Real-time Tool Condition Monitoring for Machining Operations

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〈Abstract〉

In computer integrated manufacturing environment, tool management plays an important role in controlling tool performance for machining operations. Knowledge of tool behavior during the cutting process and effective tool-behavior prediction contribute to controlling machine costs by avioding production delays and off-target parts due to tool failure.

The purpose of this paper is to review and develop the tool condition monitoring scheme for drilling operation to assure a fast corrective response to minimize the damage if tool failures occur.

If one desires to maximize system through-put and product quality as well as tooling resources, within an economic environment, real-time tool sensing system and information processing system can be coupled to provide the necessary information for the effective tool management.

The example is demonstrated as to drilling operation when the aluminum composites are drilled with carbide-tipped HSS drill bits. The example above is limited to the situation that the tool failure mode of drill bits is wear.

1. Introduction

In computer integrated manufacturing environment, the progressive introduction of small or medium size batch production systems makes tool management issue increasingly important in machining operation. Tooling can largely affect the productivity of manufacturing system involving machining operations. In automated manufacturing, tool condition monitoring is essential determinants for quality and effective manufacturing capabilities. For unmanned machining operations, the tool monitoring system has to detect every kind of failures which may cause inferior products or breakdown of machines. Microcomputer-based tool monitoring systems can be used to monitor the tool's condition or to cut tooling costs. The advantages of using tool monitoring to detect the tool's condition are:

1. Tool wear is monitored and tool changes initiated when necessary, so avoiding damage to the machine or the workpiece.

2. If there is a breakage, a signal will be produced to stop the machine tool within milliseconds.

3. The system will detect if a tool or workpiece is missing, thus eliminating wasted machine time and the likelihood of unpredictable crashes.

4. Tool life can be optimized, which means that tools need only be changed when they are worn and so reduces tool costs.

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5. Down-time is lessened, and this increases the machine tool's output.

6. The metal cutting operation is monitored automatically, limiting operator involvement.

The purpose of this paper is to review and develop the tool condition monitoring scheme to assure a fast corrective response:

1. to minimize the damage if tool failures occur or
2. optimize tool life by changing cutting tools in right time.

If one desires to maximize system through-put and product quality as well as tooling resources, within an economic environment, real-time tool sensing system and information processing system can be coupled to provice the necessary information for the effective tool management.

The example is demonstrated as to drilling operation when the aluminum composites are drilled with carbide-tipped HSS drill bits. The example above is limited to the situation that the tool failure mode of drill bits is wear.

2. Tool Condition Monitoring

With the progressive introduction of automation in machine tools and systems, it is important to be able to predict incipient tool failure or excessive wear. Hence, while a machine tool is cutting, we continuously assure that the tools are performing productively.

Tool-related monitoring methods are classified into two categories:

1. Direct methods,
2. Indirect methods.

The direct measurement of tool condition includes touch trigger probes, optical devices, proximity sensors, electrical resistance methods and radioactive techniques. Indirect methods include techniques based on temperatures in the tool or chip, sound, vibration signal, acoustic emission and cutting forces which are either measured directly, or through measurements of power, current, thrust or torque.

While the direct methods give a direct indication of the tool condition, they are not highly practical because the machining process has to be interrupted for measurement. On the other hand, indirect methods enable the monitoring of tool wear while machining is still in progress. This technique involves the development of reliable sensors for measuring process parameters, algorithms for correlation with tool condition and failure and feedback control systems for prediction of tool failure in real-time.

Most commercial systems tend to be either force-related or based on the acoustic emission method. The commercially available systems based on force-related signals may be categorized as follow:

1. Those that use a dynamometer, either on the tool block or below the turret, or below the workpiece in a drilling process.
2. Those with thrust force bearings.
3. Spindle-bearing instrumented.
4. Those with a sensor for assessing spindle deflection.
5. Power/current monitored.
6. Torque monitored, sometimes known as "torque-controlled machining."

The various sensing methods used for drilling processes that have been reported in the literature are summarized in Table 1. A further explanation of each scheme will follow in the Monitoring the Drilling Process Section. The main obstacle that one has is how one achieves consistant, accurate tool monitoring and real-time control system as a whole, while at the same time the metal cutting is in progress.

