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ORIGINAL CONTRIBUTION

Study of Tool Wear Mechanisms and Mathematical Modeling of Flank Wear During Machining of Ti Alloy (Ti6Al4V)

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Abstract Machinability of titanium is poor due to its low thermal conductivity and high chemical affinity. Lower thermal conductivity of titanium alloy is undesirable on the part of cutting tool causing extensive tool wear. The main task of this work is to predict the various wear mechanisms involved during machining of Ti alloy (Ti6Al4V) and to formulate an analytical mathematical tool wear model for the same. It has been found from various experiments that adhesive and diffusion wear are the dominating wear during machining of Ti alloy with PVD coated tungsten carbide tool. It is also clear from the experiments that the tool wear increases with the increase in cutting parameters like speed, feed and depth of cut. The wear model was validated by carrying out dry machining of Ti alloy at suitable cutting conditions. It has been found that the wear model is able to predict the flank wear suitably under gentle cutting conditions.

Keywords Tool wear · Flank wear · Abrasion · Adhesion · Diffusion

List of Symbols

A	Actual area carrying normal load, mm^2
A_J	Average cross-sectional area, mm^2
b	Width of cut, mm
C	Concentration, kg/m^3
d	Depth loss from flank face, mm
D	Diffusivity constant, m^2/s
f	Feed, mm/rev
F_t	Trust force, N
h_J	Height of welded joints torn off in shear, mm
H	Hardness of softer material, N/mm^2
H_a	Hardness of abrasive material, N/mm^2
H_t	Hardness of tool, N/mm^2
H_w	Hardness of workpiece, N/mm^2
J	Mass flux, kg/m^2s
K	Probability to form a sizable wear particle
$K\alpha$	Abrasion constant
N	Normal load, N
n	Number of welded joints
P_c	Contact pressure, N/mm^2
Q	Volumetric loss in adhesive wear, mm^3
r	Corner radius, mm
s	Distance of sliding, mm
t	Depth of cut, mm
T	Time of machining, min
v	Cutting velocity, m/min
V_{ab}	Abrasion wear volume, mm^3
V_{ad}	Adhesion wear volume, mm^3
V_{diff}	Diffusion wear volume, mm^3
V_J	Volume of each junction, mm^3
VB	Flank wear land, mm
Φ	Principle cutting angle
Δ	Time of diffusion, s

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Introduction

Titanium (Ti) and its alloys possess low mass, high strength, and excellent resistance to corrosion, and they find applications in many fields. Ti alloys are widely used in aerospace industry for manufacturing of frames, engine spares and compressors. Due to its high corrosion resistance it is widely used in production of filters, valves and reaction vessels for chemical industry. Despite of all valuable properties Ti has been perceived as a material that is difficult to machine. Ti is a poor conductor of heat and due to which the heat generated during the cutting action does not dissipate quickly causing rapid tool wear. Wear of tool is one of the most important aspects in machining of Ti alloy. In general abrasion, adhesion, diffusion and oxidation are the main mechanism causing wear of tool in any machining. Wang et al. [1] have thrown some light on the wear mechanism of coated carbide tool during machining of Ti6Al4V. According to them flank wear occur in very non uniform fashion on the tool. The delamination of coating along with the adhesion is the major cause of deterioration of tool. Joshi et al. [2] also reported various important modes of tool failure in ($\alpha + \beta$) Ti alloys. The micro level transfers of various elements from tool to workpiece and vice versa enhances the process of tool deterioration. Venugopal et al. [3] conducted experiments which revealed that the high cutting temperature obtained during the machining leads to permanent failure of the tool. Strong adhesion of workpiece elements over the tool rake face was observed. Jawaid et al. [4] suggested that the flank wear rate is rapid at higher cutting speed and feed rates, when machining Ti under dry conditions. The greater cutting temp and stresses generated on the flank face close to the nose area probably caused the reduction in yield strength of tool.

