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EXPERIMENTAL DETERMINATION OF OPTIMUM CUTTING CONDITIONS IN TURNING LOW ALLOYED STEEL WITH CEMENTED CARBIDE TOOL

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Abstract

A scientific method has been developed to determine the optimum values of machining variable, which does not involve costly and precision measuring instruments. On the basis of the existing theories and present experimental results the following have been established. Tool wear and cutting force are function of chip-tool contact process, which itself in turn is a function of cutting speed-V for given pair of work and tool materials and conditions of cut. At a definite value of V called critical cutting speed-V_c chip tool contact process and cutting force-P change abruptly. For determination of V_c curves of coefficient of chip shrinkage K vs. V may be used instead of the curves P vs. V. It has been also established that for single carbide tool material optimum value of cutting speed V_{op} is just below V_c ($V_{op} < V_c$). For double carbide tool material there exist two values of optimum cutting speed V_{op_1} and V_{op_2} where,

$V_{op_1} < V_c$ and V_{op_2} a bit higher than V_c .

Notations

S = Feed per revolution

t = Depth of cut

V = Cutting speed

V_c = Critical cutting speed

V_{op} = Optimum cutting speed

P = Cutting force

P_z = Component of cutting force along Z axis

h_f = Tool flank wear

T_1 = Tool life

K = Coefficient of chip shrinkage

L_0 = Length of uncut chip

L_c = Actual length of chip
γ_o = Orthogonal side rake angle
α = Side relief angle
α_1 = End relief angle
ψ = Principal cutting edge angle
ψ_1 = Auxiliary cutting edge angle
z = Total metal removal
z_w = Metal removal rate
ϵ = Intensity of tool flank wear
I = Wear per unit volume of metal removal.

Introduction

The country has launched a programme of intensive industrialization which includes the manufacture of machine tools, cutting tools, spare parts, agricultural and general purpose machines. This involves a huge amount of metal cutting and processing. One of the major problems faced by the machine building industries is a lack of technical know-how for proper and economic operation of the existing machine tools and this causes hindrence to rapid industrial growth in the country. In factories only a small number of engineers and almost no worker are aware of optimum conditions of machining, without which achievement of economy in industrial production is almost impossible. In practice, the values of the metal cutting variables are determined either by mere experience or selected from Engineering table (if available). None of the methods take into consideration the process constraints and hence the selected values are far away from the optimum ones. This results in low production rate and high machining cost. Moreover in the absence of research facilities at our factory levels it is quite impossible to experimentally determine the optimum values of the machining parameters using the existing theories without their modification and orientation to our country's need. In the present work attempts have been made to work out an easy method, which can be followed to choose the optimum values of cutting parameters without using costly measuring instruments. After a wide review of literature in the related field it has been observed that numerous research works have been performed by various investigators on optimization of metal cutting processes. Generally optimization is performed within the feasible region defined by the relevant constraints and with regard to the expected value of the objective function. Large number of research works were carried out by Errest (3), Gilbert (4), Armargo and Russel (1) to determine the objective criterion for optimization. According to their decisions, the objective criteria are :

i) Maximum cost (cost as criterion)
ii) Maximum production rate (production time as criterion)
iii) Maximum profit rate (profit as criterion)

It is a fact that, production costs, production rates and profit rates, all are of vital interest to any manufacturing concern. But analysis of all these criteria at a time is not possible for complexity. It is wise to use only one objective criterion, generally minimum cost (2) in determining economical cutting conditions. It should be noted that, for a given pair of work and tool materials the restrictions of feed—S, speed—V, depth of cut—t, cutting force—p, tool flank wear h_f and tool life T_L will apply whatever criterion is used to determine "Optimum Cutting Conditions".

Large number of research works have been carried out in the "Volgograde Polytechnic Institute", USSR (7), to establish the relations between the above perameters for various cutting conditions with cemented carbide tools. According to the results, the relationship between p_z and V, h_f and V, T_L and V can be represented graphically as in Figure—1, 2 & 3 respectively. Fig. I shows that upto point C_1, the dependence of p_z and V is complex, for both the cases. After that, for single carbide tool material, the curve takes a regular shape (p_z decreases with increase of V), but for double carbide tool material, the curve takes the shape as shown by dashed line, which shows a second peak at C_2.

