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A study of the tool life of TiC and TiC plus Al_2O_3 chemical vapour deposited tungsten carbide tools

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Tool life characteristics were investigated for tungsten carbide cutting tools coated with TiC and with TiC plus Al_2O_3. A low carbon steel workpiece was turned on a lathe at a feed rate of 0.206 to 0.410 mm rev^{-1} and a depth of cut of 0.1 to 0.5 mm for cutting velocities between 100 and 250 m min^{-1}. Data were analysed using both Taylor's tool life equation and Wu's tool life method. Results were similar for both methods but Wu's method seemed to give more consistent results. Compared to an uncoated tungsten carbide tool, the tool life of both the coated tools were from 5 to 7 times longer and the improvement was greater at higher cutting speeds. The TiC plus Al_2O_3 coated tool was slightly superior to the TiC coated tool. The wear mechanism and a possible explanation of increased tool life for the coated tools are discussed.

1. Introduction

When cutting is performed, the tool life of a cutting tool decreases owing to plastic deformation, oxidation and wear. Thus the methods for increasing tool life have been investigated for many decades. Recently, chemical vapour deposition (CVD) method [1, 2] has enabled the tool life to increase longer. CVD is a process of depositing the desired material onto a substrate by reacting gaseous compounds at elevated temperatures. Since TiC coating [3, 4] was developed in 1959, various kinds of coatings have been developed including TiC, TiCN, HfC, and Al_2O_3. Some composite coatings are also under investigation. A CVD coating on a cutting tool decreases the friction between the tool and the workpiece and increases the wear resistance, thus increasing the tool life. In this paper, a composite coating of TiC plus Al_2O_3 has been developed, which was superior to a single coating in wear resistance and hot hardness [5–8]. The tool life of the composite coating was compared with that of the TiC single coating. In analysing the tool life, two tool life equations were used; Taylor's equation [9] and Wu's equation [10]. The former is a typical one-variable equation, and the latter is three-dimensional variable equation. Wu's equation is more complicated but an economical procedure.

1.1. Wear test

Wear is a phenomenon whereby a material diminishes gradually from the face of the body as a result of mutual movement at the interface of the two contacting bodies [11]. There are two kinds of wear: flank wear and crater wear. Fig. 1 represents the regions of tool wear. In this experiment the flank wear was taken as a standard [12] (mean flank wearland, VB: 0.3 mm). Fig. 2 represents the typical flank wearland. There are various wear mechanisms [8, 13, 14]: adhesion wear, abrasive wear, diffusion wear and oxidation wear. These mechanisms are affected by the cutting condition.

1.2. Data processing

Taylor's tool life equation is expressed as follows:

$$TV^n = C, \qquad (1)$$

where T is the tool life (min), V the cutting velocity (m min^{-1}), n an exponent; and C a constant. Wu's tool life equation is expressed as

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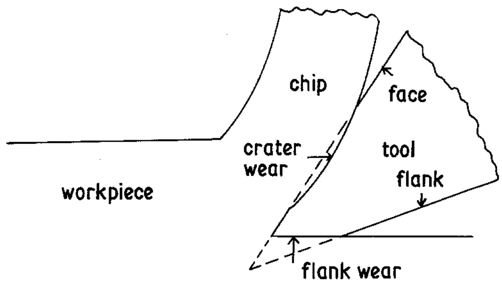

Figure 1 Regions of tool wear.

follows [10]:

$$TV^{\alpha}f^{\beta}d^{\gamma} = C, \quad (2)$$

where T is the tool life (min), V the cutting velocity ($\mathrm{m\,min^{-1}}$), f the feed rate ($\mathrm{min\,rev^{-1}}$), d the depth of cut (mm), α, β, γ are exponents, and C a constant.

Equation 2 may be expressed as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \quad (3)$$

where $y = \ln T$, $b_0 = \ln C$, $b_1 = -\alpha$, $b_2 = -\beta$, $b_3 = -\gamma, x_1 = \ln V, x_2 = \ln f, x_3 = \ln d$.

Equation 3 may be expressed in a matrix form as follows:

$$Y = BX \quad (4)$$

where Y is the matrix of y; B is the matrix of b_0, b_1, b_2, b_3; X is the matrix of x_1, x_2, x_3.