Several tool wear models are established by various researchers for different tool workpiece combinations as shown in Table 1. There is still no mathematical model existing for machining of Ti alloy with PVD TiAlN coated carbide tool because the mechanism of tool wear is still unclear. Hence, this work is an attempt to identify various wear mechanisms involved during the machining of Ti6Al4V and to develop the tool wear model to predict the flank wear of the tool insert. Flank wear modeling was chosen because it has direct influence on surface quality and dimensional accuracy of the finished product [5].

Wear Mechanisms Modeling

Abrasive Wear Modeling

Abrasive wear occurs on the softer surface when hard surface slides over it. Such wear is predominant in the case where the prevailing strain rate may result in the hard spots traversing through the point contact zone of the interface. As in machining of hardened steel the cementite phase acts as the abrasive inclusion causing abrasion wear of tool [10]. Rabinowickz et al. [11] found that the three body abrasive wear depends upon the ratio of hardness of the abrasive to the surface that is being abraded.

$$V_{ab} = \frac{K\alpha \times s \times N}{K} \times \frac{H_a^{n-1}}{H_t^n} \quad (1)$$

n and K are constants and depends upon the ratio of tool and abrasive hardness [12].

In experiments conducted by Wang et al. [1] adhesion mechanism is the main reason of tool wear. No indication of abrasive wear was observed on the tool. The source of abrasive wear is the presence of hard carbide particles in the microstructure of Ti6AL4V. But Trent and Wright [13] have found no such direct experimental evidence of abrasive wear caused by these particles on carbide tools. The significant hardness difference between the work and tool material could be the reason of absence of abrasive wear. The micro hardness measured according to ASTM E 384-89 for Ti6AL4V is 325 HV and that for the coated WC tool is 2,000 HV. It is a mandatory condition for the abrasive wear that the hardness of the abrasive particle must be more than that of surface being worn off [11]. So keeping this entire thing into view and to make the wear model simpler, abrasive wear on tool could be ignored.

Adhesive Wear Modeling

According to Rabinowickz [14] due to contact pressure and increase in temperature the welding on micro level takes place between two mating surfaces. The subsequent sliding between the two surfaces leads to the shearing of these

Table 1 Different tool wear and tool life models

Authors	Tool–work combination	Modelled	Equation
Wong et al. [6]	Coated carbide tool–low carbon steel	Abrasive	$\frac{dL}{dt} = 9 \times 10^8 \frac{A}{P_t}$
Choudhury and Srinivas [7]	HSS tool–C45	Diffusion	$hf = 0.0238\, N^{3.66} f^{1.34} d^{0.664} D_W^{4.466}$
Marksberry et al. [8]	Al_2O_3–HSLA steel	Modification of Taylor's tool life equation	$T = T_R W_G \left(\frac{V_R}{V}\right)^{\left(\frac{1}{nc}\right)\left(\frac{1}{N_{NDM}}\right)}$
Luo et al. [9]	Coated carbide–low alloy steel	Adhesion and diffusion	$\frac{dw}{dt} = \frac{0.0468 V_s F_f}{HV_f} + 97.8 \exp\left(\frac{-E}{RT}\right)$

welded joint. Figure 1 shows the flank wear caused by shearing of welded joints [15].

The adhesive wear can be considered as the main reason of tool wear because Ti alloy is one of highly chemical reactive material. The TiAlN coating protects the tool from the adhesive and diffusion wear because of its chemical stability. But after the coating gets flaked of the wear mechanism of coated tool is same as that uncoated tool.

Let us consider the total area of flank wear = VB × b

$$\text{Let us consider the total area of flank wear} = VB \times b \tag{2}$$

where VB is the flank wear (mm) and b is width of cut (mm).

The contribution to the flank wear is due to the welded junction between the tool and work material. Let there be 'n' number of welded joints.

According to Huang and Liang [16] adhesive wear volume/area is given by

$$Vad = \frac{K \times n \times V_J}{VB \times b} \tag{3}$$

Volume of each junction can be expressed as

$$V = A_J \times h_J \tag{4}$$

The K in above equation is adhesive wear constant. The value of K can be obtained with the help of Archard equation.