3. Tool Failure Criteria and Failure Mode

In order to monitor the tool's condition, the failure mode has to be identified in advance and determine the tool failure criterion based on specification and require-

〈Table 1〉 Various Schemes for Monitoring Drilling Process

Sensor/Method	Size Range	Detection/Prediction	Reference
Thrust Force	Large (10.32 mm)	Detection #	23
Torque	Large (10.32 mm)	Detection #	23
Power	Large (10.32 mm)	Detection #	23
Temperature	*	Detection #	
Acoustic Emission	*	Detection #	16
Vibration	Small (1 mm)	Prediction #	23, 29
Thrust Force Gradient	Large (5 and 8 mm)	Prediction #	26

Note: * : For Single-point turning operatin
: Real-time control was not attempted

ment of item that would be produced.

Several authors defined criteria that may be used for the failure of cutting tools:

1. Complete destruction of the cutting tool surface (of the tool).
2. The wear of the tool, to the extent that the quality of the machined surface becomes unacceptable.
3. The wear of the tool surface to some predetermined level.
4. The change of color of the drill, due to the loss of temper.
5. The change of the sound.
6. The time to removal from service.
7. Flank wear, crater wear or an increase in torsional moment.

The third criterion is probably the most widely used criterion for tool failure. The seventh criterion shows poor correlation to the tool failure criterion. The fifth criterion mentioned is very subjective, because the drill has self-sharpening qualities.

In general, the failure of a cutting tool occurs by one of two modes:

1. Fracture or chipping and
2. Excessive wear leading to plastic deformation resulting in collapse of region(s) subjected to high normal stresses acting at elevated temperatures.

Depending on tool failure mode, the monitoring system can be classified into two groups: breakage detection and tool wear monitoring. The tool monitoring systems are developed to handle tool breakge, tool wear, and collision.

4. Monitoring the Drilling Process: Literature Review

Yee and Blomquist at the National Bureau of Standards have investigated the use of vibration analysis techniques for predicting drill breakage. They determine drill wear and predict drill breakage by applying time-domain analysis to the signal from an accelerometer mounted on the workpiece. This method depends on detecting increased vibration patterns due to contact between the drill and the walls of the hole being drilled. They carried out experiments using 1 mm diameter drills and reported successful prediction of failure. From their study, they concluded that the signal/noise ratio gets smaller the farther the accelerometer is mounted from the drilling action. This technique necessitates considerable tuning for use with different machine tools and different workpieces. These results suggest that vibration analysis may be a useful technique in some, but not all machining situations.

