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Predicting Optimal Tool Replacement Time in Turning of Super Alloy Using Reliability Testing

U. Lakshminarayana[1], B. Sri Harsha Vardhan Reddy[2], K. Srinu, B. SurBabu[3] and Akula Siva Bhaskar[4]
*[1,2,3,4]Dept. of Mechanical Engineering,*UG Students, QIS-College of Engineering and Technology, Ongole*
E-mail: [2]bshvreddy@gmail.com

Abstract—*A Cutting tool is an important element in machining and its reliability influencing the total machining effectiveness and stability of machine tools. The main objective of this paper is to outline a procedure for estimating the optimal tool replacement time based on the tool performance calculated using reliability function. This paper includes the selection of suitable failure distribution, modeling of reliability function of cutting tool based on the flank wear as the major failure criteria in tool failure. The reliability testing is carried out (TTT) to give brief idea regarding the failure rate of cutting tool. In this study, the Reliability approach is used to find the reliability of cutting tool, for optimal replacement time of cutting tool in CNC turning. The reliability analysis of tool life model is employed to study the performance of tool in turning operation of D 2 tool steel using cemented carbide inserts. Three cutting parameters namely, cutting speed, feed, depth of cut are varied with each pass and flank wear is considered as tool wear phenomena for tool life model. The Experimental results are provided to illustrate the effectiveness of this approach.*

1. INTRODUCTION

Modern cutting tools are disposable inserts with one or more cutting edges. Once the edge wears out, the insert is indexed (or replaced), as a result of which a fresh edge is provided for further machining. In practice the wear on a particular cutting edge does not depend on the wear of previously used edges of the same insert. Thus, after replacement or indexing the cutting tool edge is as good as new, and the age reduction setback approaches are therefore not relevant. A special case arises when a catastrophic failure or a major fracture occurs. As a consequence, a few cutting edges or the whole insert can be destroyed at once. This would obviously reduce the maximum number of times that the tool could be indexed. However, the broken edge would not be used for further cutting. Traditional tool life models do not take into account the variation inherent in metal cutting processes. As a consequence, the real tool life rarely matches the predicted values. To compensate for this uncertainty, tools are usually replaced prematurely, which leads to unnecessarily high tool costs. In some cases, however, wear-out occurs earlier than predicted, which imposes a risk of work piece damage or rework and can lead to other extra charges. Hus and Hung [1] have studied the reliability assessment and determination of optimal replacement time for a machine tool under wear deterioration. Traditional models classifying a tool's condition use binary states, with working (success) or failure. To evaluate its reliability and decide its optimal replacement time they followed non homogeneous continuous-time Markov process. As most machine tools deteriorate over time, a multi-state discrete model was reported as a more realistic classification for quantifying the tool wear condition. They developed a reliability modeling on the basis of tool wear and stated that the length of time the tool stays in a certain state, which depends not only on its current state but also on how long it has remained in the current state. According to this model reliability assessment for the tool with the multi-state deterioration was developed. Carmen and Martha [2] presented a reliability-based analysis for calculating critical tool life in machining processes. It is possible to determine the running time for each tool involved in the process by obtaining the operations sequence for the machining procedure. Usually, the reliability of an operation depends on three independent factors: operator, machine-tool and cutting tool. The reliability of a part manufacturing process is mainly determined by the cutting time for each job and by the sequence of operations, defined by the series configuration. The reliability of the turning operation is modeled based on data presented in the literature, and from experimental results, a statistical distribution of drilling tool wear was defined, and the reliability of the drilling process was modeled. Vagnorius et al [3] proposes an age replacement model. It was assumed that penalty costs are incurred each time a tool fails before the planned replacement. The probability of such an event is determined from the tool reliability function, which models the wear-out by a mixture of Weibull distributions, while failures due to external stresses are accounted for by a homogeneous Poisson process. The optimal replacement time is then determined from a total time on test (TTT) plot. The adequacy of the proposed approach for practical application is tested and confirmed in a case study on turning of D2 tool steel with =cemented carbide tools. [4] proposed Statistical relationships between the initial wear and uniform wear periods are obtained. The results show that there is qualitative relationship between wear rate during initial wear period