Solving Equation 4 in terms of B

$$B = (X'X)^{-1}X^{-1}Y \quad (5)$$

where X' is the transpose of X, $(X'X)^{-1}$ the inverse of $(X'X)$, X^{-1} the inverse of X.

Thus b_0, b_1, b_2, b_3 are expressed as follows:

$$\begin{aligned} b_0 &= \tfrac{1}{6}(y_2 + y_3 + y_5 + y_8 + y_9 + y_{10}) \\ b_1 &= \tfrac{1}{4}(y_2 - y_3 - y_5 + y_8) \\ b_2 &= \tfrac{1}{4}(-y_2 + y_3 - y_5 + y_8) \\ b_3 &= \tfrac{1}{4}(-y_2 - y_3 + y_5 + y_8) \end{aligned} \quad (6)$$

Here y_i ($i = 2, 3, 5, 8, 9, 10$) is the value of natural logarithm of the tool life of the ith data level. Fig. 3 represents the block design.

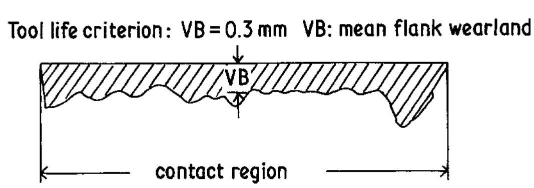

Figure 2 Typical flank wearland.

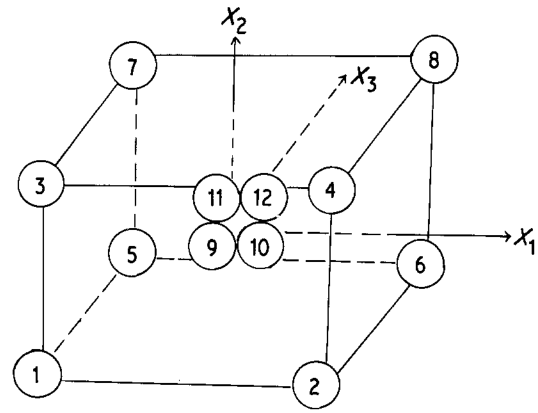

Figure 3 Block design.

2. Experimental techniques

2.1. Coating

TiC was coated using the CVD method, the reaction being as follows:

$$TiCl_{4(g)} + CH_{4(g)} \xrightarrow[1000^\circ C,\ 1\,atm]{+H_2} TiC_{(s)} + 4HCl_{(g)}. \quad (7)$$

TiC coating on a WC–6Co tool was carried out in a resistant furnace. The WC–6Co tool was placed in the chamber, and the chamber was flushed with argon gas. When the chamber was heated to 1000° C in a hydrogen atmosphere, CH_3 and $TiCl_4$ vaporized at 50° C were transferred to the chamber with hydrogen, and then the deposition was carried out. The deposition conditions are listed in Table I.

TiCl plus Al_2O_3 composite coating was carried out in a similar way, the reaction being as follows:

$$2AlCl_{3(g)} + 3CO_{2(g)} + 3H_{2(g)} \xrightarrow[1000^\circ C,\ 1\,atm]{+H_2} Al_2O_3(s) + 6HCl_{(g)} + 3CO_{(g)}. \quad (8)$$

The deposition conditions are listed in Table II.

TABLE I TiC coating conditions

Furnace	Resistant furnace
Deposition time	1 h
Deposition temperature	1000° c
Total pressure	1 atm
Partial pressure	P_{TiCl_4} : 30 torr
Reactor diameter	25 mm
Bubble temperature	40° C
Flow rate	H_2 : 300 ml $\mathrm{min^{-1}}$ CH_4 : 30 ml $\mathrm{min^{-1}}$
Used gases	$CH_4 . H_2$

TABLE II Al_2O_3 coating conditions

Furnace	Induction furnace
Deposition time	1 h
Deposition temperature	1000° C
Total pressure	100 torr
Reactor diameter	26 mm
Flow rate	total 2 litre min^{-1}
Mole fraction	H_2/CO_2 : 0.1, $AlCl_3$: 1%
Used gases	$AlCl_3$, H_2, CO_2