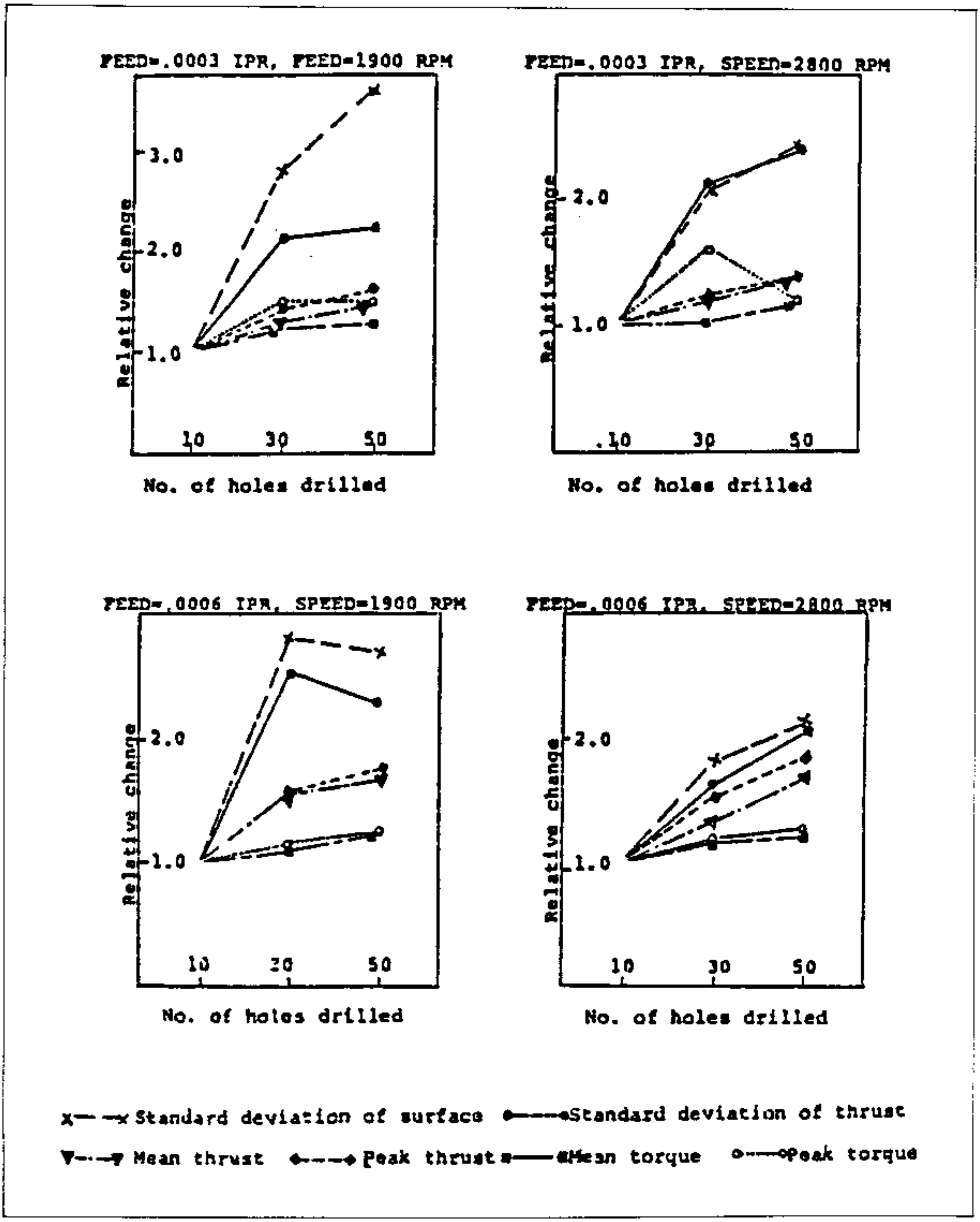
Radhakrishnan and Wu have used the dynamic characteristics of the thrust force obtained during drilling a composite material to monitor the surface quality of the hole being drilled. From their study, they concluded that static aspects such as the mean and the peak forces are unreliable, when close monitoring of the hole quality is required. 〈Figure 1〉 shows the change in the mean and peak thrust/torque with the number of holes drilled. This change is the static aspect of the forces. It can be seen that these curves do not reflect the changes in the standard deviation of the hole surface well. In comparison, the standard deviation of the thrust, a semi-dynamic aspect, showed a better indication of the hole quality. They carried out a dispersion analysis and showed that a very strong correlation existed between the changes in the standard deviation of the lamination frequency in the thrust and surface signals. 〈Figure 2〉 the dynamic aspect of the forces, shows the changes in the standard deviation of the lamination frequency component in the thrust and surface signals obtained from the dispersion analysis. It is evident from 〈Figure 2〉 that the change in standard deviation of this frequency in the thrust signal is very closely correlated with the change in the waviness of the surface under all working conditions. Therefore, this aspect of the thrust signal can be used as an on-line indicator of the waviness of the hole surface.

Thangaraj and Wright investigated real-time control systems for drilling by measuring the trust force and determining its gradient. Using a microcomputer-based feedback control system, experiments were carried out under different cutting conditions to test the effectiveness of the thrust force gradient in predicting failure. Figures 3 and 4 show the thrust force with time under the normal drilling condition and the gradient of the thrust force, respectively. Under normal drilling conditions, the gradient of the thrust force was shown to be dispersed tightly around a horizonal straight line. 〈Figure 5〉 shows the thrust force on a drill obtained while drilling a hole in which the drill failed and the drill feed was stopped manually. This figure shows a clear pattern of sharp spikes during failure. 〈Figure 6〉 shows the gradient of the thrust forces under the failure conditions shown in 〈Figure 5〉.