(WRIWP) and wear rate in uniform wear period (WRUWP) to certain extent. On this basis, a tool material rapid selection method based on the initial wear is put forward, and suitable tool materials for machining titanium alloy are selected. The experimental results indicate that this method is effective and useful. The new tool materials rapid selection can be used to select suitable cutting tool materials quickly before carrying out systematic mach inability tests with the most suitable tool materials .Murthy et al [5] focused on the sequence of 9417 performances and specification throughout the design process, and define the reliability specification at the component level that will ensure that the product reliability requirements were met. The outline of the article is as follows. It starts with a brief general discussion of performance and specification and the links between the two in the context of new product development. This is followed by a brief discussion of the design process with the process of arriving at the reliability specifications at the component level. Dasic et al [6] have studied the reliability of machining systems depends to a great extent on the reliability of cutting tool performance. By the application of statistical methods describing the breakdown of the components of machining systems in the phase of effective performance, it is possible to determine the theoretical distribution which fits best to the experiment data. The theoretical distribution models encountered more frequently as exponential, linear, normal, weibull etc. The methodology proposed stochastic modeling of tool life based on flank wear. The model was tested in the manufacturing and agricultural engineering. in [7] described the reliability of the cutting tools in the high speed turning by normal distribution model and the tool wear variation of the cutting tool from the point of reliability. studied the reliability of cutting tool performance based on the wear phenomenon through comparative analysis of theoretical distribution models, which fits the experimental results and normal model was proposed for reliability function of the tool. Huang and Liang [8] develop a methodology to model the CBN tool crater wear rate to both guide the design of CBN tool geometry and optimize cutting parameters in finish hard turning. First, the wear volume losses due to the main wear mechanisms (abrasion, adhesion, and diffusion) are modeled as functions of cutting temperature, stress, and other process attributes respectively. Then, the crater wear rate is predicted in terms of tool/work material properties and cutting configuration. Finally, the proposed model is experimentally validated in finish turning of hardened 52100 bearing steel using a low CBN content insert. The comparison between the prediction and the measurement shows reasonable agreement and the results suggest that adhesion is the main wear mechanism over the investigated range of cutting conditions. Oraby and Hayhurst [9] proposed a Non-linear regression analysis techniques are used to establish models for wear and tool life determination in terms of the variation of a ratio of force components acting at the tool tip. The ratio of the thrust component of force to the power, or vertical, force component has been used to develop models for (i) its initial value as a function of feed, (ii) wear, and (iii) tool lifetimes. Predictions of the model have been compared with the results of experiments, and with predictions of an extended Taylor model. In all cases, good predictive capability of the model has been demonstrated. It was suggested that the models are suitable for use in adaptive control strategies for centre lathe turning.Hoang Pham [10] Part II of the Handbook contains five papers, focuses on the Statistical Reliability theory. Chapter 6 by Finkelstein presented stochastic models for the observed failure rate of systems with periods of operation and repair that form an alternating process. Chapter 7 by Lai and Xie studied a general concept of stochastic dependence including positive dependence and dependence orderings. Chapter 8 by Zhao discussed some statistical reliability change-point models which can be used to model the reliability of both software and hardware systems.Hall and Strutt [11] proposed a methodology for the implementation of physics-of-failure models of component lifetimes in the presence of parameter and model uncertainties. This treats uncertain parameters as random variables described by some appropriate statistical distribution, which may be sampled using Monte Carlo methods. The number of simulations required depends upon the desired accuracy of the predicted lifetime. Dimitri [12] in―Reliability engineering hand book (volume-1)‖,chapter 4 quantifies the concepts of time to failure distributions, reliability, conditional reliability, failure rate, mean life and provides the necessary back ground in statistics and probability. Chapter 5 covers more frequently used distributions in reliability engineering in great deal: exponential, normal, log-normal, weibull etc. Dimitri [13] in―Reliability engineering hand book (volume-2)‖, chapter 5 covers the prediction of the reliability of complex components, equipment and systems. Chapter 12 covers five unique practical and very comprehensive case studies of predicting equipment, system reliabilities and comparing them with their reliability goals. Chapter 15 covers the methods of allocation or appointment of an equipment's or system's reliability goal to its subsystems, all the way down to its components. Sikdar and Chen [13] described the relationship between flank wear area and cutting forces for turning operations. A set of experiments were performed on a CNC lathe without coolant. The CNMG120412N-UJ tool insert was used to cut low alloy steel (AISI 4340). Flank wear surface area was measured by surface texture instrument (Form TalysurfTM series) using a software package. Cutting forces were measured by a KistlerTM piezo-electric dynamometer. The experimental results show that there is an increase in the three directional components of the cutting force with increase in flank wear area. Axinte et.al [14] proposed a method to obtain reliable measurements of tool life in turning, discussing some aspects related to experimental procedure and measurement accuracy. The method (i) allows an experimental determination of the extended Taylor's equation, with a limited set of experiments and (ii) provides a basis for the quantification of tool life measurement. Wang et al [15] a reliability-dependent failure rate model is used to predict the reliability of a cutting tool subject to flank wear. This model proposes an algebraic relation between the failure rate and the reliability (AE model). It involves two decay factors. One is the so-called embedded decay factor which deals with the intrinsic characteristics of cutting behavior (involving the material properties and the geometry of cutting tool and work piece), the other is the process-dependent decay factor which relates to the cutting process. Experimental results show that the proposed model is satisfactory for describing the reliability of a cutting tool under flank wear. Ebeling [16] part I of― An Introduction to Reliability and Maintainability Engineering‖ contains basic models of reliability such as failure distributions and time dependent failure models, which gives a brief knowledge about how to calculate the reliability of the system or component corresponding to the assumed distribution and failure times. Appendix, Table A.1 provides Standardized normal probabilities, which are useful in calculating the reliability of cutting tool based on the failure times. Santos [17] determined the coefficients of the Extended Taylor's Equation in machining is proposed. The technique is based on the minimization of the ratio between maximum and minimum singular values of the matrix of sensitivity of the tool life related to the machining parameter variations. This procedure generates the best set of cutting conditions to be used in tool life tests which results in a fast convergence of the coefficients and their confidence intervals. This technique was compared to the commonly used fractional factorial design when face milling AISI 1045 steel with cemented carbide cutting tools. Wardany and Elbestawi [18] presented a stochastic model for predicting the tool failure rate in turning hardened steel with ceramic tools. This model is based on the assumption that gradual wear, chemical wear, and premature failure (i.e. chipping and breakage) are the main causes of ending the toot life. A statistical distribution is assumed for each cause of' tool failure. General equations for representing toot-life distribution, reliability function, and failure rate are then derived. The assumed distributions were then verified experimentally. From the experimental results, the coefficients of these equations are determined. Further, the rate of failure is used as a characteristic signature for qualitative performance evaluation. The results obtained show that the predicted rate of ceramic tool failure is 20% (in the first few seconds of machining) and it increases with an increase in cutting speeds. These results indicate that there will always be a risk that the tool will fail at a very early stage of cutting. Klim et al [19] proposed a reliability theory to model the random nature of the wear phenomena. Consequently, a quantitative estimate of the cutting tool improvement due to the variable feed was obtained and observed that the cutting tool life can be represented for the cases studied by the statistical normal distribution, to quantify the reliability of carbide tools. Liu and Makis (1996) derived a recursive formula to calculate the cutting tool reliability in variable condition if the failure time distribution of the cutting tool can be represented by the accelerated failure time model (AFTM). The formulas for the cutting tool reliability when the processing time for each operation is random are also derived. The unknown parameters in the reliability function can be estimated from cutting tool life data obtained under either fixed conditions or variable conditions by using the method of maximum likelihood. Lakovou,et.al [20] proposed analytical models and numerical procedures for simultaneously determining the optimal cutting speed and tool replacement policy in machining economics problems with stochastic tool lives when the objective is the minimization of the machining cost per part. It is shown that the objective function is separable for certain phase type tool life distributions. Liu and Makis [21] derived a recursive formula to calculate the cutting-tool reliability in variable conditions if the failure-time distribution of the cutting tool can be represented by the accelerated failure time model (AFTM). The formulas for the cutting-tool reliability when the processing time for each operation is random are also derived. The unknown parameters in the reliability function can be estimated from cutting-tool life-data obtained under either fixed conditions or variable conditions by using the method of maximum likelihood.

