

Identifying Optimal Intervene Hazard for Cutting Tools Considering Cost-availability Optimization

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Abstract—In this paper, the optimal intervene hazard and their associated optimal tool replacement times were found considering three models of optimization, namely cost optimization, availability optimization, and cost-availability optimization. The cost-availability optimization was done by taking into consideration replacement costs, replacement times and costs of downtimes. Experimental data was collected during turning titanium metal matrix composites (TiMMCs). In the surface finishing process, cutting tool is used under low constant cutting speed, small constant depth of cut, and changeable feed rate. The Proportional Hazards Model (PHM) is used to model the tool's reliability and hazard functions using EXAKT software. The experimental results are used to construct, and then validate, the PHM model.

Keywords—Titanium metal matrix composite; cost-availability optimization; cutting tool replacement.

I. INTRODUCTION

Titanium metal matrix composites (TiMMCs) are excessively used in aerospace industry in order to improve the performance of aircrafts [1]. Despite being expensive, TiMMCs become viable in various fields such as biomedical and aerospace industry. Because TiMMCs have high wear resistance, they cause high wear rate on cutting tools. The main cause of tool failure is the progressive tool wear. For these reasons, finding the optimal tool replacement time and the optimal intervene hazard are crucial issues during turning these expensive materials since the worn tool may leave negative effects on product quality in terms of deviation from the specified dimensions and surface finish. If the tool is replaced earlier than necessary, valuable resources will be lost, and if it is replaced later than necessary the product may be scrapped [2]. Therefore, the tool replacement policy is one of the important aspects of cutting tool management.

The PHM is used in modeling cutting tool life [3]. Internal covariates such as cutting forces, cutting temperatures, progressive wear, acoustic emissions and vibration signal are considered when modeling cutting tool life. For example, In [4], the authors used a PHM considering vibration signals as a time-dependent covariate. They concluded that vibration signals are good indicators to tool wear. In [5], the author used a PHM by considering tool wear as time-dependent covariate, and found the optimal tool replacement time. In contrast, other researchers used external covariates which are indirectly correlated with tool wear, such as cutting speed and feed rate in order to model tool life and to find the optimal tool replacement time. For example, [6] used a PHM and stochastic dynamic programming for finding the optimal tool replacement times in a flexible manufacturing system. In [2], the authors used a PHM to model the tool's reliability and hazard functions considering cutting speed as the model's covariate. In [7], the authors used a PHM while considering the machining conditions as covariates and they derived a formula to assess the tool reliability under variable cutting conditions.

In this paper, the objective is to find the optimal intervene hazard and their associated optimal tool replacement times considering three optimization models, namely cost optimization, availability optimization, and cost-availability optimization. In section 2, the experimental procedure which was carried out in order to collect data that is used for constructing the model,

is presented. In section 3, a PHM is developed in order to model the tool's reliability and hazard functions using EXAKT software. In section 4, the optimal replacement policies are introduced. In section 5, the final results and discussion are presented.

II. EXPERIMENT DESCRIPTION

The experiments were conducted in the machining laboratory at Polytechnique Montréal. The work piece material is a cylindrical bar of Ti-6Al-4V alloy matrix reinforced with 10-12% volume fraction of TiC ceramic particles. The used equipment is a 6-axis Boehringer NG 200, CNC turning center. The cutting tool material is TiSiN-TiAlN nano-laminate PVD coated grades (Seco TH1000 coated carbide grades). Cutting forces signals are measured using 3-component dynamometer, then they are passing to multichannel charge amplifier, and finally they are collected by national instruments acquisition board (PXI 1000B). Since our objective is to study the tool life when it is used for surface finishing process, we limited the experiments to low cutting speed during turning metal matrix composites with carbides tools [8]. The experiments are conducted at low constant cutting speed ($v = 40\text{m/min}$), small constant depth of cut ($a_p = 0.2\text{ mm}$), and two feed rate ($f = 0.15\text{ mm/rev}$, $f = 0.35\text{ mm/rev}$). At each feed rate, 5 replications are done. Each tool, replication, has sequential inspections to measure the wear and the cutting forces. At each inspection, the flank tool wear is measured at discrete points of time through inspections using an Olympus SZ-X12 microscope, and measured forces are recorded. For example, the experimental data of tool 6 when ($v = 40\text{m/min}$), and feed rate ($f = 0.35\text{ mm/rev}$) is shown in Table I. The procedure continues until the tool flank wear reached predefined threshold ($VB_{Bmax} = 0.2\text{ mm}$). The procedure is replicated for 10 tools. Tool wear measurements for 10 tools are shown in Fig. 1.