The most up-to-date law for the adhesive wear is Holm-Archard law given by

$$Q = \frac{K \times s \times N}{3H} \tag{5}$$

The contact pressure between the tool and workpiece [16]

$$P_C = \frac{F_t}{A} \tag{6}$$

Actual contact area 'A' carrying the load is given by

$$A = n \times A_J \tag{7}$$

The hardness of the softer material is the actual contact pressure

$$P_C = H_w = \frac{F_t}{n \times A_J} \tag{8}$$

Combining above relations, the wear volume per area is given by

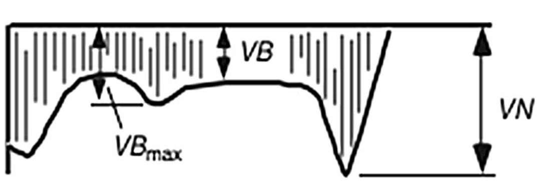

Fig. 1 Schematic of flank wear

$$V_{ad} = \frac{K \times n \times h_J \times A_J}{VB \times b} \tag{9}$$

The total volumetric wear during adhesive wear as the cutting velocity relative to tool is 'v' in time 'T'

$$V_{ad} = K \times h_J \times \frac{F_t}{VB \times H_W} \times v \times T \tag{10}$$

The value 'K' can be obtained by ASTM G99 Pin on Disk test which is a standard test for the adhesion phenomena. The reason behind choosing Pin or Disk test is on the basis that Jianxin et al. [17] obtained the similar frictional and wear behavior of WC tool for both sliding wear test and machining operation. Though, machining operation has some difference with sliding wear test, but Pin on Disk test could be viewed a case of continuous friction between work surface and flank face [18]. Also'hJ' is the torn off height of welded joint (mm) and its value is assume to be 10^{-3} [5].

Diffusion Wear Modeling

Diffusion wear involves element diffusion and chemical reaction between the workpiece and the tool, and the process is activated by high temperatures and is observed mainly at the tool chip interface. At high cutting speeds, the temperature at the tool–chip interface increases and transfer of material between the workpiece material and the tool occurs [1]. Diffusion tests conducted by Jianxin et al. [19] reveal that the elemental diffusion takes place from tool workpiece. The penetration depth reaches to around 20 micron at around 800 °C. The Fick's second law is used to model the equation

$$\frac{\partial C}{\partial t} = \frac{\partial J}{\partial x} \tag{11}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 x} \tag{12}$$

Assumptions during diffusion mechanism

(1) The diffusion is taking place in the normal direction of tool/workpiece interface
(2) The concentration of diffusing component is constant at the tool chip interface and let say concentration is equal to the density of component being diffused
(3) Diffusion coefficient D strongly depends upon the temperature
(4) The velocity of element migration is much lower than the velocity of chip flow

The solution to Fick's second law is given by

$$C\,x, t = A - B \operatorname{erf}\frac{x}{2\,\overline{D\Delta}} \tag{13}$$

Now solving the above equation by applying the boundary conditions

(a) Let at x = 0, C = C_O (density of diffused element (ρ_{ele})for all time)
Putting above boundary condition in solution of Fick'ssecond law
A = C_O as erf (0) = 0
(b) C = 0 when Δ = 0 for x > 0
Putting in solution we get
B = $-C_O$ as erf ∞ = 1

For the simplification purpose let us assume that the concentration gradient $\frac{\partial C}{\partial X}$ at any point over the interface will remain constant with time

$$\text{so} \quad \frac{\partial c}{\partial x} x = 0 = -\rho_{ele} \frac{\overline{v}}{\pi D(VB)} \tag{14}$$

Shivpuri and Hua [20] concluded the linear tool wear rate as

$$\text{Linear wear rate} = \frac{J_{X=0}}{\rho_{tool}} \tag{15}$$

Total volumetric wear due to diffusion in time 'T'

$$V_{diff} = \frac{J_{X=0}}{\rho_{tool}} \times VB \times b \times T \tag{16}$$

$$V_{diff} = \frac{\rho_{ele}}{\rho_{tool}} \frac{\overline{v}}{\pi D(VB)} \times VB \times b \times T \tag{17}$$

Total Volumetric Wear

Total volumetric wear will be the sum of volumetric wear caused by abrasive, adhesive and diffusion wear mechanisms. As abrasive wear is neglected because of huge hardness difference between cutting tool and workpiece material, the total volumetric wear is given by

$$\text{Total volumetric wear} = \text{Adhesive wear} + \text{Diffusion wear}$$

Total volumetric wear loss can also be given by the geometric wear loss of the tool material during machining process. We consider tool radius, depth of cut and principle cutting edge angle as the main factors involved in geometric loss of wear [21] as shown in Fig. 2.