2. RELIABILITY MODEL FOR CUTTING TOOL

The cumulative simultaneous wear on the flank and on the face has been chosen as the observed modes of damage. This model is therefore characterized by its formulation that takes into account the standard IS0 wear criteria V_B, on the flank. For the reliability analysis, a cutting tool has two possible states, working state and failure state. In working state a tool possesses sufficient characteristics of the working state. After machining for some time the tool find itself difficult to cut the material properly. In terms of probability it is considered as an event opposed to the working state. The transition of a tool from a working state to a failure state is defined as a failure. In practice, the failure of the cutting tool is observed as excessive wear or as a breakage. Often, the breakage of a cutting edge is due to an incompatible choice of the cutting parameters. However, for this comparative analysis of cutting tool reliability with and without variable feed, the failure by breakage has been eliminated and the wear only has been considered as a failure criteria. During the tests, no breakage failure was observed and therefore this hypothesis is valid. The main assumptions used in building the toot-life model are as follows:

I. The tool wear process is considered as a stochastic process where the tool is subjected to a sequence of hazards.
II. Chipping due to chemical wear can be equated to an increased hazard function.
III. Infant deaths (rapidly decreasing hazard function) cannot be ignored.

The various modes of tool failure, such as flank wear, gradual wear and crater wear, chip notching on the rake face (outer and inner chip notching), premature failure (primary groove on the side cutting edge, secondary groove on the end cutting edge, chipping, or breaking), failure due to thermal cracking, softening, or plastic flow, and failure due to diffusion wear. The tool life model is derived under the assumption that the flank wear follows normal distribution [6]. The probability density function of flank wear is given in equation 1.

$$f(V_B) = \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(V_B-\mu)^2}{2\sigma^2}\right) \qquad (1)$$

Where, V_B is flank wear of the cutting tool. μ, σ represents the mean and standard deviation of the flank wear.

If the average flank wear is the function of cutting parameters (speed, feed and depth of cut), then the flank wear V_B [6] is expressed by equation 2.

$$V_B = \varphi(v, f, d) \qquad (2)$$

$$\mu = E(V_B) = E[\varphi(v, f, d)] \qquad (3)$$

$$\sigma = Var[V_B] = E[(V_B-\mu)^2] \qquad (4)$$

There is an exponential relationship between flank wear and cutting parameters, thus the flank wear [6] is expressed by equation 5.

$V_B = Cv^a f^b d^c$ (5) Where, C, a, b and c are the constants, which can be obtained from experiments or even from the machining hand book. Now the probability density function of the flank wear [6] can be obtained and expressed by equation 6.

$$f(V_B) = \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(V_B-Cv^a f^b d^c)^2}{2\sigma^2}\right) \qquad (6)$$

Damage probability of the cutting tool occurred [8], [9] before time t is given by equation 7.

$$P(\tau < t) = \int_0^t f(\tau).d\tau \qquad (7)$$

Where, τ is the time of damage occurred to tool.

If the flank wear of the cutting tool is V^*_B then the probability of flank wear [6] at time t is given by equation 8.

