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TOOL WEAR MODELING OF HARDENED 42CrMo4 STEEL DEPENDING ON CUTTING PARAMETERS AND WORKPIECE MATERIAL HARDNESS DURING TURNING PROCESS

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Abstract: Cutting tool is one of the critical elements in the machining process. Tool wear describes the gradual failure of cutting tools due to regular operation Flank wear of cutting tools is often selected as the tool life criterion because it determines the diametric accuracy of machining, its stability and reliability. Tool wear in cutting process is produced by the contact and relative sliding between the cutting tool and the workpiece, and between the cutting tool and the chip under the extreme conditions of cutting area. In this work is developed the first model for predicting tool wear based on experimentally measured values and multiple regression analysis method and four factors (spindle speed, feed rate, depth of cut and workpiece hardness) at three level orthogonal experiment, during turning hardened 42CrMo4 steel using TiAlN/TiN multi-layer coated carbide inserts.

Keywords: Tool wear, Turning, Regression, Analysis, Model

1. INTRODUCTION

Aspects such as tool life and wear, surface finish, cutting forces, material removal rate, and power consumption, cutting temperature (on tool and workpiece's surface) determine the productivity, product quality, overall economy in manufacturing by machining and quality of machining [1]. Hard turning is a topic of great interest in today's industrial production and scientific research. The hard turning technology has the potential for improving productivity by replacing grinding in the process of manufacturing. In machining processes, it is necessary to attain the desired surface quality in order to produce parts providing the required functioning. The surface quality also defines some mechanical properties of the product, such as wear resistance. Being such a considerable quality, surface quality is influenced by various parameters. Since improvement of surface quality can be hindered by tool wear, resistance of the tool against thermal and mechanical loads should be taken into consideration. Looking from this aspect, an ideal tool should possess the properties of good wear resistance, high mechanical strength and high thermal stability [2].Yong and Tang [3] used a Taguchi method for optimizing the cutting parameters on tool wear in turning of hardened steel with carbide inserts. They observed that abrasion is the most dominant wear mechanism under the consistent cutting conditions, and diffusion wear under higher cutting condition.

The primary objective of this research is to develop a mathematical relationship for tool wear model (min) for Cr42Mo4 steel with TiAlN/TiN multi-layer coated carbide inserts under dry machining conditions, as a function of the cutting parameters such as cutting speed (m/min), feed rate (mm/rev), depth of cut (mm) and work material hardness (HRC).

2. TOOL WEAR (TW)

There are several types of observed cutting tool wear which are listed below:

1. Crater wears which occurs on rake surface. Crater wear can increase the working rake angle and reduce the cutting force, but it will also weaken the strength of cutting edge.
2. Flank wear which occurs on the flank face due to friction between machined surface of workpiece and tool flank. Flank wear is mainly caused by the rubbing action of the tool on the machined surface.
3. Notch wears is special type of combined flank and rake face wear which occurs adjacent to the point where the major cutting edge intersects the work surface [4]

Tool wear leads to tool failure. According to many authors, the failure of cutting tool occurs as premature tool failure (i.e., tool breakage) and progressive tool wear. Figure 1 shows some types of failures and wear on cutting tools. Generally, wear of cutting tools depends on tool material and geometry, workpiece materials, cutting parameters (cutting speed, feed rate and depth of cut), cutting fluids and machine-tool characteristics [5].

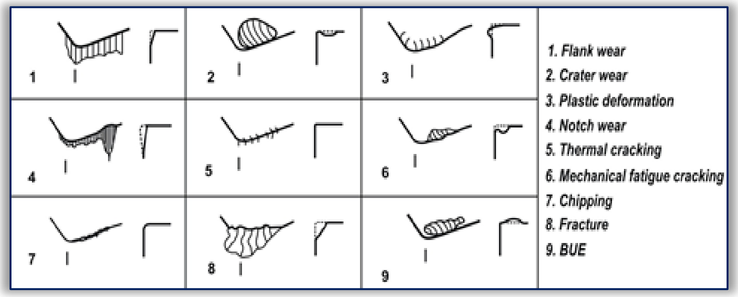

Figure 1. Types wear on cutting tools (adapted from Sandvik)

