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# Estimating the remaining useful tool life of worn tools under different cutting parameters: A survival life analysis during turning of titanium metal matrix composites (Ti-MMCs)

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ABSTRACT

Utilizing the full tool life capacity of cutting tools has always been a concern, due to the considerable costs associated with suboptimal replacement of tools. Reliable reuse of worn inserts could significantly reduce machining costs. This study aims at estimating the remaining useful life of worn cutting inserts under multiple cutting parameters during turning of Ti-MMCs, using the actual tool wear value of the worn tool as the input data. A proportional hazards model with a Weibull baseline is developed. Maximum flank wear length at the transition point between the second and third state of tool wear is chosen as the failure criteria. Tool wear, cutting speed and feed rate are considered as the covariates of the model. The reliability and hazard functions are calculated from the model and are utilized to obtain the mean residual life of inserts under different cutting parameters and tool wear levels. The accuracy of the model is validated using experimental data. The results confirmed the validity and reliability of the model.

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## Introduction

Significant costs are associated with inaccurate estimations of tool lives. It has been reported that in the USA, only 38% of the cutting tools are utilized up to their full capacity. Such non-optimal utilization of cutting tools in addition to the non-optional selection of cutting tools and cutting speeds has been estimated to have an impact up to $10 billion per year on the US industry alone [1,2].

This necessitates the development of reliable methodologies for tool life estimation. Safe and reliable reuse of worn tools could also contribute significantly to cost reduction and productivity increase. Thus, it is highly economical to establish methodologies for estimating the remaining useful life of worn inserts.

Different mathematical and experimental models have been proposed for tool life estimation for new tools. Majority of the proposed models were developed based on the force monitoring methodologies, benefiting from the correlation between the cutting forces and tool wear [3]. Moreover, numerous studies have been performed using other machining data such as workpiece dimension, surface roughness, tool temperature, vibration, acoustic emission, texture features of the machined images, cutting power and machining induced stresses [4–13].

After the recognition of the probabilistic nature of the tool were by DeVor [14], several models were proposed for evaluating the reliability of cutting inserts [15–18]. Since these models were developed based on the theory of probability, they account for errors originated from the non-homogeneities of the tool and work-piece materials. This could be an important advantage for modeling the tool life when machining particle reinforced composites, for which the distribution of reinforcing particles is responsible for considerable variability of the tool wear data.

Proportional hazards model (PHM), which is mostly used in medical applications, has been introduced by Mazzuchi [19] in machining and has been used for reliability assessment of cutting inserts and developing methodologies for tool replacement [20–22]. Aramesh et al. [23], used a PHM to estimate the total tool life in addition to the transition times between different states of tool wear, under variable cutting conditions. The advantage of this model over other statistical models is that it could account for effect of the aging and cumulative tool wear, in addition to the effect of cutting conditions. Furthermore, different variables

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including controllable variables (such as cutting conditions in machining) and monitoring variables (such as tool wear and surface roughness) could be added to the model.

Very limited work has been done to calculate the remaining life of inserts [24–28]. However, to the best of our knowledge, so far no model has been introduced implementing the tool wear itself as a variable in the model in addition to the cutting conditions, thereby being able to predict the remaining life of *worn* inserts based on the current tool wear value.

Employing a PHM in this study, tool wear was considered as the monitoring variable in addition to the controllable variables, cutting speed and feed rate. Thus, the valuable information about the remaining useful life of worn inserts under any untested cutting conditions and tool wear levels were obtained. This could be considered as the significant practical advantage of this model over the previous models, since it is capable of estimating the remaining life of any used tool, regardless of its usage history, with a simple tool wear measurement.

## Experiment set up

A Cylindrical bar of Ti–6Al–4V alloy matrix reinforced with 10–12% volume fraction of TiC particles were used as the work-piece material for this study. Dry machining tests were conducted on a 5-axis Boehringer NG 200 CNC turning center. The inserts used in this study were TiSiN–TiAlN nano-laminate PVD (Physical Vapor Deposition) coated carbide grades, with nose radius of 0.8 mm. The commercial name of this class of inserts is Seco TH1000.

During each test, tool wear was measured using an Olympus SZ-X12 microscope. The maximum flank wear length ($VB_{Bmax}$) was selected as the tool life criterion.

Microstructural and elemental analyses were performed using JSM 7600 TFE Scanning Electron Microscopy (SEM) equipped with an Oxford Energy-Dispersive X-ray Spectroscopy (EDX). Primary backscattered electron (BSE) imaging was performed with SEM for investigating the microstructure.