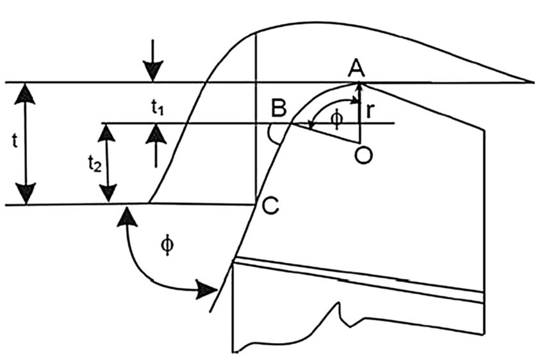

Fig. 2 Tool geometry

Total volumetric wear = Geometric wear (Flank face)

$$\text{Geometric wear Flank face} = \frac{r \times \sin\Phi + t - r + r \times \cos\Phi}{\sin\Phi} \times d \times VB \tag{18}$$

The wear is occurring on main Flank, Rake face and auxiliary Flank face. For making the equation simpler let us consider wear only at the Flank face.

The final overall equation by taking all the assumption into account can be given as

$$\frac{r\sin\Phi + t - r + r\cos\Phi}{\sin\Phi} \times d \times V = K \times h_J \times \frac{Ft}{VB\,Hw} \times v \times T + \frac{\rho_{ele}}{\rho_{tool}} \frac{\overline{v}}{\pi D\ VB} \times VB \times b \times T \tag{19}$$

The data used in Eq. (18) is as follow r = 0.8 mm, Φ = 95 °, $h_J = 10^{-3}$mm, K = 10^{-4} to 10^{-5}(detail in next section), ρ_{tool} = 14.9 × 10^{-3} g/mm^3

Now we can formulate the model by putting the value of various constants collected from

$$1.99 \times d \times VB = 2.9 \times 10^{-11} \times \frac{F_t}{VB} \times v \times T + 0.59 \times \frac{\overline{v}}{D\ VB} \times VB \times b \times T \tag{20}$$

Experiments and Discussion

Experiment to Confirm Adhesive Wear and to Find the Adhesion Wear Constant

"Pin on Disc" test is tribological testing procedure to calculate the coefficient of friction and wear constants. The standard test involves a revolving disc and a pin sliding over the disc. Experiments were performed according to ASTM G99 standard at room temperature on the ''Pin on Disc'' tribometer designed by Magnum Engineers. Ti6Al4V alloy disc of 80 mm diameter and PVD coated TiAlN-WC pin of 8 mm diameter were chosen for performing the experiments (Process parameters: Rotational speed of disc = 100,150 and 200; Load = 50,75 and 100 N; track radius = 35 mm; time = 30 min). The result obtained from Pin on disc test is given in Table 2.

The value of adhesive wear constant K from these experiments has been found out to lies between 10^{-4} and 10^{-5}. Also, the magnified pins images are taken with the help of stereo discovery V20 microscope by Carl Ziess

Table 2 Pin on disc test results

Exp no.	RPM	Normal load	Frictional force	Coefficient of friction	Wear constant (K)
1	100	50	22	0.44	7.8×10^{-5}
2	150	50	23	0.46	5.2×10^{-5}
3	200	50	25	0.50	3.9×10^{-5}
4	100	75	36	0.48	7.3×10^{-5}
5	150	75	38	0.51	1.8×10^{-4}
6	200	75	39	0.52	1.5×10^{-4}
7	100	100	43	0.43	7.0×10^{-5}
8	150	100	47	0.47	1.2×10^{-4}
9	200	100	49	0.49	1.2×10^{-4}