In Fig. II and III the peak at point C_1 indicates minimum tool wear and maximum tool life for single carbide tool meterial. With further rise in V, tool life gradually decreases. For double carbide tool meterial there are two peaks—one at point C_1, as in the case of single carbides and the other at point C_2, at a higher cutting speed. Similar results were also obtained by other researchers who worked in this field.

From the above figures, it is found that, the point V_C plays a significant role in "Economics of Metal Cutting", since the nature of the curves and also "Chip-tool-Contact" processes change abruptly at this point. Many authors denote this point at "Critical point" or "Critical Cutting Speed," or "V—critical" or simply as 'V_C'. For single carbide tool meterial $V_{op} \leqslant V_C$, and for double carbide tool meterial, $V_{op_1} \leqslant V_c$, $V_{op_2} > V_c$.

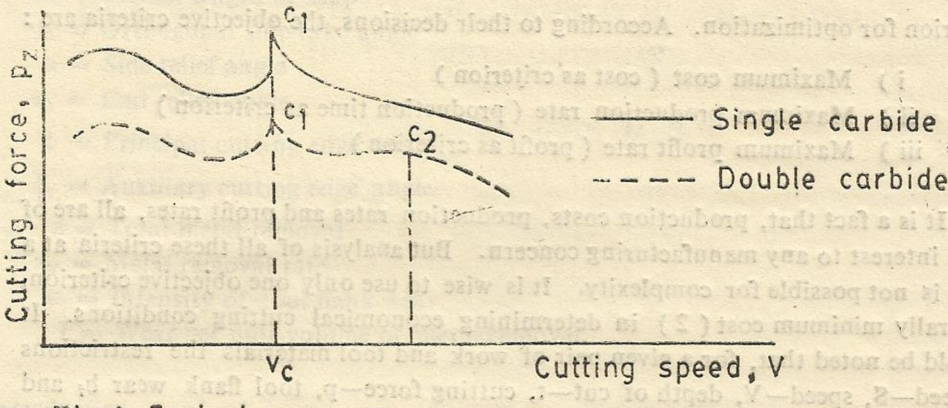

Fig. 1. Typical curve p_z vs. V

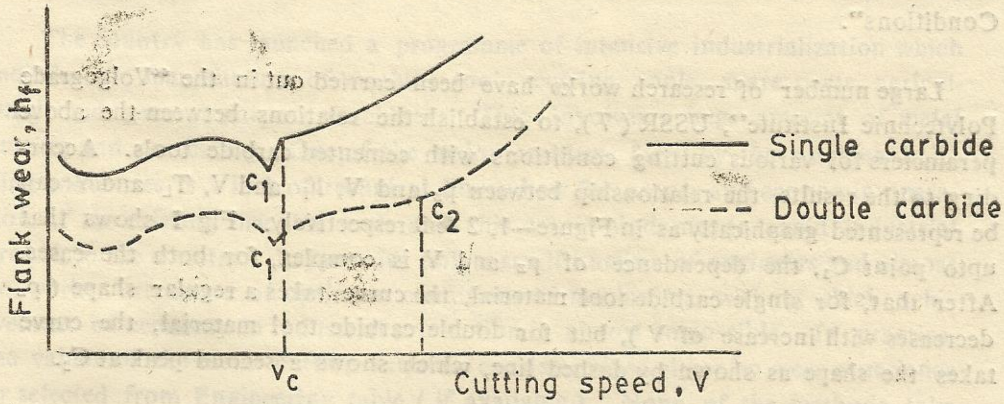

Fig. 2. Typical curve h_f vs. V

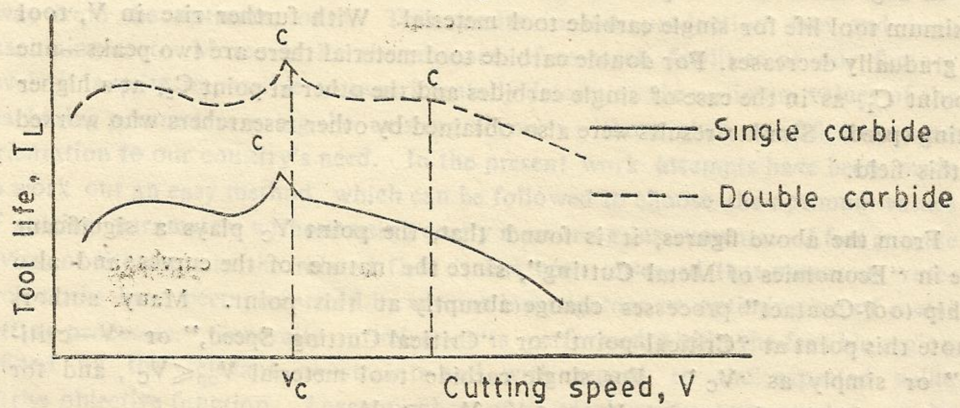

Fig. 3. Typical curve T_L vs. V

Now, in order to find out V_c according to the above discussion it would be necessary to plot any one of the three curves —$P = f(v)$, $T_L = f(v)$ or $\epsilon = f(v)$, which will require the use of costly measuring instruments. To aviod this a relationship betwen p_z and "Chip-reduction or chip shrinkage" co-efficient, K, established by Rozenberg and Eremin (6) may be used. Value of K may be calculated using a very simple relationship :

$$K = \frac{L_o}{L_c} = \frac{\text{Length of uncut chip}}{\text{Actual length of the chip}} \quad \ldots \ldots \ldots \ldots (1)$$

The value of K is affected by :

i) Cutting variables, i. e. V, s, t, etc.

ii) Cutting enviornment and auxiliary variables, such as tool geometry, Cutting fluid etc.

It should be noted that using equation (1) it is very easy to measure the value of K, which needs no costly and precision instrument.