2.2. Cutting

A low carbon steel workpiece was turned on a lathe at a feed rate of 0.206 to 0.410 mm rev^{-1} and a depth of cut of 0.1 to 0.5 mm for cutting velocities between 100 and 250 m min^{-1}. In obtaining Taylor's data, the feed rate and the depth of cut were fixed at 0.3 mm rev^{-1} and 0.3 mm, respectively. The cutting tool type was P20S (SNGN 120408) and the tool holder was CSKNR2525-12. After cutting for a certain time, the flank wearland was measured using a toolmakers microscope. As the cutting velocity varied with the workpiece diameter in turning operation, the cutting velocity was treated statistically as follows:

$$\bar{v} = \frac{\int_{D_1}^{D_2} v D \, dr}{\int_{D_1}^{D_2} D \, dr} = \frac{2\pi N(D_1^2 + D_1 D_2 + D_2^2)}{3(D_1 + D_2)}, \quad (9)$$

where $\bar{v}$ is the mean cutting velocity (m min^{-1}), v the cutting velocity (m min^{-1}), D_1, D_2, D the work-piece diameter (mm), r the workpiece radius (mm), and N the revolutions per minute (rpm).

3. Results and discussion

The coating thickness of the TiC coating was 5 to 8 μm, and that of the Al_2O_3 coating was 3 to 5 μm. Taylor's tool life equations were obtained as follows:

$$\begin{aligned} &\text{uncoated tool:} && VT^{0.23} = 209 \\ &\text{TiC coated tool:} && VT^{0.26} = 351 \\ &\text{TiC + Al}_2\text{O}_3\text{ coated tool:} && VT^{0.29} = 384. \end{aligned} \quad (10)$$

Fig. 4 shows a plot of tool life (T) against cutting velocity (V) for uncoated, TiC coated, and TiC + Al_2O_3 coated tools using Taylor's method.

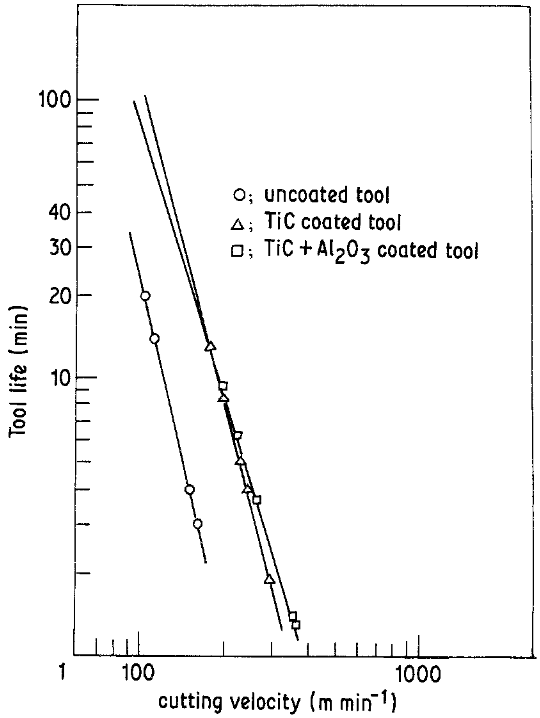

Figure 4 $T-V$ relationships for uncoated, TiC coated, and TiC + Al_2O_3 coated tools using Taylor's method.

As shown above, several facts can be deduced. First, the tool life decreases as the cutting velocity increases for every tool. In an uncoated tool, wear occurs by interdiffusion between the cobalt component of the tool and the iron component of the workpiece, by decomposition of WC, and by formation of an M_6C-type compound. As interdiffusion increases with cutting velocity, the tool life decreases as the cutting velocity increases. In a coated tool, however, no diffusion occurs because the coated layer acts as a strong diffusion barrier between the tool and the workpiece. In this case, wear occurs by abrasion [9] due to the high cutting force with increasing cutting velocity, thus the tool life decreases as the cutting velocity increases.

