Analysis and Prediction of Tool Flank Wear under Constant Material Removal Volume Condition in Turning of AISI 4140 Steel

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Abstract. AISI 4140 steel is widely used to manufacture the crankshaft of diesel engines due to some special properties. However, tool wear is aggravated by the unreasonable cutting parameters during machining process. In this paper, according to a preliminary experiment, a constant material removal volume (MRV) of 80,000mm^3 was chosen to ensure that the tool was in a uniform wear stage in the subsequent experiments. First, the worn tools were observed by means of scanning electric microscope (SEM) and energy dispersive spectrometer (EDS). It turned out that the tool minor flank wear is worst with large tool cutting edge angle (κ_r), and the coating damage, adhesive wear and abrasive wear are the main wear mechanism of the tool. Secondly, the tool wear was measured by average minor flank wear amount (*VB*) and an artificial neural network (ANN) model was proposed. Finally, the tool wear (*VB*) was predicted in different cutting parameters, results indicate that the proposed ANN model can be used as a satisfactory prediction for tool wear. The research can provide an instruction for predicting the tool flank wear, selecting cutting parameters, and increasing tool life.

Introduction

AISI 4140 (ISO-42CrMo4, GB/T-42CrMo) steel is widely used to manufacture the crankshaft of diesel engines due to its excellent mechanical properties. However, AISI 4140 steel has poor machinability and belongs to difficult-to-machine materials with high cutting resistance, high cutting temperature, difficulty in chip breaking, and severe tool wear [1]. Crankshafts can be forged from a steel bar usually through roll forging process. Generally speaking, turning is an important process to remove the large amount of material from the forged billet.

Tool wear originally depends on stress and temperature in the interface between the workpiece and the cutting tool. Severe tool wear will shorten tool life, deteriorate machined surface integrity, raise cutting temperature, and increase the manufacturing costs of enterprises [2]. Liu et al. [3] investigated the effect of cutting speed and temperature on the cutting behaviour of AISI 4140 with polycrystalline cubic boron nitride (PCBN) tool, and found the correlation between temperature from the tool wear and the chip morphology. Dhar et al. [4] researched the cryogenic cooling by liquid nitrogen jet on average chip-tool interface could reduce cutting zone temperature, improve chip-tool interaction, relieve tool wear, and improve surface finish and dimensional accuracy. Xu et al. [5] investigated tool wear mechanisms and cutting performance of the YT15 cemented carbide tool, KY1615 ceramic tool, and Ti(C, N)-based cermet tools in machining AISI 4140 at the different cutting speeds. Meanwhile, it is important to explore the rule of tool wear and propose a predictive model between tool wear and cutting parameters. Many studies have been made on the tool wear model to predict the tool wear so far. Wu et al. [6] compared the performance of random forests (RFS) - based prognostic method with feed-forward back propagation (FFBP) artificial neural networks and support vector regression (SVR) by using an experimental data collected from 315 milling tests. Nouari et al. [7] researched the uncoated cemented tungsten carbide tool performance machining AISI 4140 at various cutting speeds, the results show that diffusion is the dominant damage mechanism for tools at high cutting speeds, and established a diffusion wear model by comparison with experimental data.

In order to analyse and predict the tool wear under constant MRV condition in turning of AISI 4140 steel. First, a preliminary experiment was taken to explore the relationship between tool wear and MRV, and a constant MRV was selected to ensure that the tool was in a uniform wear stage in subsequent experiments. Second, experiments were designed by the orthogonal test method, and the tool wear (*VB*) was obtained in different cutting parameters. Finally, an ANN model was established to predict the tool wear in different cutting parameters under constant MRV condition.

2. Experimental works

2.1 Workpiece material, cutting tool, and machine tool. AISI 4140 steel was used as the workpiece material, some $\phi 150\times 600$ mm bars were used as samples, and the chemical composition and mechanical properties are shown in Table 1 and Table 2 respectively. The matrix material of insert is cemented carbide, multi-layer (TiN-TiCN-TiN-Al_2O_3-TiN) coating by chemical vapor deposition (CVD) process, and the geometric parameters of the insert are shown in Table 3. Only one type and fresh insert was used for each group of experiments, which would eliminate the effect of the tool wear, and the whole turning experiments were carried out without any cutting fluids. A computer numerical control (CNC) horizontal turning centre (PUMA-200M, DAEWOO), which has the maximum spindle speed of 6000r/min, was employed for the turning experiments.