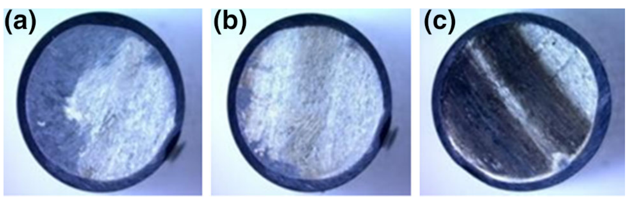

Fig. 3 *Top view* of pin and different conditions. **a** Pin image at 100 rpm, **b** pin image at 150 rpm, **c** pin image at 200 rpm

Microscopy are shown in Fig. 3. It is clear from the image that work material is getting adhering to the pin indicating strong chances of adhesion wear.

Diffusion Couple Experiment

To confirm the fact that whether diffusion is really taking place for this tool–workpiece combination, diffusion couple experiment has been conducted. The tool and workpiece is held together with the help of C clamp and placed in the furnace for around 40 min. Uncoated carbide bit was used for making a diffusion couple with Ti6Al4V because of the fact that the coating was getting flaked off even at relatively lower RPM values during pin on disc test. Also, Bhatt et al. [22] explained that the performance of PVD (TiAlN coated) WC tool is poor above 50 m/min because of its lower friction resistant, inferior thermal resistance and delamination. Three set of couples were placed in the furnace at 400, 600 and 800 °C. The sketch diffusion couple used for the diffusion test is shown in Fig. 4.

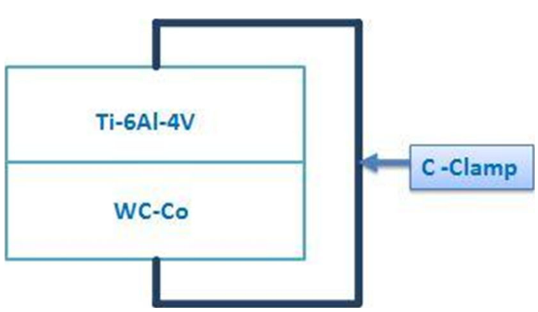

Fig. 4 Diffusion couple

EDAX Analysis

The Brucker-AXS Energy dispersive X-ray System (QuanTax 200), employed for EDAX analysis of both the tool and workpiece, was conducted after the diffusion couple experiment. The result obtained from diffusion test reveals that the elemental diffusion from tool to workpiece is taking place under static condition. As machining process is a dynamic process and temperature between the tool–workpiece interface is very high, hence the chances of diffusion during machining are relatively high. The EDAX spectra in Fig. 5 of Ti6Al4V (diffusion couple samples) convey that Tungsten (W), Carbon (C) and Cobalt (Co) is getting diffused into workpiece material.

The diffusion of W and C is of appreciable level for all the temperatures and can be considered as main reason of tool wear. The diffusion of Co from tool to workpiece can

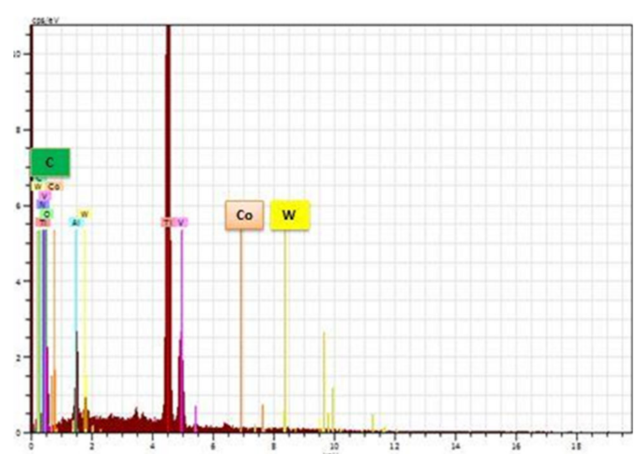

Fig. 5 EDAX spectra of Ti6Al4V after diffusion couple test confirms the presence of tool elements in the workpiece