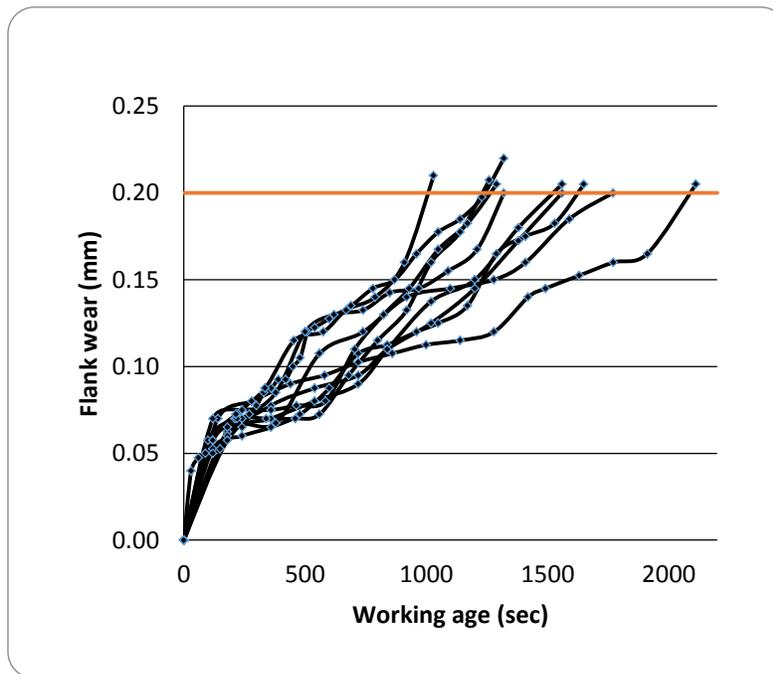


Fig. 1. Tool ware measurements for 10 tools

The time to failure TTF is calculated by interpolating. For example, from Table I, and by interpolating between the eighth and the ninth inspections, TTF is found to be 1524 sec. This interpolation is repeated for ten tools. The results for the ten tools are given in Table II.

TABLE I. EXPERIMENTAL DATA OF TOOL 6

Inspection No	Time sec	Wear mm	Radial force (f_x) N	Feed force (f_y) N	Cutting force (f_z) N
1	180	0.06	134.9	56.7	103.3
2	360	0.07	149.8	60.7	116.7
3	540	0.08	160.5	60.4	105.7
4	720	0.09	189.2	53.6	120.1
5	840	0.11	266.8	62.6	132.7
6	1020	0.1375	330.7	79.3	153
7	1200	0.15	357.5	68.6	134.1
8	1380	0.18	423.8	77.3	150.5
9	1560	0.205	515.7	92.6	175.2

TABLE II. TIMES TO FAILURE FOR THE 10 TOOLS

$(v = 40m/min),$ $(f = 0.35 mm/rev)$		$(v = 40m/min),$ $(f = 0.15 mm/rev)$	
Tool ID	Time to failure sec	Tool ID	Time to failure sec
1	1006	6	1524
2	1230	7	1560
3	1240	8	1623.3
4	1263.3	9	1770
5	1320	10	2087

III. MODEL DEVELOPEMENT

In this section, statistical model is built from the obtained experimental measurements. The PHM is selected to present the experimental data. The concept of the PHM is that the failure rate of a cutting tool depends on the age of the tool and some covariates. There are two types of covariates: internal uncontrollable, and time dependent covariates such as the cutting forces, which carry direct information about the failure process, and external controllable and time independent covariates, such as cutting speed and feed rate, which are controlled by the experimenter and has predefined determined path [9]. The failure rate is represented as the product of a baseline failure, which contains Failure times of the tools, and a positive function $\exp\{\sum_1^m \gamma_i Z_i\}$ that represents the effect of covariates on the failure rate. Where m represents the number of covariates, Z represents the value of each covariate, and γ represents the weight of each covariate. In this paper, Weibull hazard function is considered the baseline due to its flexibility in representing the probabilistic nature of tool failure, and of the machining [2, 5, 10]. The failure hazard rate at time (t) is given as follows:

$$h(t, Z; \beta, \eta, \gamma) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp\{\sum_1^m \gamma_i Z_i\} \quad (1)$$