Table 1 Chemical composition of AISI 4140 steel

Composition [ωt %]	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	Fe
	≤0.45	≤0.37	≤0.80	≤0.03	≤0.03	≤1.10	≤0.03	≤0.03	≤0.22	others

Table 2 Mechanical properties of AISI 4140 steel

Mechanical properties	Density [kg/m^3]	Hardness [HB]	Extension Strength [MPa]	Young's modulus [MPa]	Poisson's ratio
	7900	210	1300	206000	0.3

Table 3 Geometric parameters of cutting tool

Geometric parameters	Cutting edge angle [°]	Minor cutting edge angle [°]	Nose angle [°]	Rake angle [°]	Relief angle [°]	Nose radius [mm]
	95	5	80	-6	0	1.2

2.2 Preliminary experiment design. A preliminary experiment was conducted to explore the relationship between tool wear and MRV. Since tool wear is usually aggravated with the increasing of cutting parameters, the largest cutting parameters in subsequent orthogonal experiments was adopted in the preliminary experiment to ensure that the tool is not in a acutely wear stage wear in subsequent orthogonal experiments, whose cutting speed (v_c) was 400 m/min, feed rate (f) was 0.3 mm/r and the depth of cut (a_p) was 1.5 mm, while cutting speed (v_c) is 250 m/min, feed rate (f) was 0.2 mm/r and the depth of cut (a_p) was 1.0 mm in actual machining process. The worn tool was dismantled in the measuring point, and observed with handled microscope (Dino-Lite, AM413ZT) at 150 × magnifications and full resolution. The tool wear (*VB*) was obtained with the aid of Dnldrv 4 software by three measurements.

Tool flank wear can be divided into three stages by the curvature of wear curve as shown in Fig.1. Tool wear curve increases rapidly and tool is in initial wear stage when MRV is between 0 and 20,000mm^3. Tool wear curve increases steadily and tool is in uniform wear stage when the MRV is between 20,000 mm^3 and 120,000 mm^3. Tool wear curve increases steadily and in acutely wear stage when the MRV beyond 120,000 mm^3. Since tool wear is usually aggravated with cutting parameters increasing, a MRV of 80,000 mm^3 was taken in a large cutting parameters can ensure that tool is not in an acutely wear stage wear in subsequent orthogonal experiments.

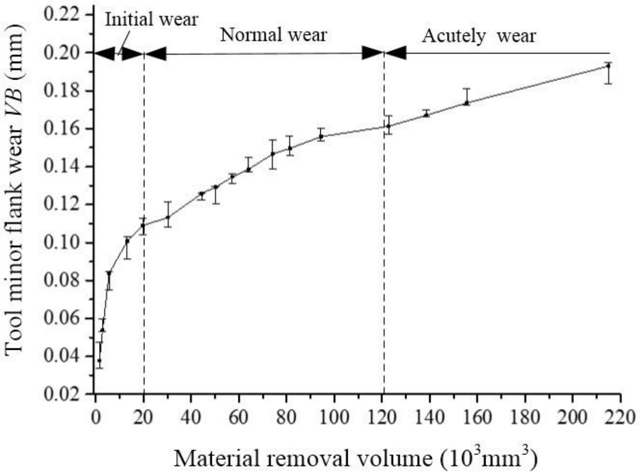

Fig.1 Tool wear curve with material removal volume

2.3 Orthogonal experiment design. An orthogonal experiment was designed and a standard $L_{25}(5^4)$ orthogonal array was selected for the experiment. Three factors (v_c, f and a_p) were taken into account and five levels were selected for each factor in this investigation. Five levels represented by '-2', '-1', '0', '1', '2' respectively, were selected for each of the three factors. The levels of each factor are shown in Table 3, a total of 25 turning experiments as shown in the four columns on the left of Table 4, were conducted randomly according to the designed orthogonal experiment. The worn tool was observed by the means as 2.2, and the tool wear (*VB*) was appended to columns 5-7 of Table 4, the mean of measuring results, upper deviation, lower deviation were calculated and also appended to columns 8-10 of Table 4.

