An experimental investigation of hot-machining to predict tool life

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ABSTRACT

An experimental investigation had been carried out for hot-machining operation of high manganese steel using a carbide cutting tool. The heating of the work-piece was carried out by burning a mixture of liquid petroleum gas and oxygen. An expression of tool life as a function of cutting speed, feed, depth of cut and temperature was developed using regression analysis. The adequacy of the model was tested. The effects of cutting conditions on tool life were also investigated.

1. Introduction

The production of exotic and smart materials has become highly indispensable to satisfy the robust design requirements for aerospace and defence sector. The machining of these materials has posed a great challenge in industries. It requires cutting tool of high strength, which is very costly, and sometimes it is even impracticable. Non-conventional machining process, another viable method, is mostly restricted to small-scale removal of material. For bulk removal of material, the growing interest for hot machining process is being developed in industry. In this method work-piece is softened by heating and thereby shear strength is reduced.

Tigham first innovated the process of hot machining in 1889, since then it has created much interest among various investigators. In early stages, materials difficult to machine under normal conditions such as stainless steel, S-816alloy, X-alloy, Inconel-X, Timken 16-25-6 and Navy Grade V, a nickel–chromium steel have been hot machined by Tour and Fletcher (1949), Armastrong et al. (1951), Krabacher and Merchant (1951) and Schmidt and Roubik (1949). Krabacher and Merchant (1951) observed that at an optimum temperature the tool life rises to a maximum value and after that it reduces. Another important observation made by Shaw (1951) is that the strain-hardenability and flow stress of material reduces with increase in temperature in hot machining.

Mukherjee and Basu (1973) carried out statistical evaluation of metal cutting parameters in hot machining. He used nickel–chromium steel as the work-piece material. The material was hardened by water-quenching from 750 °C to a hardness of 440 BHN resulting in a microstructure consisting of martensite with a few undissolved carbides distributed at random throughout the matrix. He measured tool life and surface finish. He concluded that cutting velocity, work-piece temperature, feed and depth of cut influence the tool life in the same order. They also observed that surface roughness decreases more considerably with increase in temperature than that of cutting velocity. They concluded that the influence of work-piece temperature on surface roughness is much more pronounced than on tool life.

Barrow (1966) studied the wear of carbide tools during hot machining of alloy steels. He used electric current heating. Ghosh and Basu (1966) carried out temperature distribution in a rotating cylinder with steady point heat source at the surface. Dutta (1968) carried out hot machining by friction heating. Meakawa and Kubo (1988) performed plasma hot machin-

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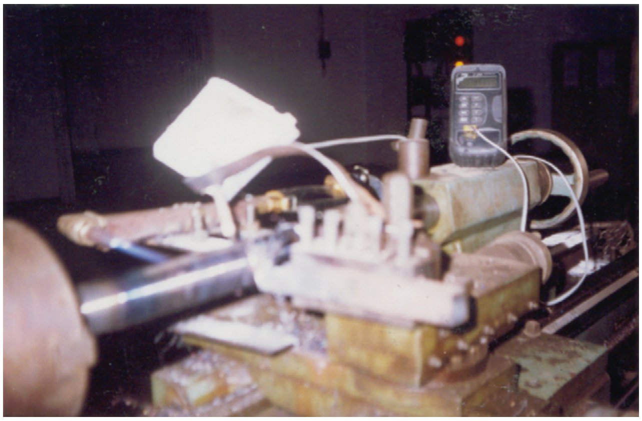

Fig. 1 – Experimental set-up of hot-machining operation.

ing for high hardness metal and new engineering materials. Roughuram and Mujo (1980) carried out hot machining by magnetization in hot machining. Ozler et al. (2000) carried out hot-machining operation using austenitic manganese steel as work-piece material using gas flame heating.

In the present investigation an attempt has been made to carry out an investigation in hot-machining operation of high manganese steel using flame heating. A tool life equation has been established from statistical analysis.