Where β is the shape parameter, η is scale parameter, the conditional survival function is given as in equation (2),

$$R(t; Z) = \exp\left\{-\left(\frac{t}{\eta}\right)^\beta \exp\{\sum_1^m \gamma_i Z_i\}\right\} \quad (2)$$

The conditional survival function $R(t; Z)$ and its derivative $\dot{R}(t; Z) = h(t, Z(t))R(t; Z)$ are used to estimate the parameters (β, η, γ) by using maximum likelihood function [11]. EXAKT software is used to estimate the PHM model and its parameters. The covariates are feed rate (f), radial force (f_x), feed force (f_y) and cutting force (f_z). All combinations are examined and tested. The best model with significant variable is found by eliminating the variables whose impact on the probability of failure is not significant and making comparison between obtained models. The best model is found when radial force (f_x) is taken as the sole model's covariate as shown in equation (3).

$$h(t, Z) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\gamma f_x} = \frac{5.99}{7406} \left(\frac{t}{7406}\right)^{4.99} e^{0.022 f_x} \quad (3)$$

Kolmogorov-Smirnov test (K-S test) is used to evaluate the model fit. The test shows that the PHM offers a good modeling for the data. The summary of goodness of fit test is automatically produced by EXAKT as in table III.

TABLE III. SUMMARY OF GOODNESS OF FIT TEST RESULTS

Test	Observed value	P-value	PHM Fits Data
Kolmogorov-Smirnov	0.174794	0.889842	Not rejected

The statistical model shows that the effect of radial force is higher than the effect of cutting force and the feed force, on the progressive flank tool wear. In Fig. 2, the experimental data of tools 1 to 5 is plotted. The graphs show that radial force is intimately related to progressive flank and carries direct information about the failure process. This is the same conclusion showed by the results of Huang and Liang [12].

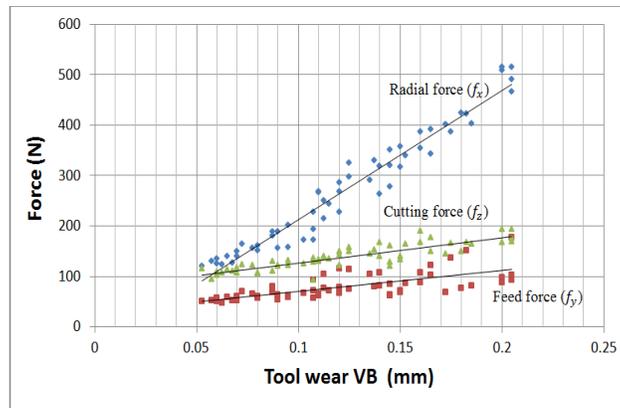


Fig. 2. Cutting forces with the progress of flank wear $v = 40\text{m/min}$ $f = 0.15 \text{ mm/rev}$

IV. OPTIMIZATION TECHNIQUES

A. Cost optimization

Expected cost/unit cycle time is written as:

$$\phi(T_d) = \frac{C_p P(T_d < T) + C_f P(T_d \geq T)}{W(d)} \quad (4)$$

Where T is the failure time, T_d is the preventive replacement time, C_f is the failure replacement cost, and C_p is the preventive replacement cost. The optimal cost is achieved when $\phi(T_d)$ is minimum where T_d^* is the optimal time to replace. $P(T_d < T)$ is the probability of preventive replacement, $P(T_d \geq T)$ is the probability of failure replacement, and $W(d) = E(\min\{T_d, T\})$ is the expected cycle length.

B. 4.2 Availability optimization

$$A(T_d) = \frac{\text{uptime}}{\text{uptime} + \text{downtime}} = \frac{W(d)}{W(d) + T_p P(T_d < T) + T_f P(T_d \geq T)} \quad (5)$$

Availability (A) is the percentage of time that cutting tool is available for machining. The optimal availability is achieved when $A(T_d)$ is maximum, where T_d^* is the optimal time to replacement, T_p is the preventive replacement time, and T_f is the failure replacement time.