Flank wear

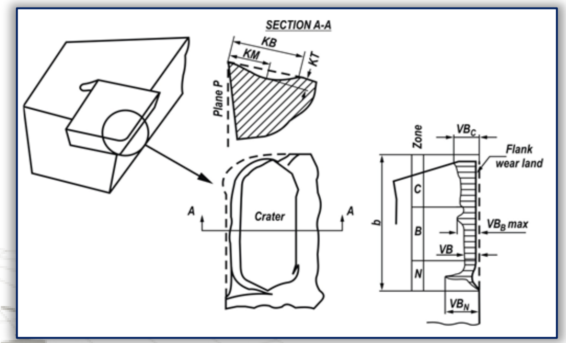

Figure 2. Types of wear on turning tools according to ANSI/ASME Tool Life Testing [6]

Flank wear (Figure 2) results in the formation of a flank wear land. For the purpose of wear measurement, the major cutting edge is considered to be divided into the following three zones: (a) Zone C is the curved part of the cutting edge at the tool corner; (b) Zone N is the quarter of the worn cutting edge of length b farthest from the tool corner; and (c) Zone B is the remaining straight part of the cutting edge between Zones C and N. The maximum VB_Bmax and the average VB_B width of the flank wear are measured in Zone B, the notch wear VB_N is measured in Zone N, and the tool corner wear VB_C is measured in Zone C. As such, the following criteria for carbide tools are normally recommended: (a) the average width of the flank wear land VB_B=0.2-0.3 mm, if the flank wear land is considered to be regularly worn in Zone B; (b) the maximum width of the flank wear land VB_Bmax=0.6 mm, if the flank wear land is not considered to be regularly worn in Zone B. Besides, surface roughness for finish turning and the length of the wear notch VB_N=1 mm can be used. However, these geometrical characteristics of tool wear are subjective and insufficient. First, they do not account for the tool geometry (the flank angle, the rake angle, the cutting edge angle, etc.), so they are not suitable to compare wear parameters of cutting tools having different geometries. Second, they do not account for the cutting regime and thus do not reflect the real amount of the work material removed by the tool during the tool operating time, which is defined as the time needed to achieve the chosen tool life Criterion [3], [10].

In order to find out suitable way to slow down the wear process, many works are carried out to analyze the wear mechanism in metal cutting. It is found that tool wear is not formed by a unique tool wear mechanism but a combination of several tool wear mechanisms. Tool wear mechanisms in metal cutting include abrasive wear, adhesive wear, solution wear, diffusion wear, oxidation wear, etc., illustrated in Figure 2. The criteria recommended by ISO3685:1993 to define the effective tool life for cemented carbides tools, high-speed steels (HSS) and ceramics are [7]:

Cemented carbides:

1. VB_B = 0.3 mm, or
2. VB_Bmax = 0.6 mm, if the flank is irregularly worn, or
3. KT = 0.06 + 0.3 f, where f is the feed.

HSS and ceramics:

1. Catastrophic failure, or
2. VB_B = 0.3 mm, if the flank is regularly in region B, or
3. VB_Bmax = 0.6mm, if the flank is irregularly in region B.

Wear mechanisms

Flank and crater wear are the two main wear mechanisms that limit a tools performance. Flank wear is caused when the relief face of the tool rubs against the machined surface. It has an adverse impact on the finish and dimensional accuracy of products that are machined. Crater wear on the other hand occurs on the rake face of the tool and affects the geometry at the chip tool interface, which in turn affects the cutting force [8].

The various mechanisms that contribute tool wear process are as bellow (Figure 3) [6, 9]: mechanical overload causing micro breakages (attrition), abrasion, adhesion and diffusion.