Table 3 Machining parameters

Cutting environment	Dry	Dry
Cutting speed (m/min)	60	80
Depth of cut (mm)	1	0.5
Feed rate (mm/rev)	0.08	0.08
Ti6Al4V bar dimensions (mm)	Diameter = 60, Length = 200	Diameter = 60, Length = 200
Machining duration (min)	30	30

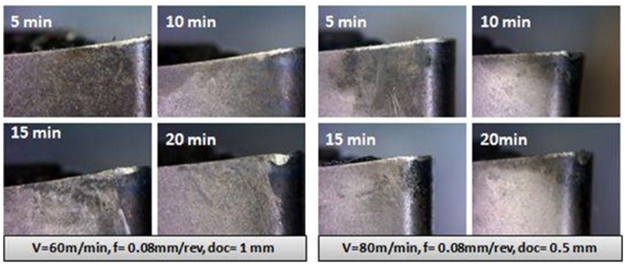

Fig. 6 Flank wear progression at various cutting conditions

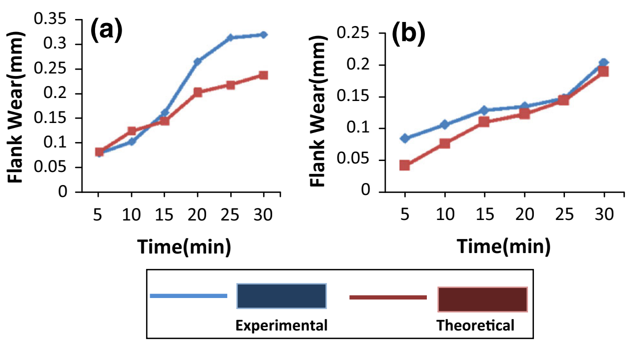

Fig. 7 Flank wear versus time. **a** Comparison between the experimental and theoretical flank wear progression at 60 m/min, **b** comparison between the experimental and theoretical flank wear progression at 80 m/min

also be considered as possible reason for tool deterioration. As cobalt is the binder material in carbide tool, diffusion of Co leads to decohesion amongst the WC grains [13]. The breakaway of WC grain leads to the crater and flank wear.

Machining Experiments

For the validation of wear equation actual machining experiments are conducted on T-6 Leadwell (Taiwan) lathe machining center. Cylindrical specimen of Ti6Al4V gripped in three jaws chuck was machined by Kennametal KC5510 TiAlN coated WC tool insert (20°Rake angle). Many authors have successfully employed this type of coated insert for the machining of Ti6Al4V with in a speed range of 50–120 m/min. The detail of experimental parameters for present work is given in Table 3.

First set of experiment was conducted at 60 m/min with 0.08 mm/rev of feed and 1 mm of depth of cut. Another set of experiment was performed at 80 m/min cutting speed. Firstly, the 1 mm of depth of cut was selected for machining. Rapid wear of tool insert was observed in this case, so then the depth of cut is changed to 0.5 mm. The feed rate is kept constant i.e. 0.08 mm/rev. The wear progression at both of these conditions can be seen from Fig. 6. The image capturing and flank wear measurement was done with the help of Ziess Stereo Discovery V.20 microscope. The measurement of wear was done after every 5 min of machining for both of the cutting conditions. The comparison between the theoretical and experimental value of flank wear with the variation in machining time is shown in Fig. 7. It can be seen from the figure that theoretical values are following the same trend as that of experimental values. This figure also confirms that the wear value increases with the increase of cutting speed.

Conclusion

A mathematical model for the tool wear during machining Ti6Al4V with PVD TiAlN coated tungsten carbide tool is developed in this thesis. All the experiments helped in knowing the possible reason for tool wear mechanism during machining of Ti alloy. Further formulation of adhesion mechanism and diffusion mechanism in the mathematical form is done by pseudo analytical approach. The value obtained from mathematical formula following the same trend as of experimental value. This formula is able to predict the wear under gentle cutting conditions. Sudden increase in the speed, feed and depth of cut leads to mechanical breakdown of tool. This wear model is unable to predict the tool wear under stressful conditions of high parameter value. The model is unsuccessful even at low speed where diffusion wear is not a criterion of tool failure.

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