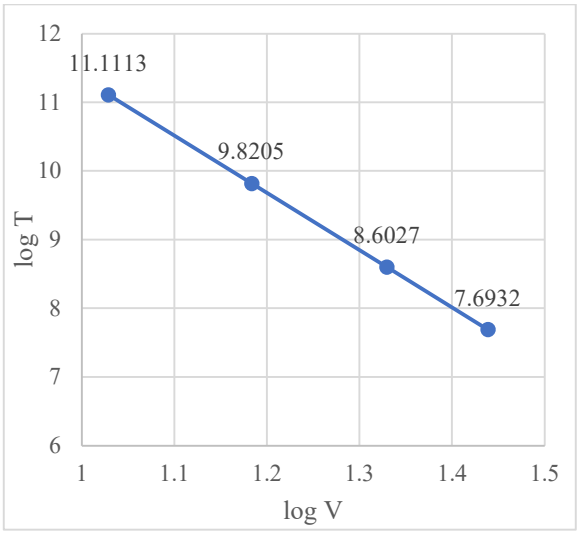


Fig. 3. Taylor log T – log V lines for both tools

12. Cutting Speed and Cutting Force

The cutting and thrust forces are kept constant for each range of cutting speeds. In practice they will reduce slightly at higher cutting speeds due to the temperature softening of the shear zone but once a steady chip formation has been achieved the variations are small compared to those of power and tool life. As the force is constant the specific energy Up = Fc/(d t) is also constant and the power increases linearly as more distance is covered per second by the constant force. This can be seen from the horizontal lines of force in Fig. 4 and straight lines of power in Figs. 5 and 6.