So, for optimization according to the proposed method it is necessary to plot the curves — $K = f(v)$ for various combinations of s and t and to determine the values of V_c for these combinations. V_c should correspond to the maximum value of K. For a single carbide tool material optimum cutting speed and more accurately cutting speed with minimum tool wear, V_{op} will be a bit lower than V_c. For double carbide tool material V_{op_1} will be also a bit lower than V_c, where as V_{op_2} will be higher than V_c.

To varify the applicability of the proposed method the following experiments were carried out.

Experimental procedure

For investigation turning operation of "Drawing roller", an important product of Bangladesh Machine Tools Factory, was chosen. Work material of the same is 10NC6 (C = 0.12%, Mn = 0.60 — 0.90%, Si = 0.10 — 0.40%, Ni = 1.2 — 1.6%, Cr = 0.85 — 1.15%, $p(_{max}) = 0.035\%$ and $s(_{max}) = 0.05\%$), which is a low and carbon low alloyed steel. Tool material chosen is the same as used in the factory for this purpose, which was P15 (containing 15% TiC, 6% Co, 79%WC — doble carbide). Tool geometry was as follows : $\gamma_0 = 6°$, $\psi_1 = 5°$, α and $\alpha_1 = 8°$, $\psi = 91°$. Diameter of the drawing roller was 73—74 mm with its length = 954 — 1207 mm. Machine tool used was a 'MTM No. 7' engine lathe with a 10 h. p. motor, spindle speed : 83, 109, 141, 182, 242, 316, 410 and 528 r. p. m. and feed : 0.20, 0.25, 0.30, 0.30, 0.40 mm/rev, close to those available in the production 'OERLIKON' engine lathe used in the BMTF for this very operation. Turning operation was performed in the Machine Shop of BUET. Sharpening of the tools were done at the CT department of BMTF, tool wear was measured with the aid of a microscope at Metrology Lab. of IPE Department and for micro-photography laboratory facilities of the Metallurgical Engineering Department of BUET were made use of.