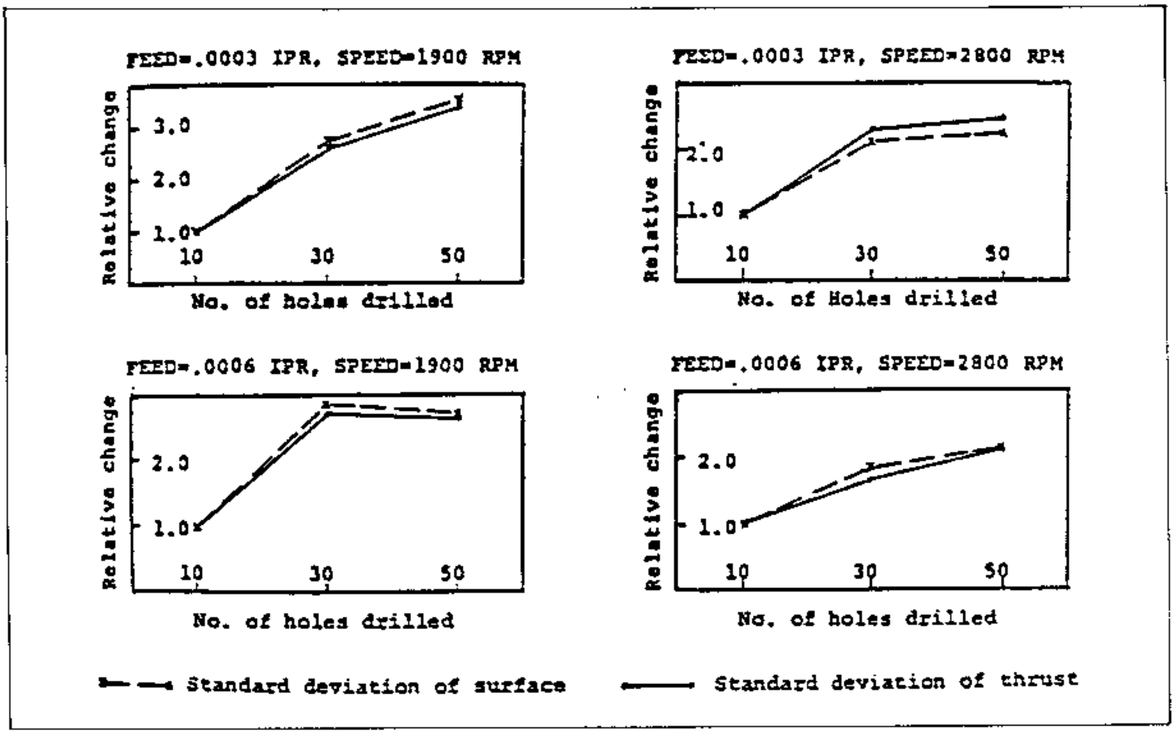
Thangaraj and Wright demonstrated that the gradient of the thrust force can be effectively used to predict failure due to excessive wear that is encountered with large drills (5 and 8 mm). However, the technique was not highly successful in predicting failure due to fracture of small drills (2 mm). In their study, it was concluded that monitoring vibrations of the drill-workpiece proved useful in predicting failure due to fracture.

It was suggested that successful prediction of drill failure under a wide range of cutting conditions will be dependent on multisensory systems. Further, they stated that the necessity exists for integrated sensor based systems and suitable algorithms to provide a framework for intelligent machine tool control systems.

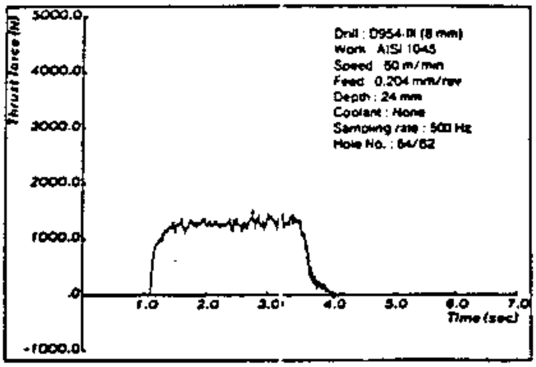
Recently, acoustic emission signals have been used in the monitoring of the tool wear and tool failure. Acoustic emission is the high frequency sound generated by the rapid release of energy by any material under strain. In machining, acoustic emission signals are generated in the deformation zones where plastic deformation of the work material take place to form the chip. In addition, acoustic emission is generated by the chip breakage and tool fracture and chipping. Moriwaki has used the acoustic emission signal from the cutting process for in-process detection of tool failure in single-point turning. He has observed a large amplitude acoustic emission signal when tool-failure (including cracking, chipping and fracture) takes place during cutting. A major hurdle in the use of these signals is in the development of appropriate filtering techniques and algorithms to separate the significant signals from the background noise generated in any metalworking process.



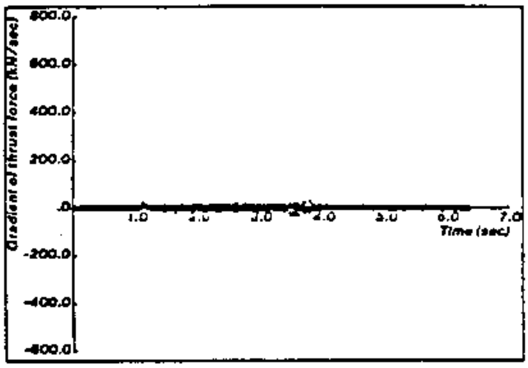
〈Figure 1〉 Relative Change in Static and Dynamic Characteristics with Number of Holes Drilled [Radhakrishnan and wu]



〈Figure 2〉 Relative Change in Standard Deviation of the Lamination Frequency Component with Number of Holes Drilled [Radhakrishnan and Wu]