2. Experimental investigation

The experimental set-up is shown in Figs. 1 and 2. A heating torch was mounted on tool carriage to provide a moving heat source while machining. The torch burned a mixture of liquid petroleum gas and oxygen. The distance of the tip of the torch from the work-piece was varied to control the temperature. A thermocouple with a digital indicator was used to measure the temperature of the work piece.

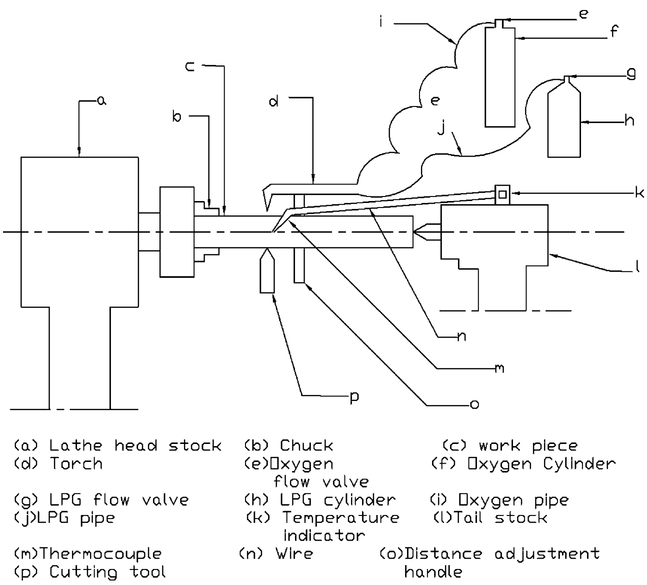

Fig. 2 – Schematic diagram of experimental set-up.

The work material used was high manganese steel. Its composition was (%): Mn12.5 C1.2 Si.4 Cr1.6 P.058 S.01 Fe84.23. The material was hardened by quenching and the hardness was measured to be $56R_c$ in Rockwell scale.

A carbide tool with specification ATP ISO (M10) was used. The tool had the following geometrical parameters:

- Side rake angle = 4.6250°.
- Back rake angle = 0.925°.
- Orthogonal clearance angle = 9.7°.
- Orthogonal rake angle = 5.2°.

The cutting forces were measured using a Syscon make strain gauge type turning dynamometer with a HSS cutting tool for hot machining condition. Chip thickness was measured using a screw thread type micrometer.

3. Design of experiment

The experiment was conducted to establish the equation of tool life in terms of four variables. The tool life was taken as the yield or response. The functional relationship of the tool life T and variables cutting speed V_C, feed s, depth of cut t were assumed as follows:

$$T = kV_C^{\beta_1} S^{\beta_2} t^{\beta_3} \theta^{\beta_4} \quad (1)$$

where k is a constant.

Taking logarithm of the expression, the Eq. (1) can be written in first order form:

$$\log T = \log k + \beta_1 \log V_c + \beta_2 \log s + \beta_3 \log t + \beta_4 \log \theta \quad (2)$$

Further Eq. (2) can be written in the form as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \quad (3)$$

where $\beta_0 = \log k$, $x_1 = \log V_c$, $x_2 = \log s$, $x_3 = \log t$, $x_4 = \log \theta$.

Since all the factors represent quantitative variables, the yield or response Y is a function of the levels of these variables. It can be written in the following form:

$$Y_{iu} = \phi(X_{1u}, X_{2u}, \ldots X_{iu}, \ldots) + e_u \quad (4)$$

where $u = 1, 2, \ldots, N$ where N represents number of observations in the factorial experiment and x_{iu} represents the level of the ith factor in the uth observation ($i = 1, 2, \ldots, k$). The function ϕ is called the response surface. The residual e_u measures the experimental error of the uth observation. The relation between Y_{iu} and x_{iu} is of the form:

$$Y_{iu} = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \cdots + \beta_i x_{iu} + \cdots + \beta_k x_{ku} + e_u \quad (5)$$