C. Cost-availability optimization

Cost-availability optimization is the combination of cost and availability optimization. The idea of optimization is minimize the cost per unit time, while taking into consideration the replacement costs, the replacement times and the costs of downtimes. For example,

Total preventive replacement cost = Fixed cost (C_p) + Cost per unit time (a) \times Downtime (T_p)

$$\psi(T_d) = \frac{(C_p+a T_p) P(T_d < T) + (C_f+a T_f) P(T_d \geq T)}{W(d)+T_p P(T_d < T) + T_f P(T_d \geq T)} \quad (6)$$

The decision rule gives us the optimal time to replacement, while considering the replacement cost and the downtime cost. Moreover, it gives us the decision of cutting tool's replacement, or the decision of keep working by monitoring the covariate (radial force) at discrete time intervals [11]. The optimal replacement decision rule was first investigated by [13]. The decision rule is shown as in equation (7),

$$T_d^* = \inf\{t \geq 0: Kh(t, Z(t)) \geq d^*\} \quad (7)$$

d is a control-limit value and d^* is the optimal level which is found by using the fixed-point iteration procedure [11, 14]. K is the difference between the replacement costs C_f and C_p in the cost analysis, and the difference between replacement times T_f and T_p in the availability analysis, and also the difference between total replacement costs including downtime costs in the combination of cost and availability analysis.

V. RESULTS AND DISCUSSION

First, the optimal replacement policy-cost analysis is performed. The preventive replacement cost is considered as $C_p = \$100$, and the failure replacement cost is $C_f = \$200$. The difference between replacement costs (K) includes the extra costs due to the consequences of unplanned (failure) replacement. The cost function graph shows the minimum cost ($d^* = \$0.0816/\text{sec}$) associated with the optimal risk level to intervene ($Kh = \$0.08163/\text{sec}$). In this case, it's clear that the fixed iteration method stopped when Kh is exactly equal to d^* , which is in accordance with equation (7). By using equation (4), and in order to minimize the cost, the cutting tool was found by EXAKT to be replaced at $Td^* = 1348.33$ sec, when the optimal hazard rate is $h = 8.16 \times 10^{-4} / \text{sec}$. When the hazard is ignored and rises to infinity (toward the right-hand edge of Fig. 3), the average cost per unit time (d) approaches the cost of a run-to-failure which is $\$0.1279/\text{sec}$, as indicated in Fig. 3 by the dashed line. In this case, the expected replacement time $W(d)$ is the replacement time only at failure and it can be calculated from equation (4), when the probability of preventive replacement $P(T_d < T) = 0$ and the probability of failure replacement $P(T_d \geq T) = 1$. The replacement time only at failure is expected to equal 1563.6 sec. The red portion in Fig. 3 represents the unplanned failures cost, and the green portion represents the preventive maintenance cost. Finally, the cost optimization shows that the optimal policy proposes more interventions; on the average every 1348.33sec for the optimal policy versus 1563.6 sec for the policy of 'run- to- failure, in order to achieve a net per unit time saving (of $\$0.046 / \text{sec}$ or 36%).

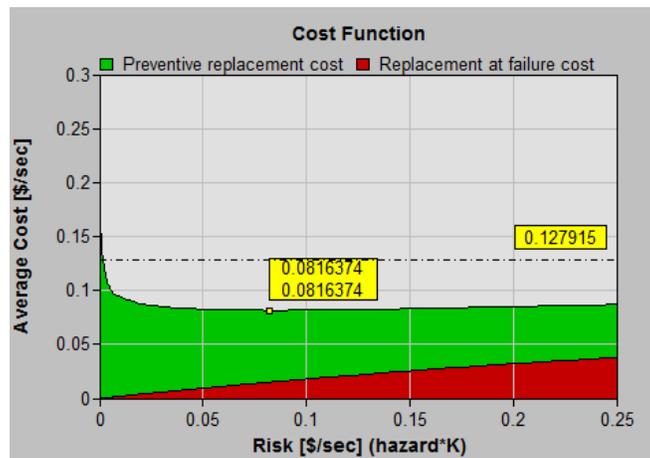


Fig. 3. Replacement policy-cost analysis

By using equation (5), the optimal replacement policy-availability analysis is performed. The preventive replacement time is given as $T_p=160$ sec, and the failure replacement time is $T_f=540$ sec. The difference between this two replacement times (K) is the extra time due to the consequences of unplanned (failure) replacement. The availability function graph shows the optimal risk level to intervene ($Kh=0.14169$). In order to maximize the availability, and by using equation 5, EXAKT found that the cutting tool should be replaced at $T_d^*= 1249.4$ sec, when the optimal hazard rate is $h = 3.72 \times 10^{-4}$ /sec . When the hazard is ignored and rises to infinity, the replacement time only at failure is 1563.6 sec. This is shown in Fig. 4, where the red portion in represents the unplanned failure downtime, and the green portion represents the preventive downtime. Finally, the availability optimization shows that the optimal policy proposes more interventions; on the average every 1249.4 sec for the optimal policy versus 1348.33 sec for the optimal cost policy, and 1563.6 sec for the policy of ‘run- to- failure. The optimal availability is found by EXAKT, based on equation (5) to be $A(Td^*)= 87.59$ % , while the availability is equal to 74.33% when the replacement is only done at failure.