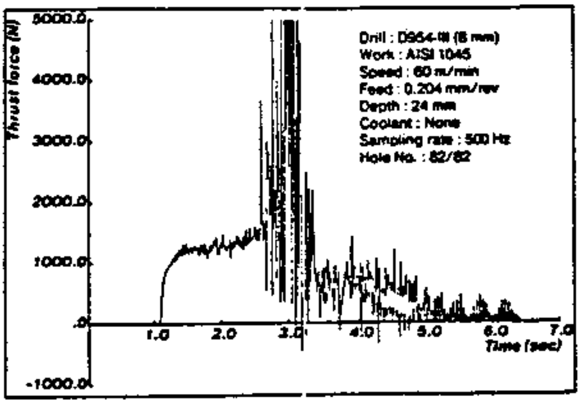
〈Figure 3〉 Variation of Thrust Force with Time under Normal Drilling Condition[Thangaraj and Wright]



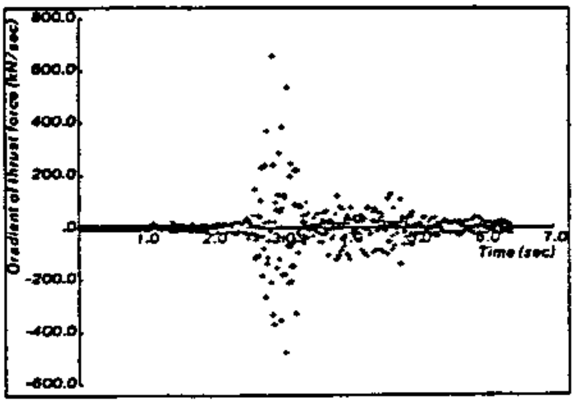
〈Figure 4〉 Gradient of Thrust Force Shown in Figure 3 versus Time[Thangaraj and Wright]

5. Tool Monitoring Case Studies

Smith described several case studies of tool monitoring systems. For effective process monitoring, it is important that the signal used should vary continuously as the tool wears, and not just at the point when it fails. In one of the case studies at Sandvik Ltd.(UK), it was shown, 〈Figure 7〉 (a), that during a drilling operation the axial force component, $_A$, provides a better indication of the cutting edge's conditions, as a function of tool wear,



〈Figure 5〉 Variation of Thrust Force with Time while Drilling The Hole in whichFailure Occurred [Thangaraj and Wright]



〈Figure 6〉 Gradient of Thrust Force shown in Figure 5 versus Time [Thangaraj and Wright]

than the torque value, M. The increase in the axial force for a worn tool is more clearly defined. The change in the force generated, while cutting, is instantly detected by the feed- force sensor, via the spindle and the bearing. The sensor transforms the force change into an electrical signal which is transmitted to the signal processing device. Once the signal is received, the processing device can immediately initiate action by the machine controller, if the tool is worn, broken or not-in-cut. 〈Figure 7〉 (b) shows how continuous monitoring of the axial force can be used to trigger four alarms:

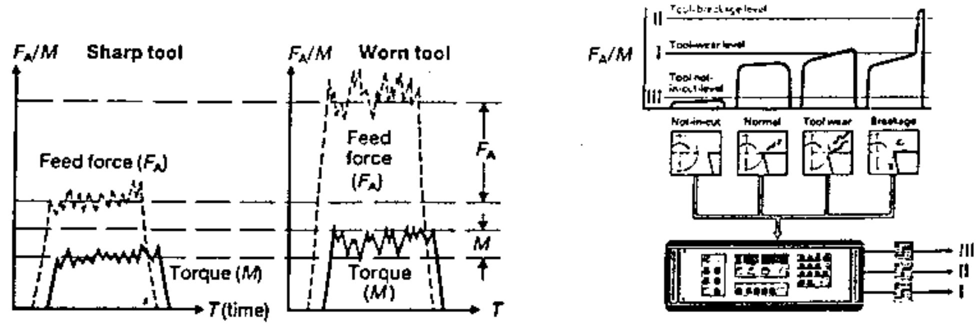
1. Level I can be used to detect tool wear. The alarm signal can be used to initiate a tool change on completion of the operation.

2. Level II can be utilized for tool breakage. This should be used to stop the machine immediately when the breakage is detected.

3. Level III may be used to monitor whether the tool is in-cut or not-in-cut, as the case may be, meaning that either the tool or the component is missing.