Variables in the experiment were speed, feed and depth of cut. Values of these parameters used in the factory (BMTF) before this investigation were as follows : $V = 52$ m/min. ($N = 225$ rpm), $S = 0.20$ mm/rev., $t = 2.5$ mm. The amount of stock to be removed by turning is 15 mm, for which three cuts were necessary (with $t = 2.5$ mm).

In this particular case optimization may be performed for three cuts as practiced in the Shop or two cuts—one rough and the other fine cuts.

In both the cases optimum combinations of V, s and t had to be experimentally determined. For investigations the following values of feed and depth of cut were chosen : $s = 0.2$, 0.25, 0.30, 0.35, 0.40 mm/rev and $t = 2.5$, 3.0, 3.5, 4.0, 4.5, 5.0 mm. For each value of s, curves $K = f(v)$ are drawn for different values of t and for each curve the value of V_c is determined.

Investigations were also carried out to varify the correctness of the shapes of curves $h_f = f(v)$ and $T = f(v)$ for the given work and tool material. These experiments were carried out with $S = 0.20$ rev/min and $t = 2.5$ mm. Curves $h_f = f(L)$ for four typical values of cutting speeds : V_1, V_2, V_3 and V_4 are drawn. To avoid wastage of work material an intensional wear, the value of which is higher than the initial flank wear was imparted to the tool by grinding. From Fig. V values of the intensity of tool wear per unit length of metal being cut ϵ was calculated and curve $\epsilon = f(v)$ was drawn (Fig. VI). For optimization with respect to V, s and t it was necessary to findout the values of intensity of tool wear per unit volume of metal removal, I and metal removal rate, Z_w for various combinations of the same variables. Values of I and Z_w for $t = 2.5$ mm. $S = 0.20$ mm/rev. $V = 46$, 66, 79 and 99 m/min and $t = 5$ mm. $S = 0.20$ mm/rev and $V = 75$ m/min. are shown in Table II.

