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Cutting Tool Life Determination Using Vibration Based Signals and Innovative Approach - A Review

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Abstract**: The objective of this paper is to define and discuss the tool life of a single point cutting tool and its importance. This shall lead towards identifying the effect of cutting parameters on tool life estimation. In the past researched mentioned in the paper like Taylor has given a formula for determining the tool life. The present paper identifies the soft computing methods to prove and relate the results as obtained by Taylor. The proposed approach shall include development of vibration analysis based expert system for tool life estimation. It encompasses the use of a vibration measurement system to collect the data for the deteriorating tool condition. In an attempt to develop a newer expert system a detailed literature is reviewed.**

Index Terms**— Tool life, Machining, Vibrations signals, Neural Network, Sensor**

I. INTRODUCTION

Tool life and tool quality are decisive criteria for the successful application of bulk metal forming in industrial production. They directly affect production costs and therefore competitiveness of the process and may as well have a considerable impact on tool supply, stability of production and last but not least delivery performance. Since tool failure is unavoidable, tool life must be properly taken into account for the calculation of tooling cost and planning of tool supply for production. [15]

Every cutting process is designed and operated upon considering the working life of the tool. The tool life can be calculated using the Taylor's formula. The difficulty is that once the cutting starts, the cutting parameters no longer remains constant as pre-decided but varies frequently. This leads to the early failure of the tool than the calculated span of tool life. Another problem arises is due to these variations in cutting parameters in the midway of machining there is no procedure to calculate the remaining life of the tool. It is proposed to develop an artificial intelligent based system which shall not only determine the tool life for any cutting parameters but during the course of machining it shall calculate the remaining life of the tool. For this purpose the vibration signals may be collected and trained against the machining process for the entire tool life and the neural network is trained to meet the objective.

The method shall include a setup for collection of data under defined cutting conditions and developing appropriate computer software for acquisition and analysis of the relevant data. The comparison will be made between data for experimental study and software study comparing the data for variation of tool wear rate, material removal rate and surface hardness using MATLAB software. The objective of this study is to predict the effects of cutting parameters on the variations of cutting forces during end milling operation on vertical milling machine. As a mandatory and important step a review of past researches is performed.

Tool life determines the rate of production in machine shop. The acceptance of part depends on how close the specifications of the work part are met. The specification of a part normally comprises of dimensional accuracy in terms of tolerance and surface finish. The performance of tool is also measured in terms of metal removal rate. It thus becomes imperative to measure the Tool Life.

The tool wear cutting condition is a crucial factor in all metal cutting processes. It's noteworthy that, direct monitoring systems are not easily implemented because their need of ingenious measuring methods. For this reason, indirect measurements are required for the estimation of cutting tool wear. Different machine tools sensors signals are used for monitoring and diagnosing the cutting tool wear condition.

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ASPECTS INFLUENCING TOOL LIFE

The main problem to define the major reason for tool failure is the large number of process parameters and their possible interactions affecting tool life, as well as the lack of any systematic approach to identify the initiating root causes of failure. A classical division of failure reasons and factors influencing tool life distinguishes between:

A. Tool specific and
B. Application specific.
They cover a very complex network of influencing factors, describing the entire forming system and all requirements for the quality of the product.

Starting from this more generalized view reasons for tool failure may be:

Tool design: critical corners or insufficient pre-stressing Causing high internal tool stresses.
Process layout: press force and/or contact pressure exceeding accept-able limits, due to an extreme grade of cavity filling or bad material flow conditions.
Tool material: too low hardness or fracture toughness ensuing cyclic plasticity and low cycle fatigue.
Tool manufacturing: improper surface finish leading to premature failure.
This list could be continued but the main obstacle still remaining for getting a clear answer to tool life problems is the difficulty to separate the influences of various parameters of the forming system due to their complex Interactions.

#for a better understanding of the problem of tool life it Is important to know which aspect of tool life is causing problems. The following types of failure (failure modes) are problematical and shall be called for improvement:

- Average of tool life too low,
- Scatter of tool life too large,
- Single tool life repeatedly out of order.