Secondly, compared with an uncoated tungsten carbide tool, the tool life of both the coated tools were from 5 to 7 times longer and the improvement was greater at higher cutting velocity. This result is consistent with P. O. Snell's results [3]. The reason for the increase in tool life for the TiC coated tool is that the hardness of TiC (3200 kg mm^{-2}) is greater than that of WC (2400 kg mm^{-2}), and the friction coefficient of TiC (0.40 at 25° C, 0.20 at 900° C) is smaller than that of WC (0.80 at 25° C, 0.35 at 900° C) [13, 15]. Once the TiC layer is formed, it acts as a different lubricant from the WC oxidation layer. In addition, the

TABLE III Level coding for uncoated tool

Level	V (m min^{-1})	f (mm rev^{-1})	d (mm)	coding		
				X_1	X_2	X_3
Level	320	0.410	0.5	1	1	1
Centre	225	0.300	0.3	0	0	0
Low	155	0.206	0.1	−1	−1	−1

TABLE IV Tool life data for uncoated tool using Wu's method

Trial No.	V (m min^{-1})	f (mm rev^{-1})	d (mm)	coding			T (min)	Results, y
				X_1	X_2	X_3		
2	320	0.206	0.1	1	−1	−1	4.1	1.41
3	155	0.410	0.1	−1	1	−1	20	2.99
5	155	0.206	0.5	−1	−1	1	3.0	1.09
8	320	0.410	0.5	1	1	1	0.3	−1.2
9	225	0.300	0.3	0	0	0	3.5	1.25
10	225	0.300	0.3	0	0	0	3.3	1.19

mutual solubility between TiC and WC is smaller than that between WC and iron. Therefore, abrasion wear is decreased because of little fusion between the TiC coated tool and the workpiece [3, 13, 15].

Thirdly, the TiC + Al_2O_3 coated tool is slightly superior to the TiC coated tool at higher cutting velocity. When cutting is performed at 100 to 180 m min^{-1}, the cutting temperature is 750 to 900° C. In this case, possible wear mechanisms are abrasion and adhesion [9, 16]. The factors affecting these two mechanisms are microhardness, thermal conductivity, and the friction coefficient. These three factors are similar for two tools at cutting velocities between 100 and 180 m min^{-1}. When cutting is performed at a cutting velocity of 180 to 400 m min^{-1}, the cutting temperature is 1000 to 1200° C [17]. In this case, the hot hardness of Al_2O_3 (70R_A at 1400 K) is greater than that of TiC (50 to 60R_A at 1400 K) and abrasive wear resistance of Al_2O_3 is better than that of TiC, thus the tool life for the TiC + Al_2O_3 coated tool becomes longer than that for TiC simple coated tool [7, 14]. In actual cutting performance, the depth of cut and the feed rate vary as well as the cutting velocity. Thus Wu's equation more accurately predicts actual experimental results.

Wu's tool life equations were obtained as follows:

uncoated tool: $TV^{2.683}f^{0.522}d^{1.399} = 385\,972$

TiC coated tool: $TV^{2.594}f^{0.612}d^{0.822} = 1\,607\,242$

TiC + Al_2O_3 coated tool:

$$TV^{2.613}f^{0.551}d^{0.748} = 214\,233 \quad (11)$$

Tables III and IV represent the level coding and the tool life data for uncoated tool, Tables V and VI for TiC coated tool, and Tables VII and VIII for TiC + Al_2O_3 coated tools, respectively.

As shown above, tool life decreases as cutting velocity, feed rate, and the depth of cut increase, while the most effective factor in the cutting variables is the cutting velocity, and the feed rate is a minor factor. Comparison of Taylor's equation with Wu's method shows similar results for both methods, so that tool life can be predicted with some accuracy at common cutting velocities. However, the tool life can be more easily predicted by Wu's equation in the case of arbitrary cutting conditions, thus Wu's method is more useful than that of Taylor.

TABLE V Level coding for TiC coated tool

Level	V (m min^{-1})	f (mm rev^{-1})	d (mm)	coding		
				X_1	X_2	X_3
High	330	0.410	0.5	1	1	1
Centre	230	0.300	0.3	0	0	0
Low	155	0.206	0.1	−1	−1	−1

TABLE VI Tool life data for TiC coated tool using Wu's method

Trial no.	V (m min^{-1})	f (mm rev^{-1})	d (mm)	Coding			T (min)	Results, y
				X_1	X_2	X_3		
2	330	0.206	0.1	1	−1	−1	8.6	2.152
3	155	0.410	0.1	−1	1	−1	40	3.689
5	155	0.206	0.5	−1	−1	1	16.2	2.785
8	330	0.410	0.5	1	1	1	1.5	0.405
9	230	0.300	0.3	0	0	0	10	2.302
10	230	0.300	0.3	0	0	0	10.5	2.351