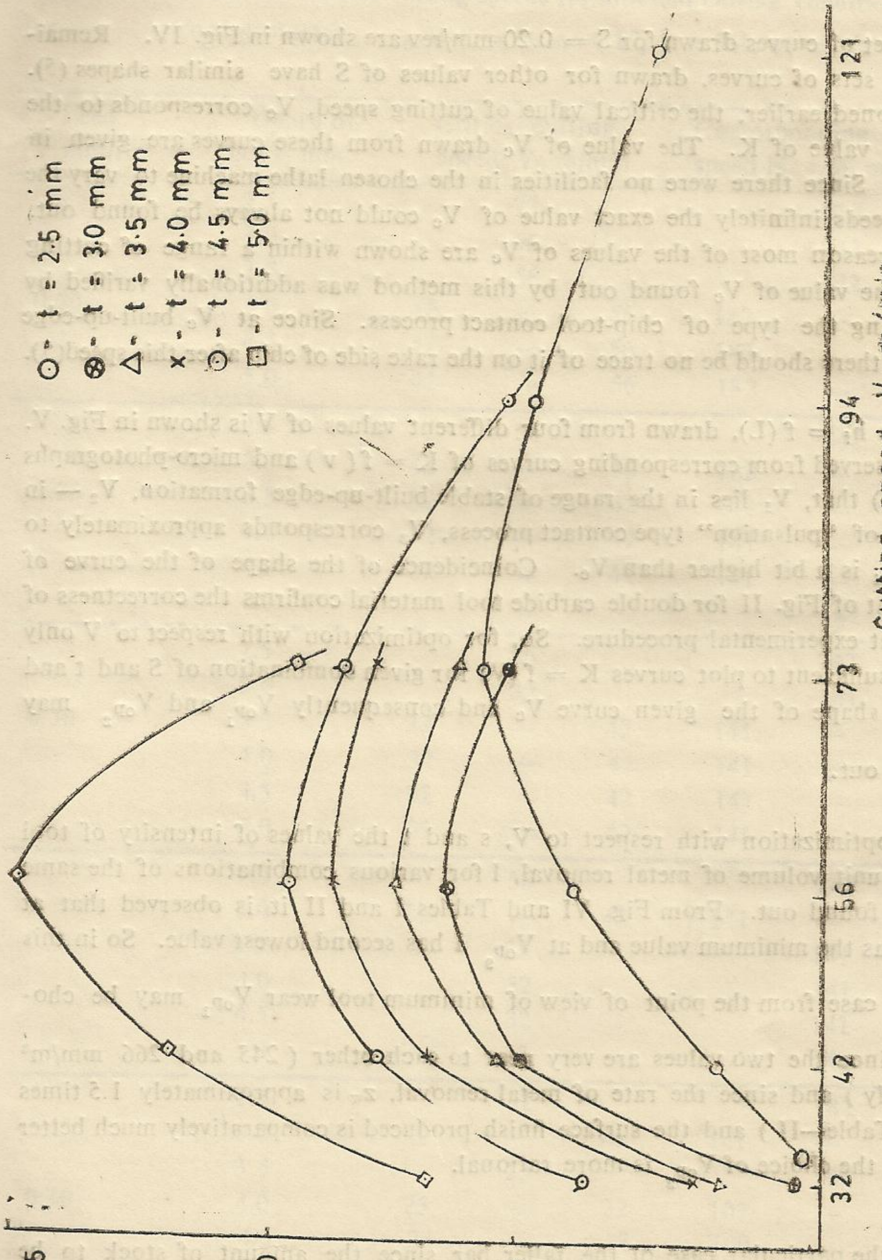

Fig. 4 Effect of cutting speed on chip-shrinkage S = 0.20 mm/rev. (from experimental data)

Results and Discussions

One set of curves drawn for $S = 0.20$ mm/rev are shown in Fig. IV. Remaining four sets of curves, drawn for other values of S have similar shapes (5). As mentioned earlier, the critical value of cutting speed, V_c corresponds to the maximum value of K. The value of V_c drawn from these curves are given in Table—I. Since there were no facilities in the chosen lathe machine to vary the spindle speeds infinitely the exact value of V_c could not always be found out. For this reason most of the values of V_c are shown within a range of cutting speed. The value of V_c found out by this method was additionally varified by investigating the type of chip-tool contact process. Since at V_c built-up-edge vanishes, there should be no trace of it on the rake side of chip after this speed(5).

Curve $h_f = f(L)$, drawn from four different values of V is shown in Fig. V. It was observed from corresponding curves of $K = f(v)$ and micro-photographs of chip (5) that, V_1 lies in the range of stable built-up-edge formation, V_2 — in the range of "pulsation" type contact process, V_3 corresponds approximately to V_c and V_4 is a bit higher than V_c. Coincidence of the shape of the curve of Fig. V that of Fig. II for double carbide tool material confirms the correctness of the present experimental procedure. So, for optimization with respect to V only it will be sufficient to plot curves $K = f(V)$ for given combination of S and t and from the shape of the given curve V_c and consequently V_{op_1} and V_{op_2} may be found out.

For optimization with respect to V, s and t the values of intensity of tool wear per unit volume of metal removal, I for various combinations of the same are to be found out. From Fig. VI and Tables I and II it is observed that at V_{op_1} I has the minimum value and at V_{op_2} I has second lowest value. So in this particular case from the point of view of minimum tool wear V_{op_1} may be chosen but since the two values are very near to each other (245 and 266 mm/m^3 respectively) and since the rate of metal removal, z_w is approximately 1.5 times higher (Table—II) and the surface finish produced is comparatively much better at V_{op_2}, the choice of V_{op_2} is more rational.