The analysis of failure mode gives the first indication about the origin of influencing parameters for later optimization concepts. In the case of average tool life being too low, it is probable that either the tool or process design has some systematic weaknesses. Large scatter of tool life in most cases results from uncontrolled stochastic fluctuations of process parameters or the influence of tool material. Problems arising from extreme low tool life of single tools in many cases results from problems with set up or handling on the press or wrong heat treatment of tool material.

METHODS OF TOOL LIFE APPROACH

RECORDING AND DOCUMENTATION OF TOOL LIFE DATA

For the purpose of collection and documentation of all necessary tool life data, the application of tool life cards in production is highly recommended. Together with additional information about the applied tools or other related production data, it may be possible to find correlations between low tool service life and certain process parameters rather easily. Therefore, apart from basic information about tool failure, like number of parts produced, type of damage, obvious cause of failure etc., the applied tool life card should show the serial number of the tool (an individual identification code connected to the batch number of tool manufacturing which is printed on every tool) as well as the order number of the part production batch. Using all these references, modern production planning systems like SAP easily allow to retrieve the relevant data from their data base about the applied tools (e.g. supplier, manufacturing operations, Inspection report, material, hardness, date of use etc.), the related production data (e.g. forging press, date of surface treatment, slug annealing and forging, specification of work-piece material etc.) or even additional information about production problems. All this information mainly helps to reveal problems with tool manufacturing or production process. Computer aided data mining, which is automatically checking all these information for possible correlations, certainly will help to support the search for failure relevant process parameters most efficiently in the near future.

ONLINE PROCESS MONITORING AND RECORDING

Tool life cards mainly support post-failure retrieval of failure relevant data about certain process conditions. However, the stochastic behavior of important, time dependant process data, which are directly influencing tool load, are not covered by this post-failure data recording system. For this purpose on-line process monitoring and recording of all less entail process parameters is recommended, which provides additional information about the individual history of each tool and which reveals unacceptable scatter of certain process conditions, for example fluctuation of press force resulting from oversized billets, due to problems with shear quality.

By applying strain gages to the stress ring system, the influence of press force on tool dimensions and part quality can be directly monitored. It is obvious that the critical part diameter shows a significant correlation with die temperature and elastic die opening. However, no critical loading conditions affecting part quality and certainly tool life, resulting from unacceptable peeks of press force as a consequence of oversized billets, could be observed from the stress ring response.

THEORETICAL MODELLING AND PROCESS SIMULATION

On-line process monitoring and tool life card system are mainly useful to analyze the influence of observed process conditions on tool life, with either stochastic or systematic appearance. It should be kept in mind, however, that all these parameters are only of secondary order for the mechanism and rate of tool failure, which primarily is determined by the level of local cyclic loading (stresses and strains) and local strength of the applied tool material.

A vibration study, as performed by Metso[17], covers the mechanical condition and the dynamic behavior of the entire machine line from stock preparation to finishing, or of specific machine sections in troubleshooting. Both current production speeds and targeted speeds are studied. The cost of the study can be quickly recovered through subsequent savings on parts purchases, problem solving, line speed up, and machine rebuilds. A vibration study may also be included as part of a larger scope Machine Analysis.

Vibration and noise in metal cutting are ubiquitous problems in the workshop. Today the industry aims at smaller tolerances in surface finish. Harder regulations in terms of the noise levels in the operator environment are also central. One step towards a solution to the noise and vibration problems is to investigate what kind of vibrations that is present in an operation. The vibrations in a specific machining operation performed on the lathe machine have been put under scrutiny in the first part of this proposed research. Analytical models have been compared with experimental results and the vibration pattern has been determined. [16]

In internal turning or boring operations, vibration is a problem. The industries are having problems performing specific boring operations. The vibrations involved during the cutting operation influence the surface finish and the manufacturers are having problems with small tolerances in boring operations. When cutting in predrilled holes the cross sectional area of the boring bar is limited. Since a general boring bar is long and slender it is sensitive to external excitation and thereby inclined to vibrate. A thorough investigation of the vibrations involved in boring operations is therefore needed. Part I of the proposed research scrutinizes the vibrations in boring operations. A solid foundation was achieved from both theoretical and experimental methods in order to analyze the vibrations involved. The theoretical methods derive from knowledge of the dimensions of the system and its suspension or boundary conditions. The experimental methods are all derived from analysis of data acquired from accelerometers and force transducers mounted on the boring bar

Vibration analysis may be undertaken as a stand-alone process, or may be part of a machine section audit or comprehensive machine analysis. Regardless of the scope of the study, a similar process will be followed.
The objective is established, a work plan is created, data is gathered using specific tools and sensors, and detailed analyses are carried out
Skilled vibration analysts will look for tell –tale “signatures” behavior and patterns that they have encountered time and time again. These signatures, similar to when a chess grand master views an in progress chess board layout, will be instantly recognized as sources of vibration excitation. Thus a skilled vibration analyst is a highly valued member of any field service or mill maintenance team.

