Tool Wear Monitoring Systems: a research

TOOL WEAR: an overview

Industrial users of cutting tools have been long searching for an answer to the problem of tool wear. All cutting tools suffer wear effects during the several machining processes, bringing a difficult problem to deal and manage, due to its unpredictability. Most tools fail either by fracturing or by gradual wear.

Generally speaking, tool wear can be seen by shear at high temperatures, plastic deformation under compressive stress, diffusion, attrition-disassociation, abrasion, seizure, thermal stress and fatigue. The different wear forms that can be easily noticed in the tool are classified as flank, crater, chipping, notching, deformation, edge cracking and catastrophic fracture.

There are some well known procedures for effective tool life monitoring with distinct fields of application. Tool wear management depend on the ability to determine and control cutting forces, surface finish and dimensional precision, all directly related to friction between tool and workpiece. Friction depends on contact area, geometry of the tool, speed and temperature.

The usual parameters related to monitoring tool life are surface texture, accuracy, tool wear pattern and chip formation. The one applied depends upon the type of operation, finishing or roughing, and often the amount of manual control and supervision involved.

In the traditional well known removal processes, practice and research had pointed out some generic procedures, but usually these require a big amount of involvement from the human being. On the other hand, they are probably still the cheapest procedures that the small industry is able to reach. They appear as lubrication practices and the usage of titanium based coated tools. Titanium nitride, titanium carbide and titanium carbonitride coatings can enhance dramatically the tool performance, while lubrication can reduce friction and therefore minimise tool wear. The benefits of friction control can be great. If one achieve full fluid separation between tool and workpiece, the required deformation forces may reduce 30% to 40%, and tool wear becomes almost null. Considerable effort has been directed to the measurement of friction for both general metalworking conditions and specific metal forming processes.

Lubricants have the ability of acting as a thermal barrier, keeping the heat in the workpiece, and away from the tooling. They also present some other desirable characteristics: their ability to act as a coolant and remove the heat from the tools; their ability to retard corrosion if left on the formed product; their ease of application and removal; lack of toxicity, odor and flammability; reactivity or lack or reactivity with material surfaces, adaptability over a useful range of pressure, temperature and velocity, surface wetting characteristics, low cost, availability, and at last but not the least their ability to flow and thin and still function.
Tooling is usually expensive, and it is expected to shape many workpieces. Wear of the tool tip can influence the final dimensions of the work piece, and therefore the tolerance control is gone. At some point, the tools will HAVE TO be replaced. Tool wear include increased frictional resistance (increased required power and decreased process efficiency); poor surface finish on the product and loss of production during tool changes. A good technology manager should be aware of all these

factors and thus should be able to select the most cost-effective process for avoiding all these problems. Several models have been develop to correlate tool life with parameters that describe the machining environment, cutting conditions, surface characteristics of cutting tool and workpiece materials. Although even more methods have been developed for tool wear sensing, none of them has achieved significant use in industry so far.

However, a new reality arises on the horizon. With the expanded use of flexible manufacturing systems and increased labour costs, unattended or less-attended operations seem to have become the practice. An automatic tool failure monitoring system that can detect the occurrences of abnormal operations is more and more required, to increase machine and tool utilisation as well as productivity, and minimise damage to the workpieces and reduce the risk of human error.

The ability to monitor tool condition from on-line data is a needed element for process automation as well as an economic way of utilisation the process tools. The usual procedures are not efficient as much of the useful life of the tools may be wasted, and high tools changes would mean higher machine downtime, decreasing thereby the system productivity. When an adaptive control of manufacturing processes is needed, tool failure comes to be an expensive constraint in the whole performance of the system. Although " in-process" monitoring techniques are to date not yet fully developed, the researchers are thoroughly looking for a solution that will meet all the requirements, cost constrains and high efficiency.

COST Implications

There exists a method for predicting the cost of changes in cutting conditions. The optimal tool replacement strategies are calculated using a wear-based model. The model's use of wear curves permits extrapolation of cost calculations to cutting conditions for which little statistical data has been collected, assuming data is available for other cutting conditions which have the same failure mechanism.