For the particular case of the faller bar since the amount of stock to be removed on diameter is 15 mm, the job can be completed with two cuts as mentioned earlier. If a stock of 5 mm on diameter be left for finish cut, depth for

Table—I. Values of critical cutting speeds for different cutting conditions

Tool geometry : $\gamma_o = 6, \alpha = \alpha_1 = 8°, \psi = 91°, \psi_1 = 5°$

Feed s, mm/rev	Depth of cut t, mm	Critical cutting speed, Vc m/min	Corresponding spindle speed N. r. p. m.
0.20	2.5	73	316
	3.0	56	242
	3.5	56	242
	4.0	42 — 56	182 — 242
	4.5	42 — 56	182 — 242
	5.0	42 — 56	182 — 242
0.25	2.5	56	242
	3.0	42 — 56	182 — 242
	3.5	32 — 42	141 — 182
	4.0	32 — 42	141 — 182
	4.5	32 — 42	141 — 182
	5.0	42	182
0.30	2.5	56	242
	3.0	32	141
	3.5	32 — 42	141 — 182
	4.0	32 — 42	141 — 182
	4.5	32 — 42	141 — 182
	5.0	32 — 42	141 — 182
0.35	2.5	56	242
	3.0	32 — 42	141 — 182
	3.5	32	141
	4.0	32	141
	4.5	32	141
	5.0	32	141
0.40	2.5	42	182
	3.0	32 — 42	141 — 182
	3.5	25	109
	4.0	25 — 32	109 — 141
	4.5	25 — 32	109 — 141
	5.0	32 — 42	141 — 182