$P(V_B \geq V_B^*) = 1 - \int_0^{V_B^*} f(V_B).dV_B$ (8) Now from

$$P(\tau < t) = P(V_B \geq V_B^*) \qquad (9)$$

$$\int_0^t f(\tau).d\tau = \int_0^{V_B^*} f(V_B).dV_B \qquad (10)$$

On substituting $f(V_B)$ of (equation 6) in (equation 9), rearranging and differentiating it with respect to t. Then the probability density function [6] of tool life f(t) is obtained as given in equation 11.

$$f(t) = \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(T_V-\mu)^2}{2\sigma^2}\right) \qquad (11)$$

Where, T_V is the time taken to reach the average flank wear V_B^* value.

Now the reliability function is given in equation 12.

$$R(t) = 1 - \int_t^{\infty} f(t).dt \qquad (12)$$

$$R(t) = 1 - \int_t^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(T_V-\mu)^2}{2\sigma^2}\right).dt \qquad (13)$$

However, there is no closed form solution for this integral, and it must be evaluated numerically [12], the transformation is given in equation 14.

$$Z = \frac{(T_V-\mu)}{\sigma} \qquad (14)$$

Where, Z will be normally distributed with a mean of zero and variance of one. Now the probability density function [12] is given by equation 15.

$$\varphi(Z) = \frac{1}{\sqrt{2\pi}} e^{\frac{-z^2}{2}} \qquad (15)$$

And Z is referred to standardized normal variate [12]. Its cumulative distribution function is given by equation 16.

$$\Phi(z) = \int_{-\infty}^{z} \varphi(z).dz \qquad (16)$$

Therefore in general, the reliability equation of cutting tool based on the failure phenomenon [12] was expressed by equation 17.

$$R(t) = 1 - \Phi\left(\frac{(T_V-\mu)}{\sigma}\right) \qquad (17)$$

Test	Cutting speed v(m/min)	Feed f(mm/rev)	Depth of cut d(mm)	Flank wear VB (mm)	Time(min)
1	120	0.1	0.2	2.99	13.40
2	120	0.1	0.4	3.00	13.22
3	120	0.1	0.6	3.01	13.10
4	120	0.15	0.2	3.04	12.56
5	120	0.15	0.4	3.06	12.42
6	120	0.15	0.6	3.09	12.32
7	120	0.2	0.2	3.12	11.58
8	120	0.2	0.4	3.18	11.30
9	120	0.2	0.6	3.20	10.44
10	225	0.1	0.2	3.30	9.28
11	225	0.1	0.4	3.33	8.54
12	225	0.1	0.6	3.39	8.32
13	225	0.15	0.2	3.42	8.14
14	225	0.15	0.4	3.48	7.20
15	225	0.15	0.6	3.52	6.33
16	225	0.2	0.2	3.60	6.10
17	225	0.2	0.4	3.65	5.20
18	225	0.2	0.6	3.69	4.47
19	300	0.1	0.2	3.72	4.12
20	300	0.1	0.4	3.78	3.21
21	300	0.1	0.6	3.80	2.29
22	300	0.15	0.2	3.86	2.10
23	300	0.15	0.4	4.00	1.50
24	300	0.15	0.6	4.11	1.20
25	300	0.2	0.2	4.20	0.56
26	300	0.2	0.4	4.26	0.27
27	300	0.2	0.6	4.30	0.27

3. EXPERIMENTAL SETUP

Turning is a widely used machining process in which a single-point cutting tool removes material from the surface of a work piece. Basically, the tool life is correlated strongly with the cutting parameters such as spindle speed, feed rate, and depth of cut. Inconel718 with 36HRc have been used for experimentation. The dimensions of the specimens are 120mm in length, 50mm in diameter. The experiments were conducted on CNC Lathe in dry condition. The cutting tool used is cemented carbide insert (CNMG 432-DM).