Table 3 Experimental factors and its levels

Factor	Level				
	-2	-2	0	1	2
v_c [m/min]	200	250	300	350	400
f [mm/r]	0.10	0.15	0.20	0.25	0.30
a_p [mm]	0.50	0.75	1.00	1.25	1.50

Table 4 Experiment design and results

Exp. No.	Cutting parameters			Tool wear (*VB*) [mm]					
	v_c [m/min]	f [mm/r]	a_p [mm]	1	2	3	Mean	Upper deviation [%]	Lower deviation [%]
1	200	0.10	0.50	0.169	0.187	0.160	0.172	-6.977	8.721
2	200	0.15	0.75	0.135	0.148	0.157	0.147	-8.163	6.803
3	200	0.20	1.00	0.126	0.135	0.129	0.130	-3.077	3.846
4	200	0.25	1.25	0.127	0.137	0.138	0.134	-5.224	2.985
5	200	0.30	1.50	0.098	0.108	0.094	0.100	-6.000	8.000
6	250	0.10	0.75	0.172	0.191	0.186	0.183	-6.011	4.372
7	250	0.15	1.00	0.151	0.169	0.145	0.155	-6.452	9.032
8	250	0.20	1.25	0.124	0.135	0.139	0.133	-6.767	4.511
9	250	0.25	1.50	0.105	0.116	0.118	0.113	-7.080	4.425
10	250	0.30	0.50	0.214	0.234	0.245	0.231	-7.359	6.061
11	300	0.10	1.00	0.174	0.184	0.188	0.182	-4.396	3.297
12	300	0.15	1.25	0.154	0.168	0.143	0.155	-7.742	8.387
13	300	0.20	1.50	0.127	0.138	0.125	0.130	-3.846	6.154
14	300	0.25	0.50	0.192	0.223	0.219	0.211	-9.005	5.687
15	300	0.30	0.75	0.200	0.206	0.203	0.203	-1.478	1.478
16	350	0.10	1.25	0.166	0.196	0.181	0.181	-8.287	8.287
17	350	0.15	1.50	0.142	0.159	0.149	0.150	-5.333	6.000
18	350	0.20	0.50	0.181	0.208	0.214	0.201	-9.950	6.468
19	350	0.25	0.75	0.189	0.200	0.182	0.190	-4.211	5.263
20	350	0.30	1.00	0.159	0.173	0.167	0.166	-4.217	4.217
21	400	0.10	1.50	0.171	0.172	0.176	0.173	-1.156	1.734
22	400	0.15	0.50	0.195	0.221	0.232	0.216	-9.722	7.407
23	400	0.20	0.75	0.181	0.183	0.179	0.181	-1.105	1.105
24	400	0.25	1.00	0.139	0.154	0.160	0.151	-7.947	5.960
25	400	0.30	1.25	0.143	0.160	0.165	0.156	-8.333	5.769

3. Results and discussions

3.1 Analysis of tool wear morphology and mechanism. Large cutting edge angle (κ_r) is usually used to reduce deflection deformation and dimensional error during turning process of slender shaft parts. The nose angle (ε_r) is a constant value for a selected tool, and the sum of cutting edge angle (κ_r), nose angle (ε_r) and minor cutting edge angle (κ_r') is 180 degrees. Therefore, the large cutting edge angle (κ_r) aggravates the friction between minor flank and machined surface, since minor cutting edge angle (κ_r') is decreased with cutting edge angle (κ_r) increasing, made tool minor flank wear be serious.

Tool wear topography and mechanism was observed by scanning electric microscope (SEM) and energy dispersive spectrometer (EDS) are shown in Fig.2, and the wear belt is uniform and consistent, no serious chipping and cracks. There are some adhesive materials which are mainly made of Fe and Al elements on the tool minor flank face, and the iron filings which explain there were adhesive wear happened on during turning. It could also be seen that, there was coating damage on tool minor surface, and a large amount of Al element was detected in the middle of the wear zone, which indicated the outermost layer of TiN coating had been completely worn away. The micro-scratches show that, there was abrasive wear on the tool minor surface.