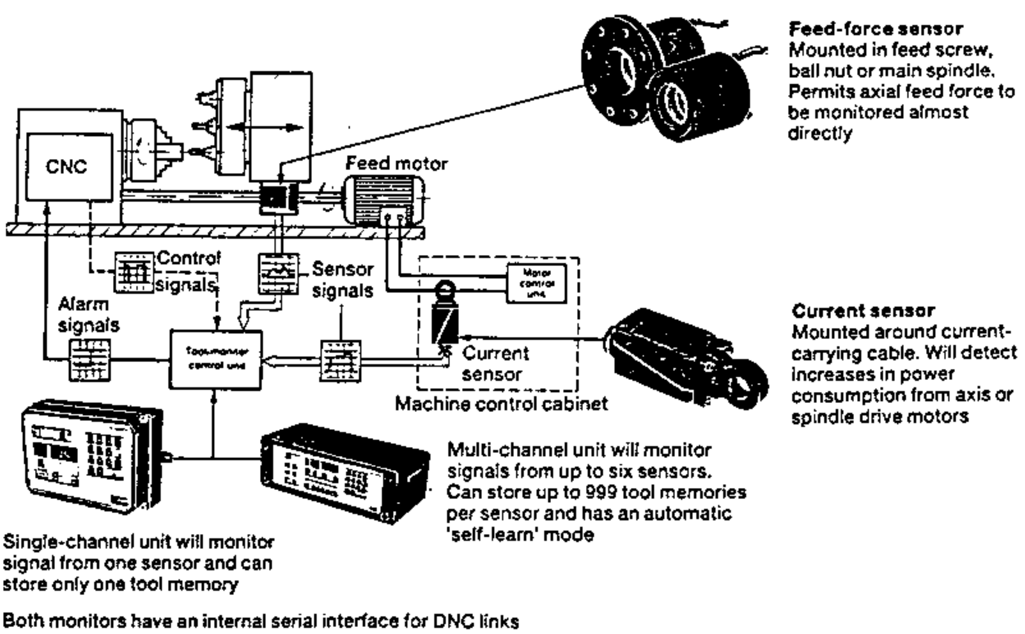
4. An additional level can be used for crash protection. Like Level II, this alarm signal should be used to stop the machine immediately and, in so doing, protect the machine tool.

〈Figure 7〉 (c) illustrates the monitoring positions for a turning center, showing the possible positions for the sensor. These signals are continuously monitored by a single or multi-channel control unit, any alarm signals are passed back to the machine's control unit for the appropriate action to be taken. 〈Figure 8〉 shows the case study done at Krupp Widia Co. on monitoring for tool breakage and wear/land collisions, using piezoelectric sensors. At the moment a tool breaks, there is a significant rise in the cutting force, followed by a sharp drop, as indicated in 〈Figure 8〉 (a). This pattern is a telltale sign of tool breakage and forms the basis on which the tool breakage system works. The digital breakage monitoring system continuously monitors the upper- and lower-force values. If these values deviate from the norm, because of tool breakage, the sensors react immediately. Within 2 milliseconds of the breakage, a command is issued to stop the feed motor, thus preventing any continued operation with a damaged tool. The tool-wear circuitry is similar to that for tool breakage detection. The wear monitoring system is a digital system. It is based on the rise in the force level that occurs over the lifetime of the cutting edge and is operated by checking the rise against the force differential, based on a reference cutting edge operated until blunt. The wear threshold is obtained by adding the initial force value of a new cutting edge to the differential of the reference tool. Once the limit is



(a) *The difference in signals from a sharp tool and a worn tool*

(b) *Continuous monitoring of the axial force can be used to trigger alarms at different levels*



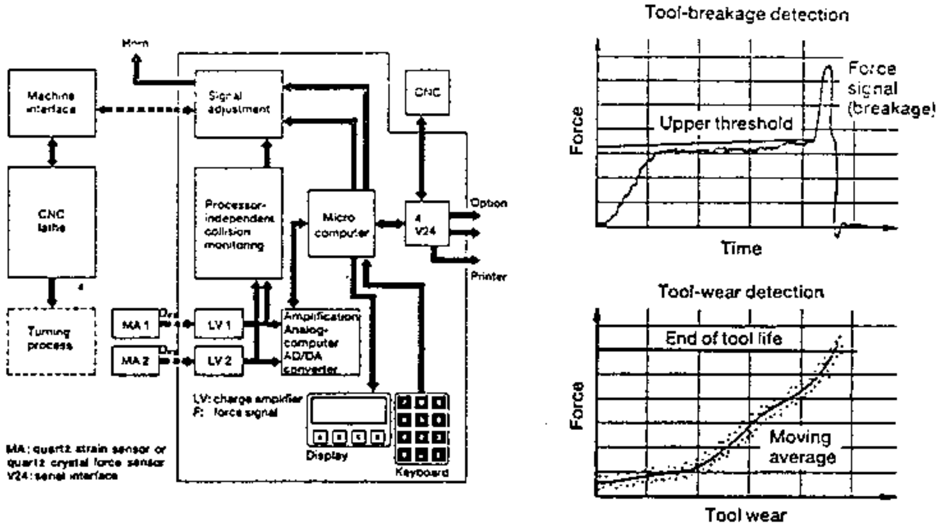
(c) *Monitoring positions*

〈Figure 7〉 How, When, and Where to Monitor Tooling [Smith]