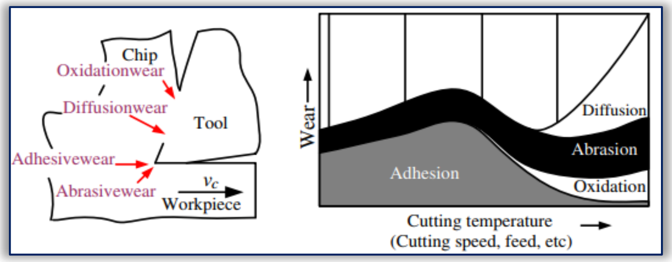

Figure 3. Wear mechanism in metal cutting

The above wear mechanisms may occur simultaneously, or one of them may dominate the process. These mechanisms can lead to several types of wear; however, two types of them, which called crater and Flank wear, are most distinguished.

Flank wear typically increases with the time of cutting, as shown in Figure 4. a. At the beginning, at phase 1, there is an initial faster increase that is followed by a steady increase in proportion to cutting time, phase 2. When the wear reaches a certain size, it will accelerate and may lead to a sudden failure of the edge, phase 3.

As it seen in (Figure 4), there is a linear relationship between flank wear size and turning time. So, using the experimental data and by fitting with this figure as a reference line, the tool life time of experiment can be estimated.

Flank wear characterized by wear land (or Height) h_f of wear band. Flank wear formation depends on:

- Cutting Conditions (f, d, v_c, tool angles) and
- Properties of work material and tool material

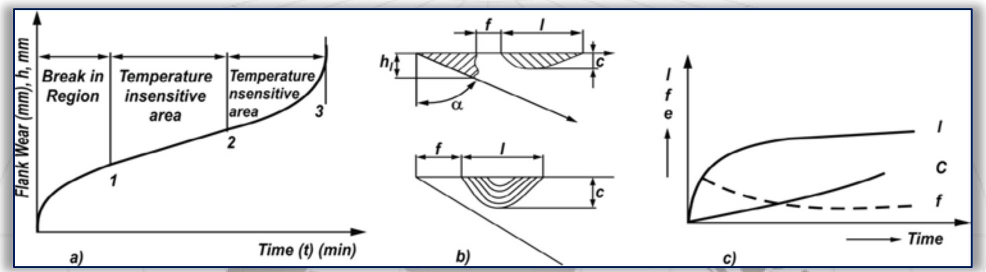

Figure 4. Flank wear features: a) Three stage flank wear curve, b) Various elements of flank wear and crater wear, c) Variation of various crater wear with time [10]

Corner wear: occurs on the tool corner. Can be considered as a part of the wear land and respectively flank wear since there is no distinguished boundary between the corner wear and flank wear land. We consider corner wear as a separate wear type because of its importance for the precision of machining. Corner wear actually shortens the cutting tool thus increasing gradually the dimension of machined surface and introducing a significant dimensional error in machining, which can reach values of about 0.03~0.05 mm (Figure 5) [11].

Top view shows the effect of tool corner wear on the dimensional precision in turning.

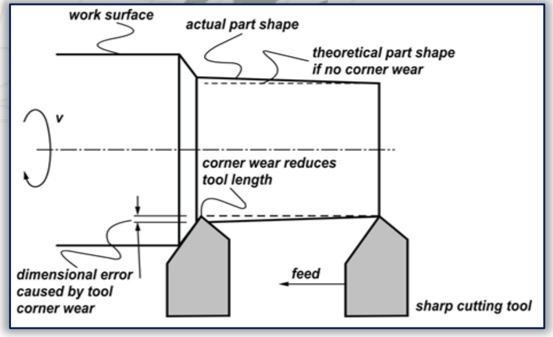

Figure 5. Top view showing the effect of tool corner wear on the dimensional precision in turning

Wear control

As it was discussed earlier, the rate of tool wear strongly depends on the cutting temperature, therefore, any measures which could be applied to reduce the cutting temperature would reduce the tool wear as well. The Figure 6 shows the process parameters that influence the rate of tool wear:

Additional measures to reduce the tool wear include the application of advanced cutting tool materials, such as coated carbides, ceramics, etc.

3. DESIGN OF EXPERIMENT

The parameters (factors) considered in this paper are cutting speed (v_c), feed rate (f),depth of cut (a) and hardness of Workpiece material hardened at three levels (35; 45 and 55HRC). The cutting tool wear and tool life was chosen as a target function (response, output).