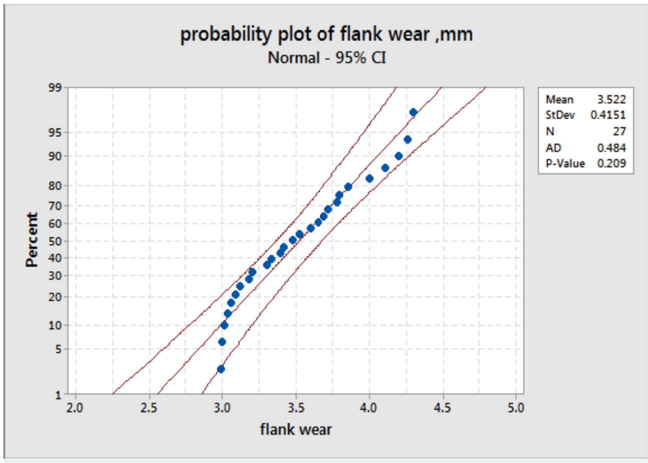
The turning is done for a length of 70mm, cutting speed (V): 250-440 rpm, feed (f): 0.2-0.6 mm/rev, depth of cut (d):0.5-2.5 mm. Totally 10 inserts were used for machining (i.e. 40 cutting edges). Each cutting edge was used until it worn out .The machining process was done in dry condition (without lubricant). The turning was done for a length of 70mm.Thus 40 individual cutting trials were carried out under various combinations of cutting parameters mentioned above and the table.1 shows the corresponding readings.

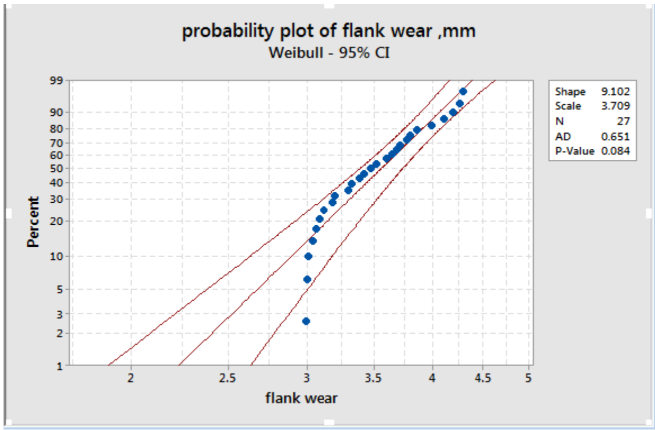
Table 1: Flank wears readings

(i)	T(i)	Σ (j=1-i)T(i)	T(t(i))	(i/n)	T(t(i))/T(t(n))
1	0.27	0.27	7.29	0.037	0.038
2	0.27	0.54	7.29	0.074	0.038
3	0.56	1.1	14.54	0.11	0.076
4	1.20	2.3	29.9	0.14	0.157
5	1.50	3.8	36.8	0.18	0.194
6	2.10	5.9	50	0.22	0.263
7	2.29	8.19	53.99	0.25	0.284
8	3.21	11.4	72.39	0.29	0.382

9	4.12	15.52	89.68	0.33	0.473
10	4.47	19.99	95.98	0.37	0.506
11	5.20	25.19	108.39	0.40	0.572
12	6.10	31.29	122.79	0.44	0.648
13	6.33	37.62	126.24	0.48	0.666
14	7.20	44.82	138.42	0.51	0.730
15	8.14	52.96	150.64	0.55	0.795
16	8.32	61.28	152.28	0.59	0.803
17	8.54	69.82	155.22	0.62	0.819
18	9.28	79.1	162.62	0.66	0.858
19	10.44	89.54	173.06	0.70	0.913
20	11.30	100.84	179.94	0.74	0.949
21	11.58	112.42	181.9	0.77	0.960
22	12.32	124.74	186.34	0.81	0.903
23	12.42	137.16	186.84	0.85	0.986
24	12.56	149.72	187.4	0.88	0.989
25	13.10	162.82	189.02	0.92	0.997
26	13.22	176.04	189.26	0.96	0.999
27	13.40	189.44	189.44	1.00	1.00

Minitab-17. In reliability modeling normal distribution and weibull distribution are the two widely used distributions for modeling failure models. The following fig.3 represents the normal probability plot of the experimental readings and fig.4 shows weibull distribution plot.