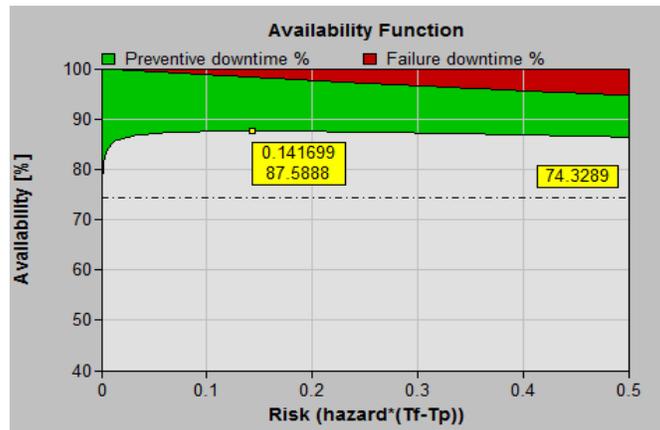


Fig. 4. Replacement policy-availability analysis

Cost-availability optimization, which is done by using equation (6) is shown in Fig. 5. The values of replacement costs in the cost analysis are ($C_p=\$100$, $C_f= \$200$) and the values of replacement times in the availability analysis are ($T_p=160$ sec, $T_f= 540$ sec). The cost per unit time during downtimes is given as ($a=\$0.15$ /sec). These parameters are used to find the optimal replacement time. The cost and availability function graph shown in Fig. 5 gives the optimal risk level to intervene ($Kh=\$0.1087$ /sec) In order to minimize the costs of replacement and downtime simultaneously, the cutting tool should be replaced at $T_d^*= 1348.33$ sec when the optimal hazard rate is $h = 7.6 \times 10^{-4}$ /sec . Finally, cost-availability optimization shows that the optimal policy proposes intervention, on the average every 1339.52 sec for the optimal policy versus 1348.33 sec for the optimal cost policy, 1249.4 sec for the optimal availability policy, and 1563.6 sec for the policy of ‘run- to- failure. The summary of the results of the three optimization models is given in Table IV.

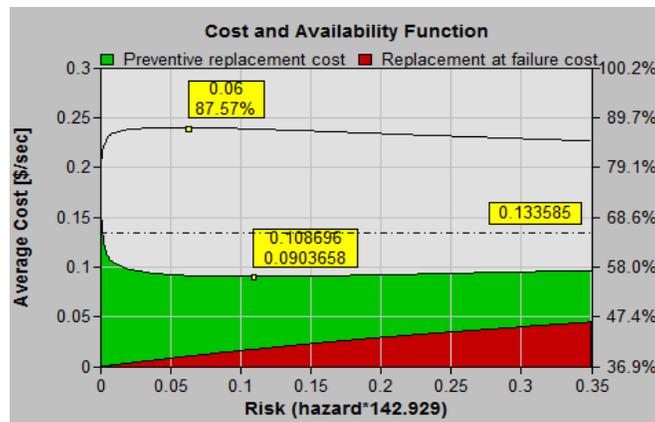


Fig. 5. Replacement policy-cost and availability analysis

TABLE IV. SUMMARY OF ANALYSIS

Policy	Expected Time Between Replacement sec	Intervene hazard /sec	Savings with respect to run to failure %
Optimal cost	1348.33	0.000816	36.2
Optimal availability	1249.4	0.000372	13.26
Optimal cost- availability	1339.52	0.000760	32.4 cost 12.93 availability
Run to failure	1563.6	Infinity	0

VI. CONCLUSION

Experimental data was collected during turning titanium metal matrix composites (TiMMCs). Due to the importance of these composites, tool life optimization was studied. The optimal intervene hazard and their associated optimal tool replacement times were found by considering three optimization's models. The software EXAKT was used. The results show that finding the optimal intervene hazards that use of optimal replacement times lead to savings that range from 32% to 36%, and an increase in availability of 87%, approximately.

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BIOGRAPHY

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