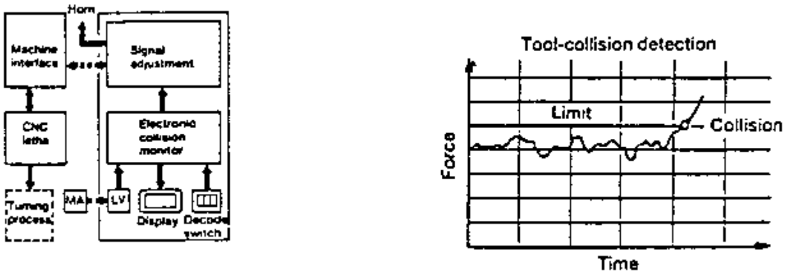
exceeded, the system indicates that the tool is worn and should be replaced. A typical graph of the tool-wear pattern produced during the tool's useful life is shown in 〈Figure 8〉 (a). The collision monitoring system is shown in 〈Figure 8〉 (b). The operating principles, as applied to a turning center, are that the strain transducer measures the deformation in the turret during machining and then compares it with a preset threshold value. If the measurements exceed the threshold, a command is given within 3 milliseconds to stop the feed motor, and no damage to the machine or workpiece occurs.

6. Adaptive Control System for Tool Monitoring

Control systems are designed to act upon abnomal



(a) The tool-breakage and tool-wear detection system



(b) The collision-monitoring system

(Figure 8) Tool-condition Monitoring System[Smith]

conditions of cutting tool in real time. Alarm signals, control signals and sensor signals are processed through adaptive control algorithm which has real link to machine unit. Those adative control algorithm should be capable of providing an automatic means to control the machine control unit continuously while the cutting operation is in progress.

Adaptive control algorithm divide into two main groups, adaptive control optimization part and adaptive control constraints part. The first part of algorithm requires some form of in-process measurement to assess such factors as tool-wear rates, spindle defection, and vibration under production environment. They are dependent upon reliable sensors and the programming work to realize such situations is difficult. The second part of algorithm is realized with easiness and low cost. In general, this part senses the rotational cutting forces and adjust feed rate. If a condition arises where the feed rate falls below a preset limit, syster tool is called up to complete the machining operation. This makes up a feedback loop in which continuous monitoring by the sensors, and updating of the machine control unit using adaptive control, produce optimal cutting conditions for the combination of tool and workpiece.

The benefits of using an adaptive control system are:

1. By maintaining a constant cutting power, cutting

force and feed force, the tool life is extended.