13.Graphs of MRR, Cutting Speed Cutting Force

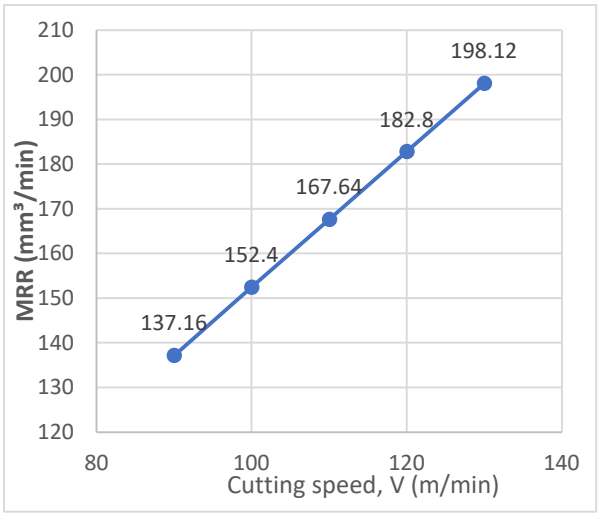


Fig. 4a. Material removal rate against cutting speed for both tools

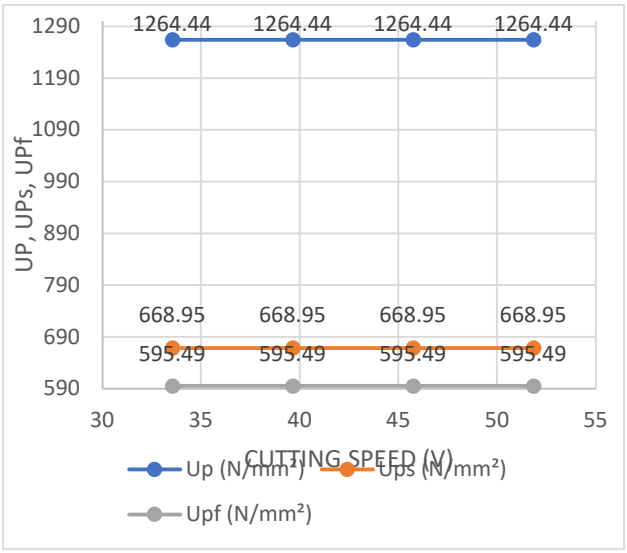


Fig. 4b. Cutting and thrust force against cutting speed

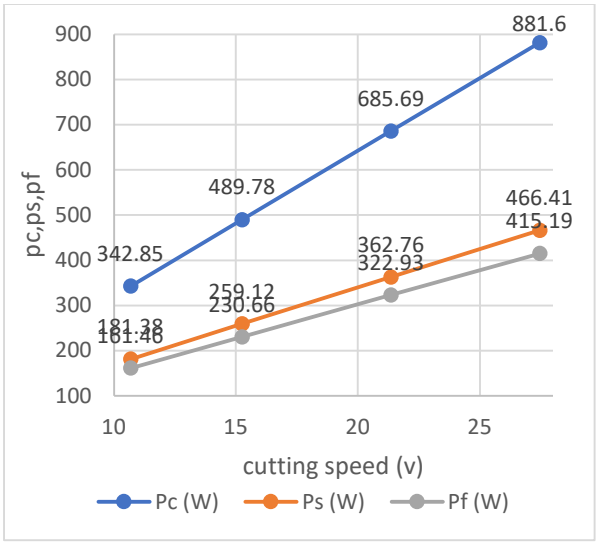


Fig. 5. Cutting, shear and friction power – HSS tool

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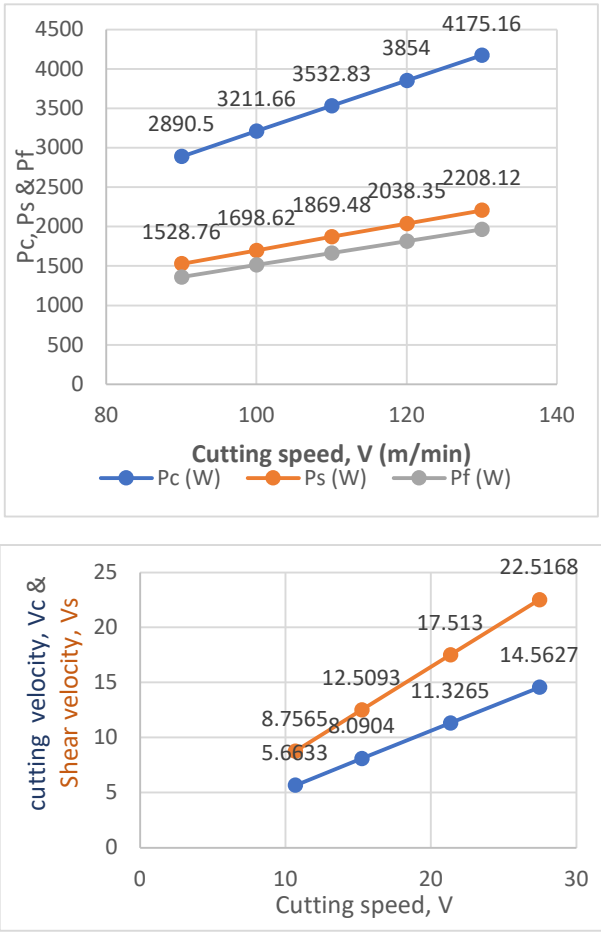

Fig. 6. Cutting, shear and friction power – Carbide tool

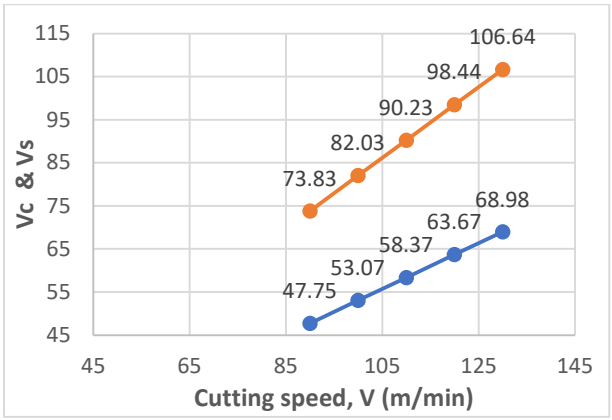

Fig. 7. Cutting speed (v) and cutting velocity (V_c), Shear velocity (V_s) for HSS Tool, Carbide Tool

14. Conclusion

1. With identical geometry and forces, both tools share the same shear-zone state: μ = 1.482, β = 55.98°, r=0.5305,tc = 0.2394 mm, φ = 31.99° and γ = 1.548. The resultant force of 2063.84N is recovered from all three force pairs.
2. The specific energy is 1264.44N/mm² at every speed for both tools; 52.9% goes into shearing and 47.1% into rake-face friction, so nearly half the heat is released at the tool–chip interface.
3. Chip velocity, shear velocity, MRR and all three power components rise in exact proportion to cutting speed, while tool life falls as an inverse power of speed.
4. For HSS (n = 0.12) the log T – log V slope is −8.33, so a 157% rise in speed costs about 99.96% of the tool's life. The constant C = 230m/min gives unrealistic HSS lives and should be replaced by a value near 60m/min for absolute predictions.
5. For carbide (n = 0.25) the slope is −4.00. The tool life decreases from 7.72 to 1.77min between 90 and 130m/min, and the metal being removed per edge goes down by approximately two-thirds. If it were closer to 76m/min, it would have a 15-minute lifespan.
6. Carbide offers at least 3.28 times the removal rate of HSS but demands 3.3 to 12times the power. Speed selection should therefore balance removal rate against tool-change cost, machine power and edge life rather than simply maximise speed.

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