One benefit of building wear curves into a probability model is that cost calculations are possible even when little lifetime data is available for some of the cutting conditions. A second benefit is that the importance of run-in wear in determining preventive maintenance schedules and cost impact becomes apparent.

Monitoring Systems: from *Tribology* to *Chaos Theory and Fractal models*

The science known as 'Tribology' can be mentioned as the first attempt to 'wear' monitoring and diagnosis. It studies the interacting surfaces in relative motion and of the practices related thereto. When a tool failure used to happen, there was a whole procedure for examining the surface of the affected parts. There was a first level of examination, which investigated the cracked or damaged surfaces deeply with a binocular microscope, and a second level of examination by means of electron microscopy. Then the acquired data was analysed and interpreted in order to provide solution to failure problem, and establish good practices that would avoid the failures to happen again. Wear could be combated by either of two methods: by altering the conditions of service to provide a less destructive environment or by selecting a more resistant material for the worn component. This is the main reason for the growing popularity of the Titanium covered tools - its reliability. Its an easy and less expensive method, and it came to be the chosen course of action concerning to avoiding wear problems.

Besides examining the surfaces, practice and research have pointed out some more efficient measures to control factors that are also responsible for tool wearing. These procedures are:

* *VIBRATION Analysis*

Some experiments have alredy achieved interesting results; a study using a vibration transducer as a worn tool detector showed that the amount of vibration energy increased as the length of the cutting edge wear-land increased. This happened frequently, even when the cutting parameters were varied within wide ranges. It was concluded that the vibration signals vary with tool failure in some frequency ranges, and in practice they are widely used in tool condition monitoring. With the growing sophistication of transducers and instrumentation used in vibration measurement and analysis, this technique will soon become more practical and cost-effective.

Another team of researchers experimented a non-contact system aiming to minimise the instrumentation effects. They used a Laser Doppler Velocimeter. An avalanche type photodiode photodetector was used to follow the Doppler signal. The measurement system was tested by reading the free torsional vibration of circular shafts with varying diameters, lenghts and boundary conditions in a milling machine. Two useful results were achieved: the forcing frequency spectral power increases with increasing tool wear; the spectral power associated with natural frequency harmonics did not vary in any clear manner with wear but probably depended on cutting conditions.

** FORCE Monitoring*

There is a good correlation between the dynamic cutting force and flank wear. Since the dynamic force was observed to have a good correlation with the tool wear, it is possible to use a personal computer to monitor the dynamic force during the machining process. A software has been developed to track the dynamical tangencial force signals to give a pre-warning of immitent tool failure. The system allows continuous monitoring of tool wear or intermittent stoppages and monitoring. The results can be displayed in either the DOS or Windows environments.

Two criteria can be set to indicate the on-set of tool failure. The first one is reached when the percentage drop of the dynamic force from its maximum amplitude exceeds a predetermined threshold value. It is also confirmed when the gradient of the dynamic curve exhibits a negative value. A pre-warning of tool failure will be cativated and the machine may be stopped for tool change.

A force model simulates the effects of wear and predicts the resulting changes in forces, accompanying the worn tool. This has the potential to alter the current approach to wear and greatly improve process efficiency and tool utilization. It can be used during design to estimate part errors,

fixture requirements and tool life, but it can also be incorporated into an on-line tool condition monitoring system for estimating current wear, scheduling efficient tool changes and detecting the deterioration of part quality based on a measured force signal.
Actually, there are going some research lines in this last direction, in many manufacturing engineering departments of some big and respected technology Universities. The most modern ones deal with cutting force signal coefficient of variation, histogram analysis, and the theory of chaos (as the behaviour of the tool is not lineary predicted) and researchers are looking forward to stablish the basis of a better monitoring system from this results.

Another study has used a tube type dynamometer as a force transducer. The results showed that feed and thrust forces are influenced much more by tool wear than the main cutting force.Other strategies have been proposed for monitoring tool wear by processing force signals. After thorough investigation, it was discovered that the force achieved relatively high positive levels for short periods of time at both the beginning and the end of the cut. The level of duration of these positive excursions increased rapidly with even small amounts of tool wear, but also sensitivty to other system parameters including overall rigidity.