A vibration study will typically
Yield the following benefits:

- Determination of the dynamic behavior of machine sections.
- Determination of the mechanical condition of the machine.
- Determination of the feasibility of a possible capacity increase.
- Most cost effective implementation of rebuilds.
- Prediction of future mechanical problems and reduction of unplanned shutdowns.
- Scheduling of service actions based on prioritized maintenance recommendations.
- Savings on roll rebuilds by relocating old rolls to positions where they can still be used.
- Solutions to problems such as barring and gear train failures.

Vibration Measurements taken during production include:
- Mechanical condition measurement (e.g. vibration, dynamic run-out, etc)
- Synchronized measurements

- •Operating deflection shape measurements
- •Paper samples
- •Noise level measurements (where applicable)

II. LITERATURE REVIEW

When it comes to calculating the tool life we must recall nearly last one decade that has been capitalized by calculation and statistical analysis of tool wear and tool life. We have often believed that tool wears' basic mechanisms and various kinds of wear produced at the tip of the tool can be well determined depending on the experimental measurements of different tool wears and application of suitable statistical techniques and because of this it was possible to predict the tool life and hence the intervals of changing the tool after it is worn out. This period was marked my exclusive and intensive work on popular concept of "data bases on machining parameters" but parallel forecast was directing towards poor future prospects for the cutting process following the high energy coming into play because of HSM- high speed machining and economical constraints clubbed with each other. On the contrary the point to be noted is that various recent developments in machine tools, automation, computerized controls and in addition the improvement in the cutting tool material, various protective coatings and special geometrical shapes make such intense forecasts completely wrong and undermines the argument of flaw. The degree of use of the machining operations has increased notably which is a good sign. The new improvements in cutting materials increase the tool efficiency costs of performing machining operations and also tremendously increase the cutting reliability and quality of products.

Various Tool Monitoring Techniques are:

D.E. Dimla Sr.(2004) has done an experimental investigation aimed at identifying and isolating effects of cutting conditions on cutting forces and vibrations from those arising as a result of cutting tool wear. Machining test cuts were conducted using sharp and worn inserts and the effects of cutting conditions (depth of cut, cutting speed and feed rate) studied. Signals were recorded with significant variation of the cutting conditions when the tool was relatively fresh/sharp and/or old/worn such that only the effects of cutting conditions alteration were pronounced on the signals. Time and frequency domain was used to pinpoint the exact nature of changes on the signals due to alteration of the cutting conditions. The depth of cut and feed rate was deemed to affect the signal characteristics significantly and a specific frequency band most sensitive to the changes identified. **M. Rogante(2009)** have done tool condition monitoring (TCM) of dry turning processes on automatic lathes, and describe the information generated by different measuring systems applied to the single point turning situation. The outputs measured were correlated with the state and wear rate of the cutting tools. Semi-finishing and rough-shaping tests have been carried out at different cutting speeds. The behaviors of the utilized power, the tool-holder shank vibrations and the surface roughness vs. pass number were studied. Taylor's equation was determined for the three types of inserts used. The parameters investigated show that the results are directly influenced by degree of the tool wear and also give indications when the tool insert has reached the end of its life. {8]

Methods by Researchers:

All the above mentioned changes reduce the challenge of calculating the tool life in a conventional method. Valery Marinov's notes on tool wear and tool life says that the life of a cutting tool can be terminated by a number of means, although they fall broadly into two main categories:

1. Gradual wearing of certain regions of the face and flank of the cutting tool, and
2. Abrupt tool failure.

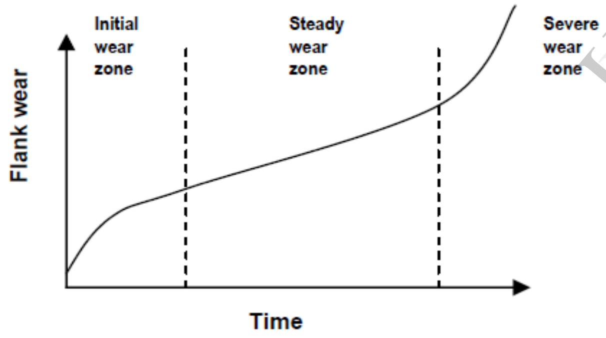
Considering the more desirable (case 1) the life of a cutting tool is therefore determined by the amount of wear that has occurred on the tool profile and which reduces the efficiency of cutting to an unacceptable level, or eventually causes tool failure (case 2).

***Shaw** classified* tool wear types according to the system developed by: [9]

1. Adhesive wears which occurs when the mating surfaces come close enough together to form strong bonds. If such bonds are stronger than the local strength of the material, a particle may transfer from one surface to the other.
2. Abrasive wears which involves the loss of material by the formation of chips, as in abrasive machining. For such a type to be initiated it is necessary that one material be harder, or have harder constituents, than the other member of the sliding pair; or, that hard particles be formed by chemical reaction of the wear debris.
3. Diffusion wear which results when surface temperatures become very high and surface velocities are very low, allowing the solid state to play a role in the wear process.[9]

Andri popa & co. carried out similar kind of work as our proposed research. In their research drilling tests were carried out on ø 80 mm forged bars, usually as raw material in turbine **discs manufacturing. Same heat treatment is carried** out on the bars as the discs (write outcome of the paper i.e. conclusion [10]

If we talk about the flank wear, it is necessary that we perform some experiment till the moment flank wear of the tool receive to criteria size but it takes large time and incur high costs. The wear time curve came into picture to prevent this. In case of almost all the cutting tools the wear time curve tentatively follows the pattern similar to what is shown in the figure [1] below, which has three distinct wear zones i.e. steady wear, initial wear and severe wear. It must well be taken care that the tool should be discarded before the moment it reaches the severe wear zone. When we carry out the machining process for several times, the wear after each cutting pass is noted down and by extrapolating the wear time curve the time for limiting flank wear is calculated. The same approach shall be implemented for our proposed research work too. The only difference shall be of the neural network and analysis platform we have adopted which is vibration.



(Relationship between time and flank wear)

The figure displays that there is a linear relationship between flank wear size and turning time. Therefore, with the help of experimental data and using this figure as a reference line, the tool life can well be estimated.
We know that relationship between tool wear and turning time is as follows:

W= a +bt

W= Amount of flank wear

T= turning time and a,b= constants and therefore the tool life "T" is given by ;

$$\mathbf{T = \frac{W_{max} - a}{b}}$$

In the proposed research the factors highly taken into consideration are ; cutting velocity(v), feed rate (f), depth of cut (d).
Broadly we observe that;

$$\text{Effect of factor} = \frac{\sum \text{responses at high level} - \sum \text{responses at low levels}}{\text{Half the number of runs in the experiment}}$$

When the tool wear reaches an initially accepted amount, there are two options,

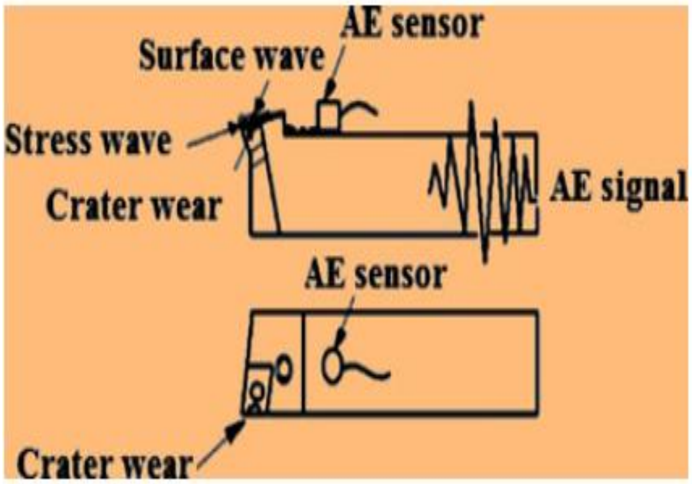
- To re-sharpen the tool on a tool grinder
- To replace the tool with a new one.