Since β_0 occurs in every equation, it is customary for the sake of uniformity to introduce a dummy variable x_{0u} which has the value 1 for every observation. For four variables, the relation of response and variable is as follows:

$$Y_{iu} = \beta_0 x_{0u} + \beta_1 x_{1u} + \beta_2 x_{2u} + \beta_3 x_{3u} + \beta_4 x_{4u} + e_u$$

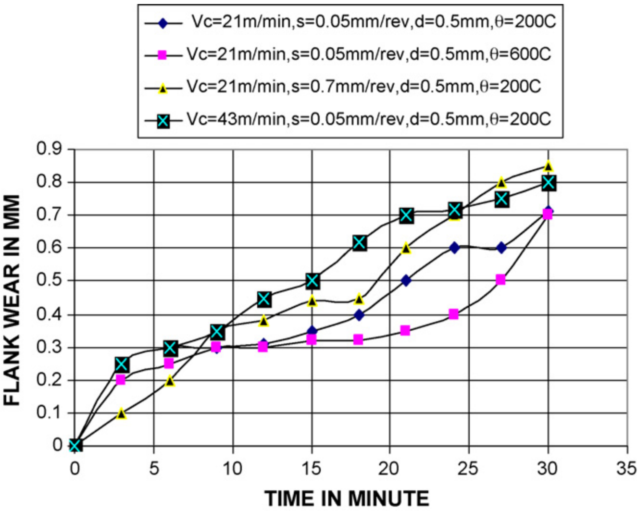

Fig. 3 – Variation of width of flank wear land with respect to time for first set of cutting variables.

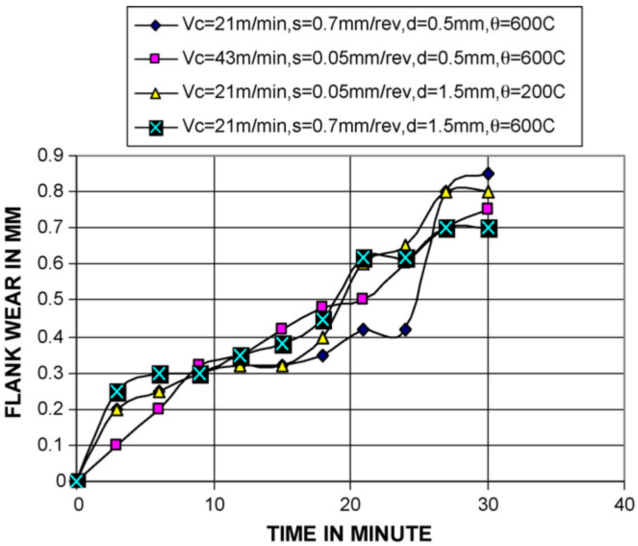

Fig. 4 – Variation of width of flank wear land with respect to time for second set of cutting variables.

In the current investigation the values of the limiting factor were as follows:

- Cutting speed $V_c = 22–43$ m/min.
- Feed $s = 0.05–0.7$ mm/revolution.
- Temperature $\theta = 200–600\,^{\circ}$C.
- Depth of cut $t = 0.5–1.5$ mm.

4. Results and discussion

The flank wear height of tool was measured under a microscope for a fixed time interval for each factor of combination and 10 readings were taken for each case. The variations of flank wear with respect to time were plotted in Figs. 3–6. For