To sum up, measuring cutting forces is one of the most commonly used techniques in detecting tool failure. The results can be quantitatively different for sensing tool wear in various studies, and hence these results cannot be used even empirically from one step to another.

** SPC: Statistic Process Controlling*

In unattended manufacturing, worn tools must be changed on a statistical basis. SPC is a quality control method which aim is to control the variables in the process itself, instead of controlling the product features.

The initial step for SPC and metalworking is to determine what element in the manufacturing process is producing the biggest variation.

One process characteristic that does change over time is tool wear, but tool wear cannot be monitored directly in real time. Instead, the operator examines characteristics of the cut that indicate how worn the tool is. Most of the machining-processes are monitored by measuring features on the part produced. In a period of time equals to an hour, SPC would take only one measurement, against the traditional 40 or 50 measures in the traditional process. These measurements may be plotted on several different charts, control charts, histograms and Pareto charts. All of these can be produced by hand or computer and are used to organize and analyse data. The control chart shows a midpoint that corresponds to the process average, an upper control limit that corresponds to three standard deviations above the average, and a lower control limit that corresponds to three standard deviations below the average. If all the points on the chart fall within the upper and lower control limits, then the process is said to be in statistical control. A frequency histogram or a simple bar chart are able to show the variation in measurements. Pareto charts are similar to histograms, except that these bar charts are always arranged from high to low. Pareto principle states that not all the causes that are responsible for a phenomenon occur with the same frequency or the same impact. Only a few of these causes may be largely responsible for a phenomenon. Therefore, controlling those relatively few causes or characteristics can significantly influence that phenomenon.

It seems to be a very reliable monitoring process, because if one can predict what will happen with tools, than one can optimise tool use. However, there is still some reluctancy from the machinists to make a switch to SPC, cause they usually don't believe that only a single set of measures can provide enough returns. Nevertheless, SPC is said to be still reliable even if fewer measurements are taken, and less frequently. It is a system that does not have to be time-consuming or expensive. It is not necessary to spend from £500 to £20,000 on software packages or computer networks for small or medium size shops, since the basis of SPC is the measurements.
There is a caution in the direction of investing the right time to analyze and learn from the charts instead of just producing them to satisfy customer requirements. One problem that many shops face is whether to use SPC for shorter runs. In this case, different quality control methods should be used, but still a quality plan can help a lot. There is a possibility of monitoring the metallurgical properties or check things that will help to control tooling dimensions. SPC might seem complicated and scary since statistics are involved. But once the statistics underlying are understood, the charts provide more confidence to the users and the manager.

** PRESETTING*

Another monitoring method is known as Presetting. It allows operators to set tools faster than they usually can on a machine and to set tools more accurately as well. Some presetters can measure tools automatically, achieving a high accuracy without operator intervention. A big advantage of this process is that it allows to start part producing within the required dimensional tolerance as soon as they begin cutting chips. On the other hand, when tools are not the correct lenght, tha machine tool's controler does not have an accurate idea of the tool tip's location, and this confusion can lead to costly mistakes. Therefore, when the part program is being optimized, a tool of specific lenght must be used. By continuing to use tools of the same lenght throughout the whole application, the operator can set the CNC machine within the optimized program's parameters, ensuring that productivity and output remain at their maximum levels and tool wear is minimized.

This process can be enhanced by the addition of video technology. By using a presetter's tool-inspection capability to accurately gage wear during an application and changing tools only when they have worn past a certain point, the operator can get the full life out of the tools. For safety, the operator makes the interval short enough to ensure that even the fastest wearing tool is cahnged before it breaks. As a result, most tools that are changed on a regular schedule are cahnged well before they have fully worn.

The best method, considered the ultimate presetter, combines the presetter's tool setup and inspection capabilities with sophisticated software. The unit can perform the functions of a complete tool-management system, and the user can store data on individual components and select the relevant data when it is needed to assemble a complete tool. A fully integrated presetter can exchange data with other machines on the shop's network quicly and directly. Tool lists for particular jobs can even be downloaded to the presetter.