## Methodology

Survival analysis is a statistical technique for modeling the time till the occurrence of an event (s) of interests (e.g. a pre-defined $VB_{Bmax}$ in machining), and to find the relationship of this time to different variables of a study (e.g. cutting conditions in machining). Depending on the purpose of the study, the event, and covariates of the study should be defined. Usually, for the engineering purposes, the event is defined as the failure [29].

After defining the failure criterion and covariates of the study, sequential machining tests should be performed based on the design of experiments, and continued till the defined failure criterion is reached. The collected experimental data will be used to establish the specific data layout necessary for the development of the survival model. The data consists of important information such as the time to the desired event (survival time) and the event status (failure status in our case) at any observation [29]. In the Experimental procedure section, the experimental procedure required to establish the data layout for the proportional hazards model (PHM), used in this study, is explained.

Once the required data is collected, the parameters of the proportional hazards model (PHM) will be estimated, using EXAKT software. Reliability, hazard functions will be obtained and used to calculate the mean residual life of inserts till failure, using Mean Residual Life (MRL) function. The required statistical procedure is explained in the Statistical procedure section. At the end, the results from the model were validated with the experimental results. The experimental and statistical results are presented in the Results and discussion section. The sequential steps required for the development of PHM are presented in Fig. 1. The complete procedure for tool life estimation of *new* tools (without considering the tool wear as a covariate) under different cutting conditions is explained in our previous work [23].

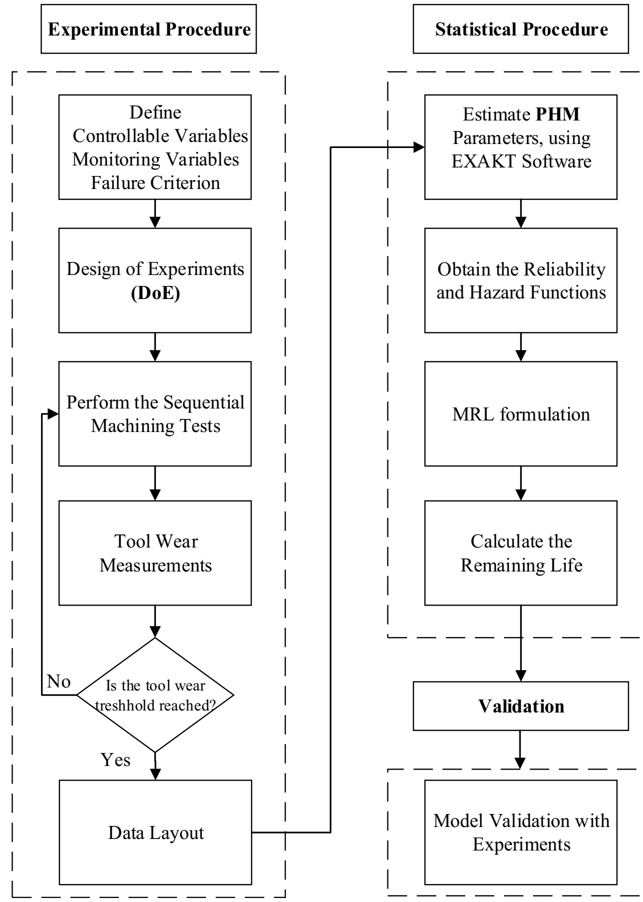


**Fig. 1.** Sequence of steps required for calculating the remaining tool life via PHM.

### *Experimental procedure*

For the machining processes, the failure is usually defined, in terms of the permissible maximum tool wear. The tool wear curve demonstrates three states; initial, steady and rapid states of tool wear. Severe vibration, temperature and cutting forces are induced at the third (rapid) state. Thus, during any machining process it is highly recommended not to enter this state. The tool wear associated with the transition between the second and third state is often regarded as the tool life criterion [30]. This criterion, which is also called the permissible tool wear $VB_{BC}$, is adopted for this study, based on the experimental results.

Variables (also called covariates) of the study could be classified as controllable and uncontrollable (monitoring) ones. Controllable covariates are those that can be controlled during a process such as cutting speed, feed rate and depth of cut in machining. Monitoring or uncontrollable covariates mostly change in response to the controllable ones and are monitored during a process. They have influence on the process but cannot be adjusted during a process, such as surface roughness and tool wear in machining process. In this study, cutting speed and feed rate are considered as the controllable covariates of the study, and tool wear is considered as the monitoring covariate.

The design of experiments consists of a $2^2$ design enhanced with an additional center point. The cutting conditions are selected

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