This second possibility applies in two cases, (i) when the resource for tool re-sharpening is exhausted. Or (ii) the tool does not allow for re-sharpening, e.g. in case of the index-able carbide inserts.

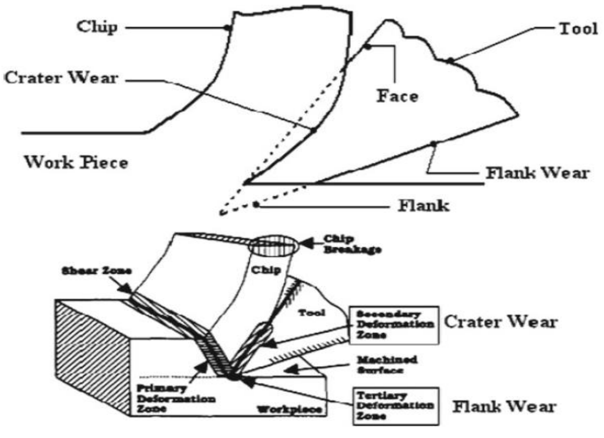
Gradual wear occurs at three principal locations on a cutting tool. Accordingly, three main types of tool wear can be distinguished,

- crater wear
- flank wear
- corner wear

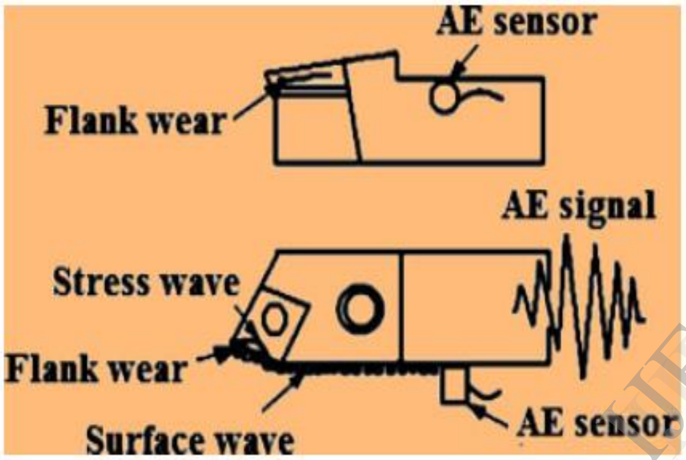
Figure shows the crater wear occurred on the rake face of the tool. This crater wear emits stress wave, which propagates as spherical wave front and becomes surface wave on the rack face of the tool and travels on the top surface of the tool holder. Hence, the suitable position of the sensor



(Propagation of stress wave due to carter wear)



(Types of tool wear)



(Propagation of stress wave due to flank wear)

The Taylor Equation for Tool Life Expectancy provides a good approximation.

$$VcT^{\wedge}n= C$$

A more general form of the equation is

$$V_cT_n \ X \ D^xS^y = C$$

Where:

- V_c =cutting speed
- T=tool life
- D=depth of cut
- S=feed rate
- x and y are determined experimentally
- n and C are constants found by experimentation or published data; they are properties of tool material, work piece and feed rate.

If tool life is predicted on the basis of flank and carter wear measurement all other type of tool wear will consider a new overall parameter to consider tool wear as a collection of different kinds of wears spotted at the tip of the tool which is difficult to separate in the form of ordinary locations.

III. RESEARCH MOTIVATION

The reason for working on this activity is to anticipate the tool life while the machining is in process. The failure of cutting tool results in poor surface finish, increased vibrations in the machines, increased cutting forces & power consumptions, overheating of tools etc. It therefore becomes imperative to anticipate the tool failure and determine the tool life. Tool life as defined by the amount of material removed before it cease to work is in major depends upon the cutting parameters viz; cutting speed, depth of cut and feed rate. The tool life as calculated by using the above formula no longer remains useful when the tool is in operation and therefore the behavior of cutting parameters and their effect on tool life becomes important. While working online it is rather difficult to determine the tool life as while machining the variation in cutting parameters and the specification of work leaves the operator in critical situation to predict the tool life. The effort in the direction of developing a system with which the effect of various parameters and their characteristics affecting the tool life can be consolidated will bring about a significant contribution on the shop floor where the operator may get an opportunity to predict the tool failure, expected life of the cutting tool and determining its remaining life.