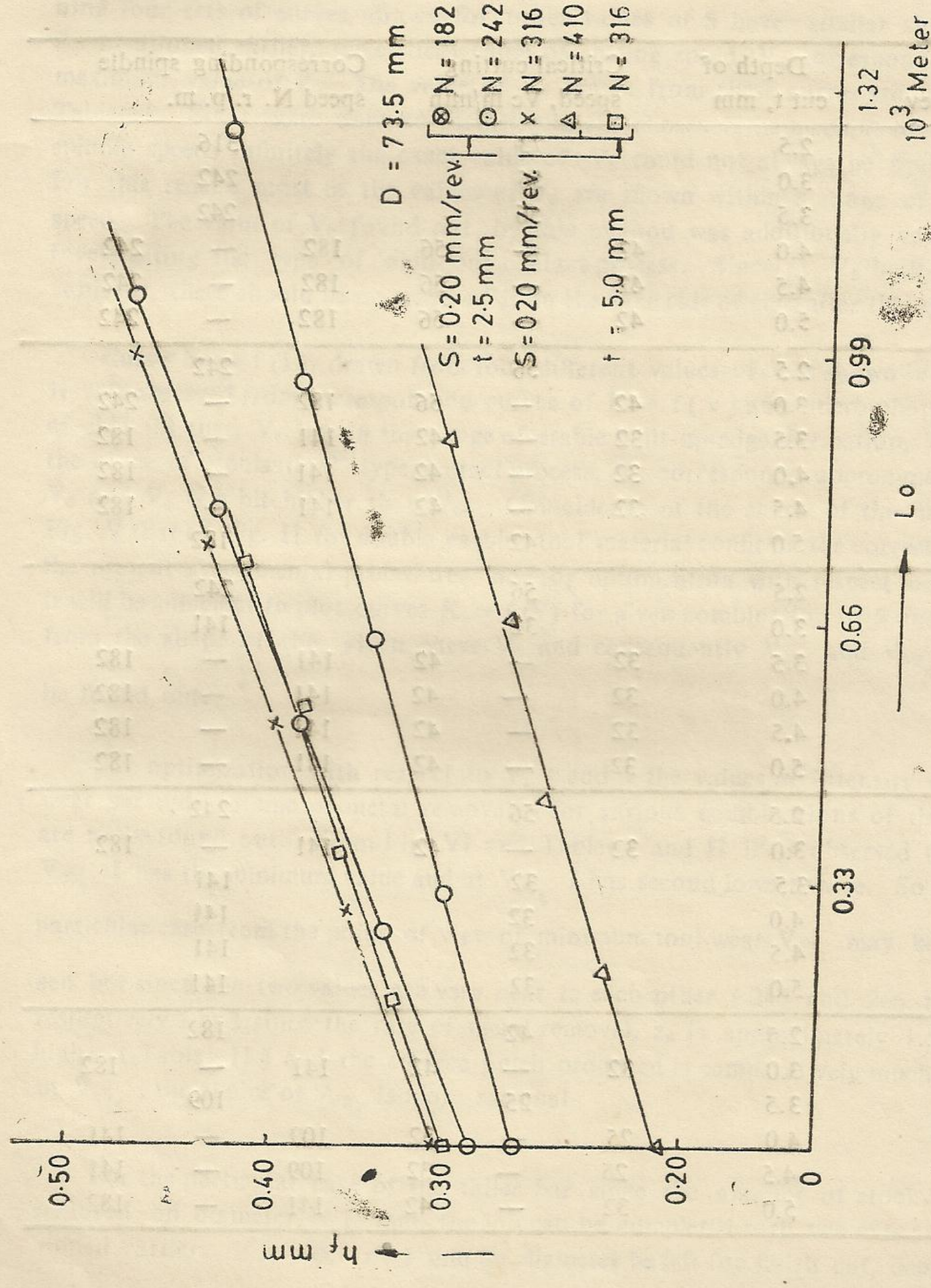

Fig.5. Effect of length of cut on flank-wear (Evaluated from test data)

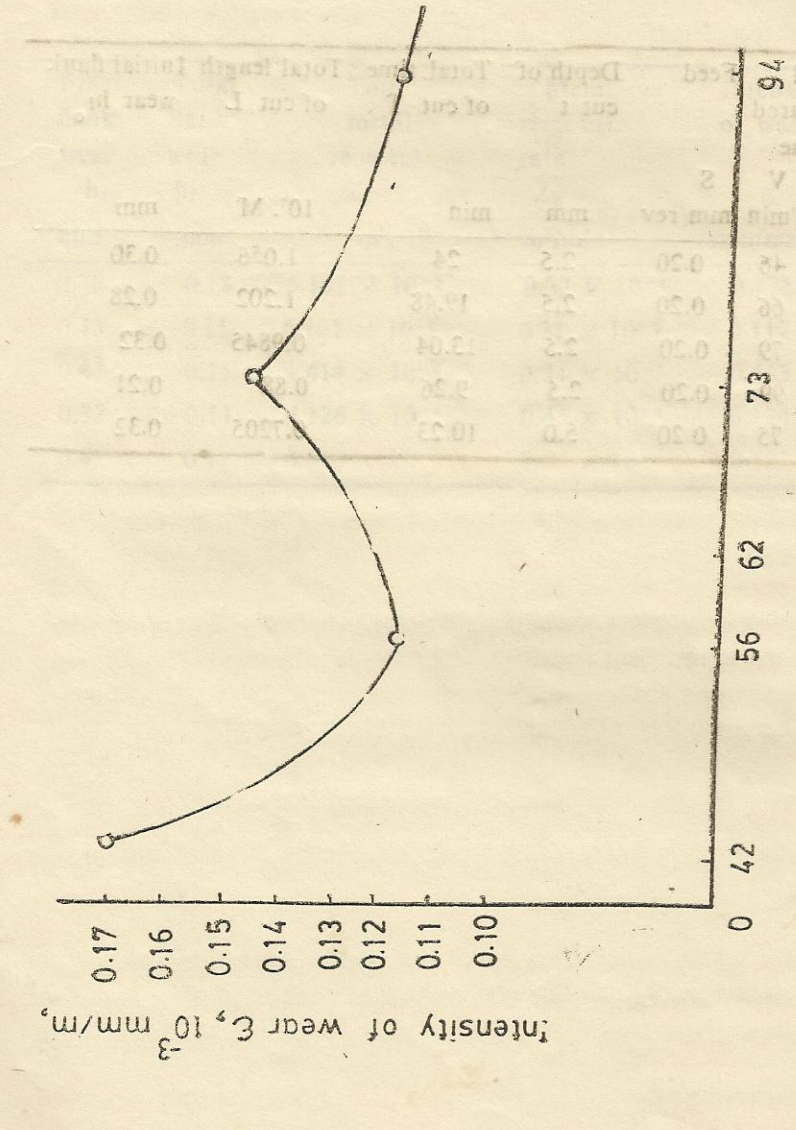

Fig. 6. Effect of cutting speed on Intensity of wear at S = 0.20 mm/rev. t = 2.5 mm (Evaluated from test data)

Table—II Test Result.