TABLE VII Level coding for TiC + Al_2O_3 coated tool

Level	V (m min^{-1})	f (mm rev^{-1})	d (mm)	coding		
				X_1	X_2	X_3
High	343	0.410	0.5	1	1	1
Centre	225	0.300	0.3	0	0	0
Low	155	0.206	0.1	−1	−1	−1

4. Conclusions

1. The tool life equations were obtained as follows:

Taylor's equations

uncoated tool: $VT^{0.23} = 209$

TiC coated tool: $VT^{0.26} = 351$

TiC + Al_2O_3 coated tool: $VT^{0.29} = 384$

Wu's equations

uncoated tool: $TV^{2.594}f^{0.522}d^{1.399} = 385\,972$

TiC coated tool: $TV^{2.594}f^{0.612}d^{0.822} = 1\,607\,242$

TiC + Al_2O_3 coated tool:

$$TV^{2.163}f^{0.551}d^{0.748} = 214\,233.$$

2. Tool life decreases with cutting velocity, depth of cut, and the feed rate for every tool. Compared with an uncoated tool, the tool life of the coated tools were 5 to 7 times longer and the improvement was greater at higher cutting velocity. The tool life of TiC + Al_2O_3 coated tools was similar to that of a TiC coated tool at common cutting velocities, and the former was slightly superior to the latter.

3. Compared with Taylor's method, Wu's method seemed to give more consistent results.

4. If we are to increase the tool life, use of a composite coating as well as optimum cutting conditions are advisable.

References

1. ELSE BREVAL and SAKARI VUORINEN, *J. Mater. Sci.* **15** (1980) 361.
2. J. M. BLOCKER Jr, *J. Vac. Sci. Technol.* **11** (1974) 680.
3. P. O. SNELL, *Jermkont. Amer.* **154** (1970) 413.
4. N. G. ODREY, L. TONGSON, J. V. BIGGERS, B. E. KNOX and I. HAM, *Thin Solid Films* **79** (1981) 83.
5. NAM P. SUH, *Wear* **62** (1970) 1.
6. W. SCHINTLEMEISTER, O. PACHER and K. PFAFFINGER, *J. Electrochem. Soc.* **123** (1976) 924.
7. T. SADAHIRO, S. YAMAYA, K. SHIBUKI and N. UJJIE, *Wear* **48** (1978) 291.
8. W. SCHINTLEMEISTER and O. PACHER, *J. Vac. Sci. Technol.* **12** (1975) 743.
9. G. BOOTHROYD, "Fundamentals of Metal Machining and Machine Tools" (McGraw Hill, New York,

TABLE VIII Tool life data for TiC + Al_2O_3 coated tool using Wu's method

Trial no.	V (m min^{-1})	f (mm rev^{-1})	d (mm)	Coding			T (min)	Results y
				X_1	X_2	X_3		
2	343	0.206	0.1	1	−1	−1	8.3	2.116
3	155	0.410	0.1	−1	1	−1	32	3.466
5	155	0.206	0.5	−1	−1	1	14	2.639
8	343	0.410	0.5	1	1	1	1.7	0.531
9	225	0.300	0.3	0	0	0	10.1	2.313
10	225	0.300	0.3	0	0	0	10.0	2.302

1975) p. 108.
10. S. M. WU, *J. Eng. Ind.* **86** (1964) 105.
11. H. CZICHOS, "Tribology" (Elsevier, Amsterdam, 1978) p. 45.
12. C. K. SINGH and S. VAJPAYEE, *Wear* **62** (1980) 247.
13. A. D. SARKAR, "Wear of Metals" (Pergamon Press, Oxford, 1976) p. 42.
14. A. G. KING and W. M. WHELDON, "Ceramics in Machining Processes" (Academic Press, New York, 1966) p. 115.
15. F. P. BOWDEN and D. TABOR, "The Friction and Lubrication of Solids" (Oxford University Press, Oxford, 1981) p. 52.
16. WILLIAM D. SPROUL and M. H. RICHMAN, *Metals Technol.* **3** (1976) 489.
17. A. T. VIJAY, "Influence of Metallurgy on Machinability" (ASM, USA, 1975) p. 347.

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