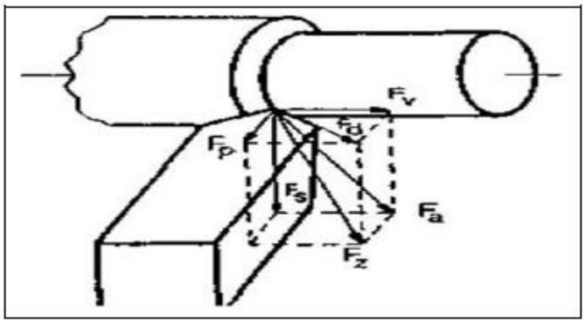


Fig 1 Cutting forces acting on the cutting tool during turning [3]

IV. DEVELOPMENT OF SYSTEM

It is proposed in this paper to develop a system incorporating artificial intelligence with inbuilt intelligence based on the concept of neural network.

The experimental work was divided into two series: The main aim of the first experiments series was the quantification of tool wear evolution as a function of cutting time for different process parameters combinations. This was carried out in accordance with long-duration wear tests as stated by standard ISO 3685. The purpose behind the second experiments series was to investigate the effects of process parameters on tool life, surface roughness and cutting forces, then to establish a correlation between them using the response surface methodology (RSM).[11]

4.1 Vibration Analysis

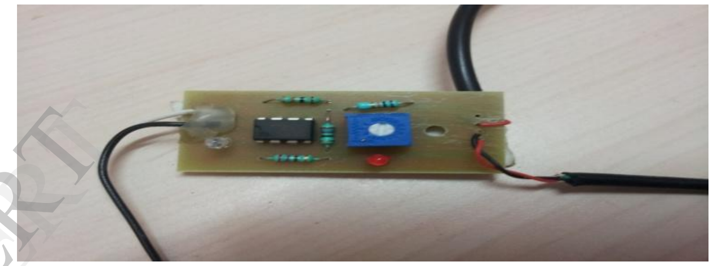
The cutting process causes a kind of vibration peculiar for its cutting characteristics. It is planned to establish a relationship for the vibration observed for various cutting conditions. For every combination of *cutting speed, feed rate and depth of cut*, keeping other factors as constant a vibration shall be recorded which shall truly reflect the machine performance.

Controlling vibration phenomena in production machines is one of the approaches for improving their efficiency. This also applies to cutting tool vibrations generated during machining, when the magnitude of the vibrations directly influences work piece surface quality. Continuous efforts to enhance cutting performance have revealed that machining quality may be improved if a tool is assisted with high-frequency vibrations.

(Developed System for Data Collection of Vibration Signal)

Vibration is widely used for condition monitoring of rotating machinery. However, vibration has not been used to the same extent in tool condition monitoring, probably because as a method it is rather sensitive to noise which is present in cutting processes.

Vibration measurement together with thrust force has been used in the tests reported in. The purpose of the tests has been to obtain signal for the development of a diagnosis tool capable of recognizing tool wear. In the tests tool wear has been recorded with a vision system. In theory, sound measurements could be expected to give the same information as can be detected using vibration measurements because in the structural boundary the mechanical vibration of the structure or tool/work piece contact is partly transferred to airborne vibration, i.e. sound. However, quite a number of factors influence how the mechanical vibration is transferred and how it takes place at the different frequencies. Also there is a great difference when the influence of disturbances from outside sources is compared in vibration and sound measurements.

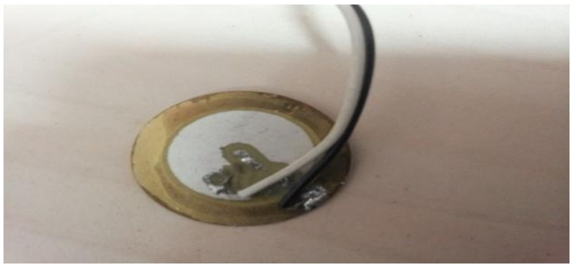


The result that proves vibration is the most effective method of all of the tested methods. A higher frequency range from 0.5 to 40 kHz for vibration measurements shall be tested with very thin drills. The reason for looking at this kind of frequency range is that the rotational natural frequencies fall into that range since for a drill of 1 mm diameter the natural frequency could be about 25 kHz and for a drill of 3 mm diameter it could be about 7 kHz. In the reported examples the band-pass filtered vibration signal has given more clear indication of both tool wear and failure than the feed force signal [13].