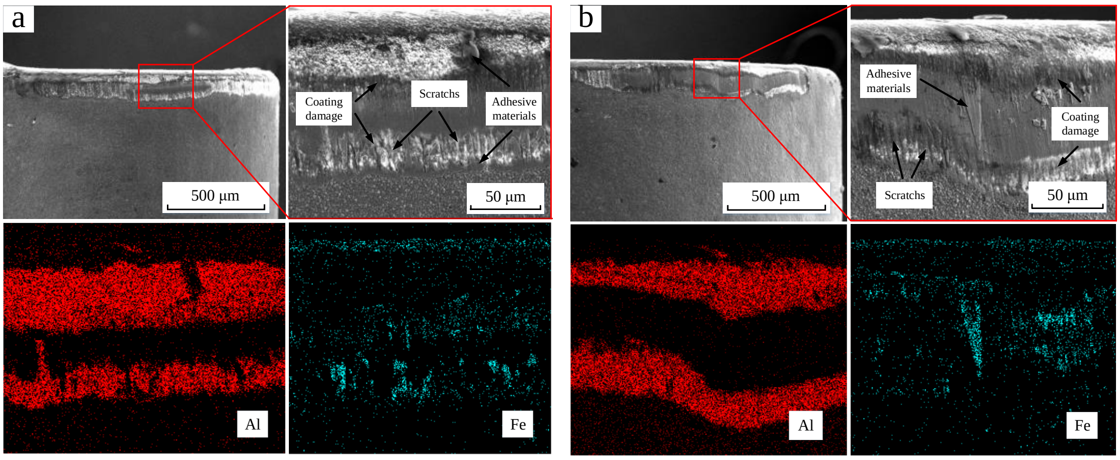

Fig.2 Tool wear in different cutting parameters: (a) 11th group, (b) 18th group.

3.2 Prediction of tool wear. An ANN model was used to predict tool wear (*VB*). Cutting speed (v_c), feed rate (f) and the depth of cut (a_p) were used as an input layer parameters, and the tool wear (*VB*) was used as an output layer parameter, and the structure of ANN model are shown in Fig.3. The equation (1) was used to determine the approximate range of the number of hidden layer nodes, and the final determination of m=8 by repeated attempts to contrast.

$$m = 2n+1, m = \sqrt{n+q}+a, m = \log_2 n \tag{1}$$

where, m is hidden layer nodes, n is input layer nodes, q is output layer nodes, a is a variable (a=1~10).

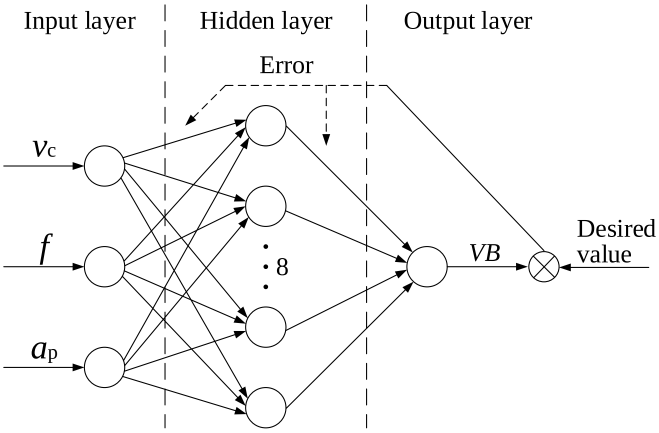

Fig.3 The structure of ANN model for tool wear

Table 5 Relative errors between predicted value and actual value

Experiment number	Cutting parameters			Experimental *VB* value [mm]	Predicted *VB* value [mm]	Relative Error [%]
	v_c [m/min]	f [mm/r]	a_p [mm]			
1	200	0.10	0.50	0.172	0.183	+6.39
4	200	0.25	1.25	0.134	0.146	+8.96
12	300	0.15	1.25	0.155	0.153	-1.29
17	350	0.15	1.50	0.150	0.159	+6.00
24	400	0.25	1.00	0.151	0.163	+7.95

The ANN model was established by MATLAB. TANSIG, TRAINGD, and LEARNGDM were selected as the transfer function, training function, and learning function respectively. The ANN model was trained by the 20 samples selected randomly in 25 samples, other 5 samples was used as testing samples. The prediction relative error of ANN model achieved the predetermined value of 0.001 after 15764 times training. The testing relative errors are shown in Table 5, and are within 10%, which indicates the ANN model has high accuracy in predicting tool wear under constant MRV condition.

3. Conclusions

Some experiments were carried out to research tool wear in different cutting parameters under constant MRV in turning of AISI 4140 steel, and an ANN model was established to predict the tool wear. The main conclusions can be summarized as follows,

(1) The tool minor flank wear is worst with large cutting edge angle (κ_r) and the coating damage, adhesive wear and abrasive wear are the main form of tool failure of the tool.

(2) An ANN model which was trained by back-propagation algorithm to predict tool flank wear (*VB*). Error analysis shows that the ANN model can have satisfactory prediction accuracy under the constant MRV condition during turning process.

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