OPTICAL measurement

Optical sensing can only be used between cutting cycles when the tool is removed from the workpiece and as such is not strictly an " in process" technique. It appears to be accurate and reliable. It has its share of problems: it is difficult to detect tool wear lands if a built-up edge or metal deposit exists. There are some optical devices in use to predict and analyse tool wear. A system using image analysis by usage of CCD cameras coupled to an expert system has been proposed for tool life management in flexible manufacturing cells.
Fibre optic sensors were also being used for in process measurement of tool flank wear. The technique is relatively inexpensive to implement and can be applied to either conventional production lathes or NC lathes.

There is another possibility, by using a microscope furnished with a vidicon followed by some electronic circuits to measure the wear land by line scanning the magnified image of the flank wear.

Acoustic Emission (AE)

AE is attributable to many sources, such as elastic and plastic deformations of both the workpiece and the cutting tool, friction, fracture of the workpiece, wear and failure of the tool. AE provides a means of sensing tool wear or tool fracture, since spectral analysis has been found to be the most informative for monitoring tool failure in some machining operations, like turning, for instance.

The flank wear of a cutting tool was successfully measured by monitoring the gradual increase of the acoustic emission signal level. However, this method was shown to be a poor diagnostic method for single-cutter tools where mark signal periodicity was absent. A tool wear sensing method was proposed using a threshold counter to perform an alternate pulse count. It was possible to detect the presence of defects such as splintering and cutter-edge build-up since the signal level generated were well above normal wear variation limits. It was concluded that the total count of AE had good correlation with flank wear, and could be used as an index for in-process tool wear sensing. It is important to bear in mind that the selection of the threshold voltage is crucial and some prior experimentation must be conducted.

Another study showed that AE parameters did not exhibit a define trend with tool wear but a general random behaviour plus sudden variations related to process deterioration phenomema. Monitoring methodology was thus presented based on a cumulative energy count function. A common threshold was proposed, to give a suitable early warning for tool deterioration. Another proposition that has risen from the studies was a quantitative model relating the peak value of an RMS AE signal to both the fractured area and the resultant cutting force at tool fracture.
Concluding, AE as a monitoring method appears to have a quick response time and consistency, and seems to be more sensitive to tool fracture than cutting force measurements and tool vibration analysis, although no experimental evidence of this has been made until the present date.

The change in the root mean square of AE signals was found to be the best indicator of the tool failure process for the subject tool-work combination.

A useful monitoring system has to be featured with a high success rate of detection, fast response and high reliability. AE based systems were found to be the best indicator of failure and wear patterns, and tests with simulated and actual experiments data for particular cases showed a success rate of 92.3% and 75%, respectively. Now there is a need to be investigated deeply for other tool-work combinations.

Conclusion

A wide variety of tool failure sensing techniques have been developed over the past years. Unfortunately, few of them have been used in industries successfully, since many of them are sort of ' single-minded' in what they are capable of detecting and diagnosing. Therefore, a universal approach cannot be derived based on one measurement technique alone.
The relationships between tool failure and its causes need to be fully understood, and an attempt should be done to attend the following requirements:

1. More reliable and practical criteria which reflect tool wear on-line
2. Techniques that respond to the rigorous of a CAM/CIM environment
3. Effective tool changing strategies in unmanned manufacturing
4. Faster data processing strategies, to control the compensation of the cutting tool during precise operations
5. Sensing instrumentation which are more practical and cost effective and suited to the industrial environment

FUTURE TRENDS

The Theory of Chaos is being researched ever since the non linearity of machine tool dynamics was established. Now researchers are using this fact to devise better monitoring diagnostics and control systems. A qualitative comparison of various computational schemes for state phase construction is made, and using fractal analysis an estimation procedure is successfully developed to relate the fractal dimension spectrum of the time-series data to tool-wear estimates. The models based on theory of chaos and monitoring systems thus developed help in relating the seemingly random sensor signals with the dynamics of the system under consideration, thus making the observers more scientific. The achieved pattern consists of a control variable - speed, state variable, vibration amplitude and the optimal variation (target). This network will be used to determine the optimal control strategy (planning the control path) for chatter control. This strategy could be generalized to any model-based process control.

Besides the theory of Chaos, the recent researches also concentrate in neural networks, but unfortunately there is not enough information available to provide not even a brief overview of this last one.

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