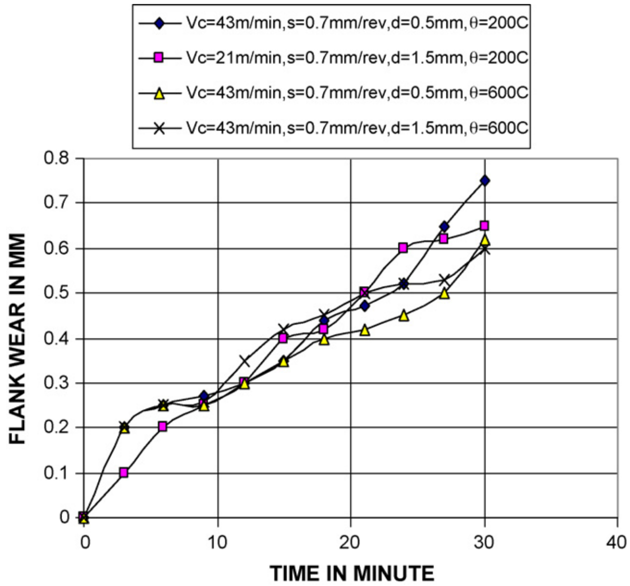

Fig. 5 – Variation of width of flank wear land with respect to time for third set of cutting variables.

each factor combination the tool life was determined taking 0.4 mm of flank wear height as the tool life criterion. The tool life is indicated by dotted line in the graph for each factor combination.

The variation of mean chip-reduction coefficient with respect to temperature of workpiece is shown in Fig. 7. It is observed that the chip-reduction coefficient reduces with increase in temperature. Hence the machinability of the material improves with increase in temperature. The variation of average non-dimensional tangential cutting force F_C and

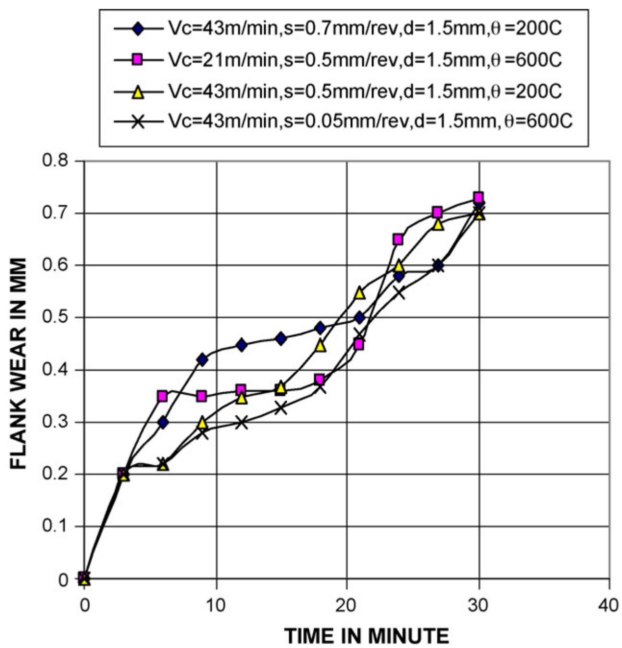

Fig. 6 – Variation of width of flank wear land with respect to time for fourth set of cutting variables.

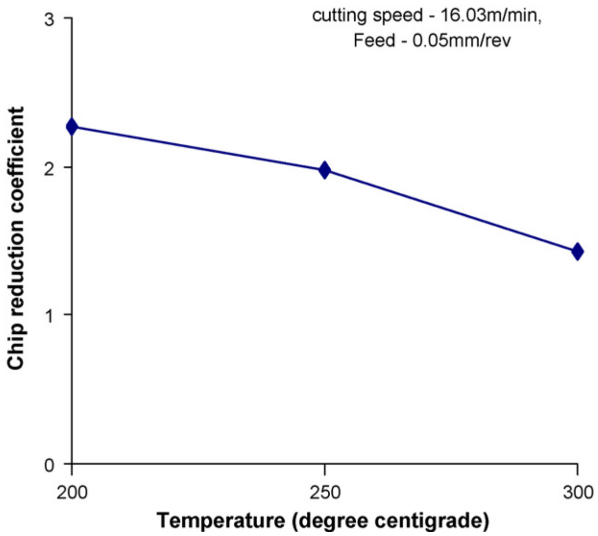

Fig. 7 – Variation of chip-reduction coefficient with respect to time.