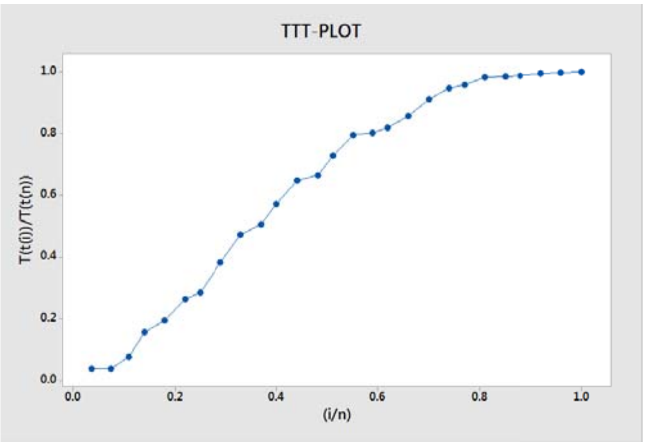




region of the straight lines and only a very few are out of the region when compared to the weibull probability plot. Hence flank wear in the present case follows normal distribution and the assumption has been proved.

4. TTT-TRANSFORMATION

The main advantage of the non-parametric approach is its simplicity. All that is needed to construct an empirical TTT-plot is a data table similar to the one shown in table 2. Such a table can easily be made with a spreadsheet program or even by hand calculation. The advantage of the parametric approach, however, is the possibility of predicting results outside the test region.Total time on test plot analysis of the cutting tool gives brief idea about the failure rate. This method is used for analyzing whether the failure data of the tool follows upward trend or downward trend (i.e., the increasing failure rate or decreasing failure rate). The method uses a total time on test plot for a component, which has normal distribution characteristics



The reliability function for the tool life was derived using flank wear as the major phenomenon.The validation of the assumed flank wear distribution was done using statistical software MINITAB-16.The reliability of the cutting tool can be calculated with the derived reliability function with the help of the—Standardized normal probability tables‖.

4.1 Reliability of cutting tool

The reliability of the cutting tool can be calculated from the derived reliability function (equation 5.17) with the help of the—Standardized normal probability tables‖. Failure of the insert follows normal distribution with mean of 7.01 min and standard deviation of 3.19 min, then calculate the reliability of insert at t=13.40 m

$$R(t) = 1 - \Phi\left(\frac{(T_V - \mu)}{\sigma}\right)$$

$$Z = \frac{(T_V - \mu)}{\sigma}$$

For t =13.40

From the standardized tables $\varphi(z)=0.97615$

Therefore $R(13.40)=1-0.97615=0.02385$

$R(7.20)=48\%$ and $R(0.56)=97\%$

From the above reliability calculations

i. at 13.40 minutes the performance of the cutting tool is 2.3% and the probability of survival is 0.023.
ii. at 7.20minutes of time the tool performance is 48% and the probability of survival is 0.48.
iii. at 0.56 minutes of time the tool performance is 97% and the probability of survival is 0.97.

5. CONCLUSION

In this work reliability modeling of cutting tool was used for finding the reliability of the cutting tool based on the progressive wear phenomenon and the replacement costs based on the age replacement policy. The proposed approach can be applicable to other types of tools which develop a premature failure. The tool life followed the normal distribution. Based on the normal distribution the reliability function for cutting tool was developed. It is not necessary that failure phenomenon always follows normal distribution. For few cases the failure phenomenon may also follow some other distributions such as exponential, weibull and gamma distribution, in such cases the shape factor and scale factor comes into picture which will give more accurate information regarding the reliability of cutting tool. In the present case based on the reliability of cutting tool, tool performed properly for a time period of 2 min to 6 min. There after its performance gradually decreases. Therefore for this particular case the optimal replacement the cutting edge should be indexed after every 6 minutes of starting machining. Calculations reveal that the tool performance is optimum under the following cutting conditions. Speed: 120-300rpm, feed: 0.-0.2mm/rev, depth of cut: 0.2-0.6 mm.

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