Theoretical N rpm	Theoretical V m/min	Actual Measured value N rpm	Actual Measured value V m/min	Feed S mm/rev	Depth of cut t mm	Total time of cut T min	Total length of cut L 10^3. M	Initial flank wear h_{f_c} mm
182	42	200	46	0.20	2.5	24	1.056	0.30
242	56	289	66	0.20	2.5	19.48	1.202	0.28
316	73	342	79	0.20	2.5	13.04	0.9845	0.32
410	94	434	99	0.20	2.5	9.26	0.88	0.21
316	73	323	75	0.20	5.0	10.23	0.7205	0.32

Final flank wear h_{f_1} mm	Total flank wear h_f mm	Total metal removal Z m^3	Metal removal rate Z_w m^3/min	Intensity of wear ϵ $mm/mx10^{-8}$	Wear per unit volume of metal removal I mm/m^3
0.48	0.18	5.162×10^{-4}	0.22×10^{-4}	0.171	348.70
0.43	0.15	6.121×10^{-4}	0.31×10^{-4}	0.117	245.10
0.47	0.15	4.414×10^{-4}	0.34×10^{-4}	0.153	339.80
0.32	0.11	4.126×10^{-4}	0.45×10^{-4}	0.124	266.60
0.42	0.11	6.640×10^{-4}	0.65×10^{-4}	0.137	150.60

rough cut should be 5 mm. It is experimentally proved that with this value s of t, values of s more than 0.2 mm/rev. can not be taken. For higher values of the tool cracks. Now fot $t = 5.0$ mm, $s = 0.2$ mm/rev. and $V_{op} = V_{op_2}$, which corresponds to $V = 75$ m/min, curve $h_f = f(L_o)$ is drawn (Fig. IV) and intensity of tool wear per unit volume of metal being cut is calculated and shown in Table—II along with the rate of metal removal for these values of V, s and t. From Table—II it is seen that value of I for these conditions is very low and this is approximately 1.78 times lower than the corresponding value of I for $t = 2.5$, $s = 0.2$. At the same time removal rate z_w is approximately 1.44 times higher.

Now we have three variants for comparison :

i) turning by two passes (cuts) — (variant—1) : initial cut with $V = 75$ m/min, $s = 0.2$ mm/rev., $t = 5.0$ mm and final cut with $V = 99$ m/min, $s = 0.20$ mm/rev., $t = 2.5$ mm.

ii) turning by three passes (cuts) — (variant — 2) each cut with $V = 99$ m/min.

iii) existing factory variant, — (variant — 3) : turning by three passes (cuts) and each cut with $V = 53$ m/min, $s = 0.20$ mm/rev., and $t = 2.5$ mm.

It has been proved by economic analysis (5) that, variant — 1 is most economic amongst the above mentioned variants. Economic advantage of variant-1 in machining 1000 pieces over variant — 2 is approximately Tk. 26,140.00 and over variant — 3 for the same lot is approximately Tk. 95,120.00.

The following may by concluded from the above mentioned :

It is possible to find out optimum cutting speed if only the shape of the curve $K = f(V)$ is known.

For single carbide tool material there is only one optimum cutting speed V_{op} where V_{op} is a bit lower than V_c. For double carbide tool material there are two values of optimum cutting speed — V_{op_1} and V_{op_2} where, V_{op_1} is a bit lower than V_c and V_{op_2} little higher than V_c.

For double carbide tool material minimum intensity of tool wear per unit volume of metal removal, I lies at point V_{op_1} and second lowest value of I lies is at V_{op_2} .

Though from the point of view of minimum tool wear V_{op_1} is more advantageous, but cost of production is lowest at V_{op_2} . Moreover, surface finish attained at V_{op_2} ↑ is much higher than at V_{op_1} . So, for practical purposes V_{op_2} can be proposed as optimum cutting speed for double carbide tool material in machining the investigated material.

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