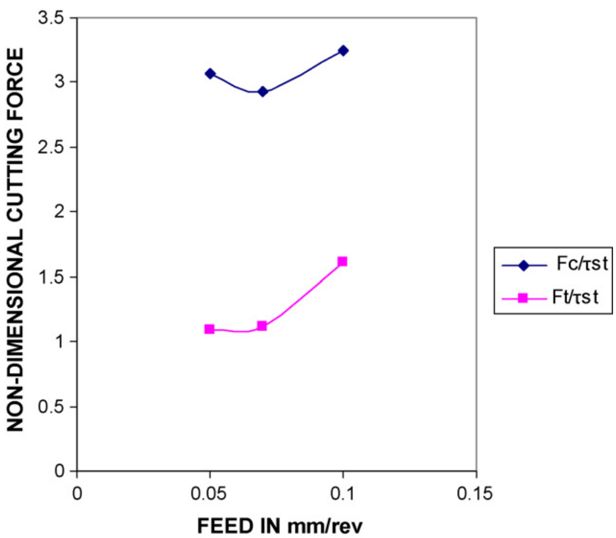

Fig. 8 – Variation of non-dimensional cutting force and thrust force with respect to time.

thrust force F_t with respect to feed with workpiece heated to a temperature of 350 °C is shown in Fig. 8. It is observed that both cutting force and thrust force increase with increase in feed. The non-dimensional cutting force is found to be higher than the non-dimensional thrust force which symbolizes a normal machining operation. The chip produced at high temperature is of continuous type whereas it is discontinuous type in room temperature. It is evident from the shape and size of chip that hot machining operations yields higher tool life, better surface finish and lower power consumption.

The factor combinations expressed in coded scale are arranged in tabular form together with the observed values of tool life in Table 1.

$$[A] = [X] = \begin{bmatrix} +1 & -1 & -1 & -1 & -1 \\ +1 & -1 & -1 & -1 & +1 \\ +1 & -1 & +1 & -1 & -1 \\ +1 & +1 & -1 & -1 & -1 \\ +1 & -1 & +1 & -1 & +1 \\ +1 & +1 & -1 & -1 & +1 \\ +1 & -1 & -1 & +1 & -1 \\ +1 & -1 & +1 & +1 & +1 \\ +1 & +1 & +1 & -1 & -1 \\ +1 & -1 & +1 & +1 & -1 \\ +1 & +1 & +1 & -1 & +1 \\ +1 & +1 & +1 & +1 & +1 \\ +1 & +1 & +1 & +1 & -1 \\ +1 & -1 & -1 & +1 & +1 \\ +1 & +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & +1 & +1 \end{bmatrix}$$

$$[B] = [X][X^T]$$

$$[C] = [B]^{-1}$$

$$[D] = [C][A]$$

$$[F] = [D][E]$$

where $[E]$ represents the experimental tool life.

$$[E] = \begin{bmatrix} 1.2553 \\ 1.3802 \\ 1.0212 \\ 1.2984 \\ 1.1511 \\ 1.2553 \\ 1.2095 \\ 1.218 \\ 1.1761 \\ 1.2905 \\ 1.1414 \\ 0.9269 \\ 1.2844 \\ 1.2164 \\ 1.2765 \end{bmatrix}$$

$$[F] = \begin{bmatrix} 1.2008 \\ -0.0455 \\ -0.0293 \\ -0.015 \\ 0.0532 \end{bmatrix} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix}$$

Hence the equation of tool life can be written as follows:

$$Y = 1.2008 - 0.04555x_1 - 0.0293x_2 - 0.015x_3 + 0.0532x_4$$

$$\log T = 1.2008 \log 10 - 0.0455 \log V - 0.0293 \log s - 0.015 \log t + 0.0532 \log \theta$$

$$\log T = \log(10^{1.2008} V^{-0.0455} s^{-0.0293} t^{-0.015} \theta^{0.0532})$$