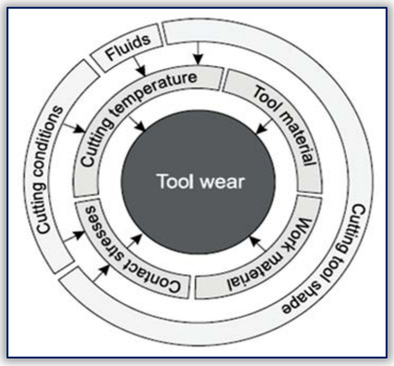

Figure 6. Cutting tool wear as a function of basic process parameters [11]

Since it is obvious that the effects of factors on the selected target function are nonlinear, an experiment with factors at three levels was set up (Table 1).

Table 1. Experimental setup at three level factor

Cutting factors and their levels					
No.	Factors	Code level	High level (1)	Middle level (0)	Low level (-1)
1	v_c, m/min	X_1	180	135	100
2	f, mm/rev	X_2	0,285	0.214	0.178
3	a, mm	X_3	1.5	0.85	0.5
4	HRC, N/mm^2	X4	55	45	35

A design matrix was constructed on the basis of the selected factors and factor levels (Table 2). The selected design matrix was a full factorial design $N=2^k+n_0$ (k= 4- number of factors, n_0 = 8 – number of additional tests for four factors) consisting of 24 rows of coded/natural factors, corresponding to the number of trials. This design provides a uniform distribution of experimental points within the selected experimental hyper-space and the experiment with high resolution.

Table 2. Experimental results of tool wear and tool life

Test	Coded factors					Performance measures
No	X_0	X_1	X_2	X_3	X_4	TW (mm)
1	+1	-1	-1	-1	-1	0.151
2	+1	-1	-1	-1	1	0.322
3	+1	-1	-1	1	-1	0.211
4	+1	-1	-1	1	1	0.122
5	+1	-1	1	-1	-1	0.313
6	+1	-1	1	-1	1	0.411
7	+1	-1	1	1	-1	0.282
8	+1	-1	1	1	1	0.325
9	+1	1	-1	-1	-1	0.453
10	+1	1	-1	-1	1	0.372
11	+1	1	-1	1	-1	0.351
12	+1	1	-1	1	1	0.292
13	+1	1	1	-1	-1	0.224
14	+1	1	1	-1	1	0.233
15	+1	1	1	1	-1	0.224
16	+1	1	1	1	1	0.652
17	+1	0	0	0	0	0.251
18	+1	0	0	0	0	0.264
19	+1	0	0	0	0	0.384
20	+1	0	0	0	0	0.425
21	+1	0	0	0	0	0.354
22	+1	0	0	0	0	0.254
23	+1	0	0	0	0	0.371
24	+1	0	0	0	0	0.451

The factor ranges were chosen with different criteria for each factor, aiming at the widest possible range of values, in order to have a better utilization of the proposed models. At the same time, the possibility of the mechanical system and manufacturer's recommendations are taken into account.

Machining conditions used in the experiment are shown in Table 1. All of the trials have been conducted on the same machine tool, with the same tool type and the same cutting conditions.

Machine tool: Production lathe PA22, P = 12 kW, speed range n = 22 - 2200 rpm, feed rate range f = 0.08 - 2,5 mm/rev, Max. Workpiece diameter d_{max} = 450 mm, Distance from chuck to the tail stock L = 2250 mm, Figure 4.

Figure 4. Lathe machine PA22

Figure 5. Measurement microscope Carl Zeiss

Workpiece material: Hardened 42CrMo4 (EN 10250) steel at three levels of hardness HRC (35; 45 and 55), with dimensions L x D = 300x80 mm. Heat treated at temperature 800-8500^{o}C, cooled in the furnace to the temperature 460°C and complete annealing the steel in the air. Its chemical composition is as follows: 0.39-0.42% C; 1.04-1.06% Cr; 0.22-0.24% Mo; 0.72-0.76% Mn; 0.2-0.22% Si other components approx., 98% Fe. Tensile: strength: 900-1000 N/mm², Brinell hardness: 260-330 N/mm².