When the tool is new and just sharpened the metal removal rate will be quick and vibration observed may be for its minimum value. As the cutting progresses and tool begins to wear the cutting performance too deteriorate leading to the increase in vibration observed in the machine. Thus it may be speculated that since the beginning of cutting till the ultimate tool failure the machine may behave differently and the vibration during each work cycle may progressively rise. These vibrations minimum in the beginning may end with maximum at tool failure. Therefore it may be stated that the tool performance can also be monitored with the help of vibrations generated and by establishing the relationship between the tool performance and related vibration observed a relationship may be established between the tool life and vibrations observed.

4.2 Signal Analysis

The kind of signal analysis methods used is of some importance. Sometimes it looks as if some researchers think that if the measured signal is acceptable then it would be possible with a clever diagnostic tool to solve everything. Unfortunately this is not the case.



(Sensor used to sense the vibration signal)

The diagnosis always needs to be based on reliable and meaningful information and this is where signal analysis can help by providing effective features as a basis for diagnosis. The role of signal analysis could be described as a tool which tries to pick up the meaningful information out of the mass of information. In many cases the dilemma is that the more sophisticated methods need a lot of raw signals and it takes time to collect this raw material and it also takes time to perform the calculations. Consequently, many of the most sophisticated methods are not suitable, e.g. for tool breakage monitoring.

FINAL CALCULATION

Usually a number of statistical parameters such as root mean square (RMS), arithmetic mean, standard deviation and kurtosis are calculated and these are then used for comparison and diagnosis. With almost all of the measuring signals the most common parameter to look at is the RMS value, which also is actually the value that is normally seen if the signal is drawn with a plotter or looked at with a voltage meter. The RMS value contains all the energy in the signal and therefore also all the noise and all the elements that depend on the cutting process. Therefore, it is not the most effective parameter but has retained its place because it is so easy to produce and understand. Besides, it does actually work when compared to other statistical parameters. [13]

The recorded signals are considered as the representation of tool condition. The signals as recorded for different tool wear condition relates to the tool life. The most deteriorated tool condition indicates the total tool wear while the initial grounded tool indicates tool condition ready for begin cutting with equal ease. As the cutting begins the metal removal rate is high with good surface finish and within the specified tolerance limit. As the cutting progresses the tool bound to wear and tear resulting in degraded surface finish leading to replacement or regrinding of the tool after it completely worn out.

In the proposed work the condition of the cutting tool is related with the vibration detected. When tool is just ground the vibrations signals displays a unique feature which changes with the deteriorating tool condition. Thus a set of vibration signals recorded for various tool conditions from initial till it's worn out shall provide a pattern which leads to establish a kind of relationship that as the tool deteriorates the vibration signal changes. The changes in vibration signals from its initial stage to final are correlated to the tool life. For establishing this, the vibration signal is to be recorded for various stages of its tool life. With this it may be concluded that observing the vibrations at any stage of metal cutting or tool condition, the tool condition and its expected life and left over life can be determined.

The entire process may be accomplished in the following steps.

1. Select a single point cutting tool ready for use with optimum cutting angle.
2. Set the machine for a given set of cutting speed(m/min), depth of cut(mm), feed rate(mm/rev)
3. Calculate the tool life using the Taylor's tool life equation.
4. Set the position of the vibration sensor close to the cutting tool for recording the related signals.
5. Start metal removal and record vibrations simultaneously
6. Continue metal removal till the tool worn out
7. Determine the time of machining and amount of metal removed with the tool to determine the tool life.
8. Change the cutting parameters and repeat steps 1-7

The signal features thus collected may be used for training a neural network. The network thus formed shall be trained for establishing the tool life based on the vibration features recorded. The network may be so trained that for any given tool wear condition the network may indicate at which stage of tool life the tool is and thus the tool life and the remaining tool life can be correctly ascertained.

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