$$T = \frac{10^{1.2008} \theta^{0.0532}}{V^{0.0455} s^{0.0293} t^{0.015}}$$

Table 1 – Observed values of tool lives

Sl. no.	Experimental tool life T_E (min)	Computed tool life T_C (min)	$\frac{(T_E-T_C)^2}{T_C}$
1	18	20.2158	0.2429
2	24	21.4325	0.3076
3	12.92	18.7115	1.7926
4	10.5	19.5672	4.2016
5	19.88	19.8377	0.00009
6	14.16	20.7449	2.09
7	18	19.8854	0.1788
8	16.2	19.5135	0.5627
9	16.52	18.1112	0.1398
10	15	18.4057	0.6302
11	19.52	19.2013	0.0053
12	13.85	18.8875	1.3436
13	8.45	17.8152	4.9232
14	19.25	21.0822	0.1592
15	16.46	19.2474	0.4037
16	18.9	20.4089	0.1111

5. Test of adequacy of the postulated model

Adequacy of the postulated model is tested by χ^2-test and by analysis of variance as given in Table 2.

From the above table, the summation of $(T_E - T_C)^2/T_C$ is obtained to be 17.09239. Since the number of levels in experiment is $N = 16$, the degree of freedom $= N - 1 = 15$. From the table, the χ^2-value for degree of freedom 15 and probability of 5% confidence level is 24.996. Since the obtained value is much less than the above value, the equation is very probably correct.

5.1. *Effect of cutting parameters*

The effects of different cutting parameters on tool life are analyzed from Table 1. A_i, B_i, C_i and D_i represent tool lives corresponding to low and high level of cutting velocity, feed, depth of cut and temperature, respectively with the suffix $i = 1$ corresponding to low level of factor where as suffix $i = 2$ corresponds to high level. The average tool lives are computed for high and low level of factors separately and their differences are tabulated in Table 3.

Table 2 – Analysis of variance

Sl. no.	Factors					Tool life, T_E	$\log T_E$
	X_0	X_1	X_2	X_3	X_4		
1	+1	−1	−1	−1	−1	18	1.2553
2	+1	−1	−1	−1	+1	24	1.3802
3	+1	−1	+1	−1	−1	12.92	1.1113
4	+1	+1	−1	−1	−1	10.5	1.0212
5	+1	−1	+1	−1	+1	19.88	1.2984
6	+1	+1	−1	−1	+1	14.16	1.1511
7	+1	−1	−1	+1	−1	18	1.2553
8	+1	−1	+1	+1	+1	16.2	1.2095
9	+1	+1	+1	−1	−1	16.52	1.218
10	+1	−1	+1	+1	−1	15	1.1761
11	+1	+1	+1	−1	+1	19.52	1.2905
12	+1	+1	+1	+1	+1	13.85	1.1414
13	+1	+1	+1	+1	−1	8.45	0.9269
14	+1	−1	−1	+1	+1	19.25	1.2844
15	+1	+1	−1	+1	−1	16.46	1.2164
16	+1	+1	−1	+1	+1	18.9	1.2765

Table 3 – Difference in tool-lives for high and low level of factors

Level	Factor A	Factor B	Factor C	Factor D
Low level	17.9063	17.4088	16.9375	14.4813
High level	14.795	15.2925	15.7638	18.22
Difference	3.1083	2.1163	1.1737	3.7387

It is evident from Table 3 that tool life is greatly influenced by workpiece temperature and cutting speed. The temperature of workpiece plays a significant role in improving the tool life. The significance of feed on tool life is more than the depth of cut. There is increase in tool life with decrease of cutting speed, feed and depth of cut but tool life increases with increase in work-piece temperature. However, the limiting highest temperature will be the recrystalisation temperature of workpiece, as higher heating temperature beyond that may induce unwanted structural changes in the work-piece material.

6. Conclusion

A tool life equation is developed for machining hardened high manganese steel for hot-machining operation. The model adequacy is tested using χ^2-test. The tool life is influenced by work-piece temperature, cutting speed, feed and depth of cut in that order. So the effect of temperature of work-piece is found to be the most significant on tool life. However the recrystalisation temperature of work-piece limits the maximum value of temperature. The chip-reduction coefficient decreases with increase in temperature.

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