Cutting inserts: Experiments were performed using commercially available PVD TiAlN/TiN multi-layer coated carbide inserts type SNMM120404, tool holder ISO PCBNR /L 2020K12.

Measuring equipment: Microscope Carl Zeiss 15x8 (Figure 5), Spectrometer Metorex Arc-met 930, Hardness meter Krautkramer-mic. 10.DL.

4. SELECTION OF LEVELS FOR PROCESS VARIABLES

In order to develop the tool wear prediction model, four factors and three levels for each of them are selected. The selected process parameters for the experiment with their limits, units and notations are given in Table 1.

The experiments were carried out at the cutting length of 280 mm in the dry condition.

The flank tool wear measurements were made on the cutting insert surface directly after every twenty cuts on the Workpiece 42CrMo4 and results are shown in Table 2. After recording the flank wear, the insert was fastened back the tool holder.

5. TOOL WEAR MODEL

Many authors suggested linear and exponential empirical models for tool life as functions of machining parameters.

In this paper, regression method is applied to develop a mathematical model to predict the tool wear and the tool life for turning of 42CrMo4 steel. The relationship between the independent variables of process parameters (spindle speed v_c, feed rate f, depth of cut a and Workpiece hardness HRC) tool wear TW and tool life TL can be represented by the following mathematical model [12, 13].

$$TW = C_{TW} \cdot v_c^{\ m} \cdot f^{\ n} \cdot a^{\ p} \cdot H^{\ q} \qquad (1)$$

where, C_{TW} constants (empirical), TW is the tool wear in (mm),v_c - cutting speed in m/min, f - feed rate in mm/rev, a - depth of cut in mm and H Workpiece hardness HRC in N/mm², respectively m, n, p, q are constants.

Multiple linear regression models can be obtained by applying a logarithmic transformation that converts non-linear form of Eq. (1) into following linear mathematical form:

$$\ln TW = C_{TW} + m \ \ln v_c \ + n \ln f + p \ln a \ + q \ln H \qquad (2)$$

The linear model of Eq. (2) in term of the estimated response can be written as:

$$Y - \varepsilon = p_0 X_0 + p_1 X_1 + p_2 X_2 + p_3 X_3 + p_4 X_4 \qquad (3)$$

where y is the logarithmic value of the tool wear respectively tool life, p_0, p_1, p_2, p_3 and p_4, are regression coefficients to be estimated, x_0 is the unit vector, x_1, x_2, x_3 and x_4 are the logarithmic values of cutting speed, feed rate, depth of cut, Workpiece hardness and ε is the random error.

The regression analysis technique using least squares estimation was applied to compute the coefficients of the exponential model. The following exponential model for tool wear was determined and is given, respectively:

$$TW = 0.0132 \cdot v_c^{\ 0.465} \cdot f^{\ 0.378} \cdot a^{\ -0.05} \cdot H^{\ 0.370} \qquad (4)$$

The prediction's mathematical models obtained (4) is adequate as it meet the condition [14]:

$$F_{R\,LF} = \frac{s_{LF}^{\ 2}}{s_E^{\ 2}} = \frac{0.17913056}{0.056247} = 3.19 \le F_t = 3.57 \qquad (5)$$

where; F_t =3.57 – The value of F-distribution quantization table for $f_{LF}(n_1)$=12; $f_E(n_2)$=n_o-1=7 and level of significance α=0.05 [15].

6. CONCLUSIONS

In this paper a mathematical model is presented that defines the change in the width of the flank wear.

Tool wear was studied by applying a full design of experiments on effective parameters that have effect.

Continuously a regression model between selected factors and tool wear was introduced. Experimental observation indicates that tool wear will increase with cutting speed, feed rate, and Workpiece material hardness, while decrease with depth of cut.

The investigations of this study indicate that cutting speed has maximum effect (0.465), followed by feed rate (0.38), Workpiece hardness (0.37) and depth of cut has minimum effect (0.05).

By using analysis of variance for obtain the significant factors, it was distinguished that all main factors have significant effect on tool wear except depth of cut with its exponent (0.05). It is important to use the right tool for the right cutting condition in order to reduce tool wear and fracture, increase machining accuracy, and increase tool life and productivity.

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