2. Damage to the workpiece or cutting tool is prevented.

3. The main spindle motor is protected from overload.

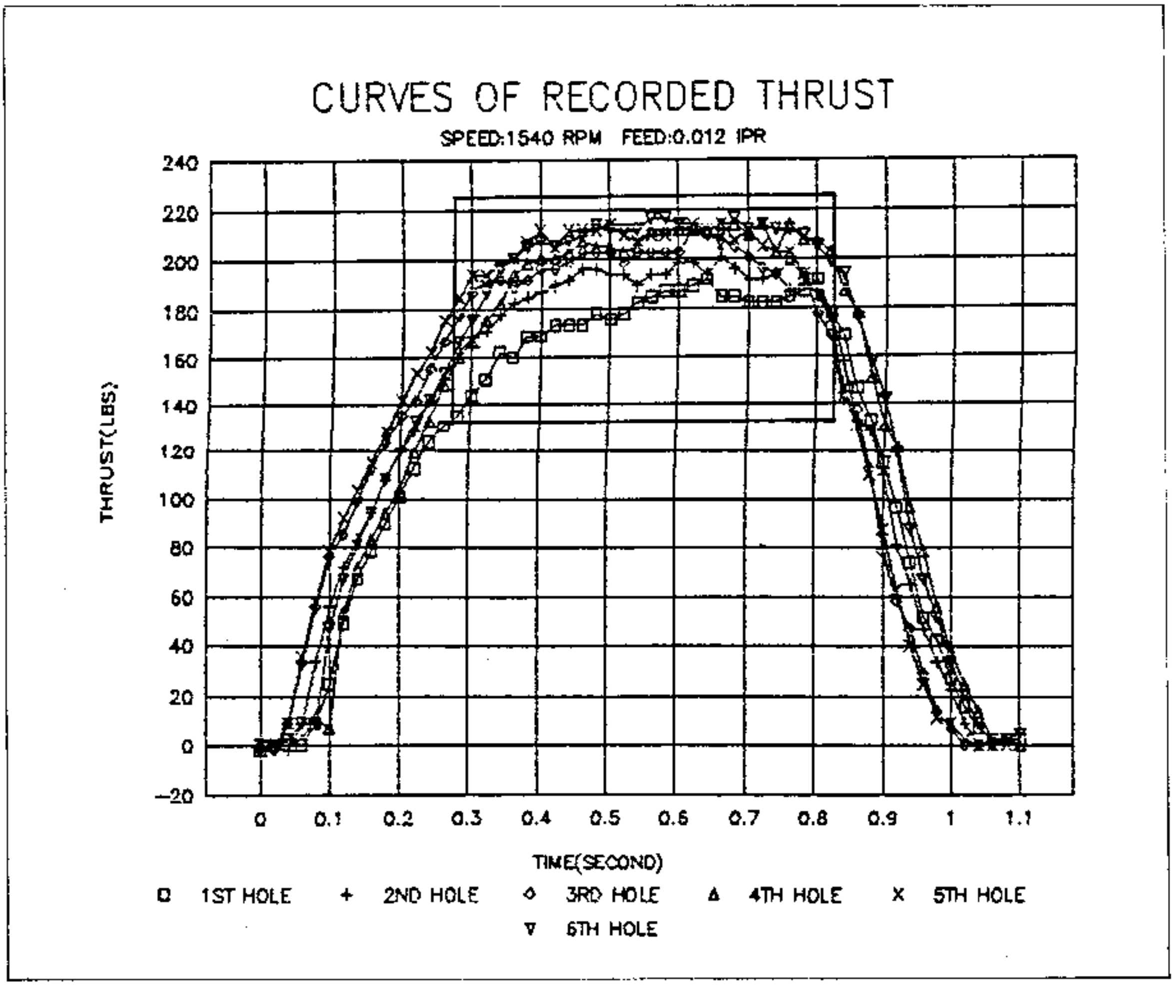
4. Optimal stock-removal rate are possible, under steady-state machining conditions.

5. When unpredictable air gaps occurs, the fastest possible travel can be used.

6. The operator's experience, or the program's efficiency, may differ for different cutting operations, but with adaptive control this technical gap can be eliminated.

7. Example

Dural aluminum bars were drilled at operating onditions: speed 1540 rpm, feed 0.012 ipr, depth of cut .25 inch, with a water coolant. Drilling dural aluminum, with 0.25 inch diameter carbide-tipped HSS drills, results indicated that the drill failed by excessive wear and exhibited audible failure symptoms. The dynamometer, DAS 16 A/D plug-in board, IBM PC, relays are used to get and process the thrust force generated that is a good indirect indication of drill bit wear(cutting edge condition).The cutting force data obtained by averaging



(Figure 9) Curves for Thrust as recorded for a Drill Bit(First 6 Holes are Superimposed) the recorded data values within the rectangular area shown in 〈Figure 9〉. These data epresent the thrust force on the drill after the drill enters the workpiece and actually starts a full cut. The mean values of all the pooled cutting data values for each hole constitute the mean tool performance curves. In addition to the mean performance values, variance and individual 3 sigma upper and lower limits at each hole were calculated along with control limits. Drill performance functions can be fitted in order to track the central tendency behavior of the thrust force over usage as well as operating conditions. The tool performance function of cutting thrust function would be

$$f(t, s, f, d) = \beta_0 s^{\beta_1} f^{\beta_2} d^{\beta_3} t^{\beta_4}.$$

where β_0, β_1, β_2, β_3 and β_4 are regression coefficients, which are determined from historic data.

s: machining speed (rpm)
f: feed rate(ipr)
d: depth of cut (in)
t: cutting time (min)

The tool performance critical limit(threshold) can be defined at various thrust force levels, depending on hole quality characteristics and perhaps drill bit regrinding requirements. As to failure point criterion, based on experience gained during the experiments, thrust forces ranging from 210 lbs to 225 lbs have been found to be adequate, as far as quality of holes, surface finish and tolerances to hole specification are concerned, for Duralcan aluminum, when IMCO brand carbide-tipped HSS drill bits are used to produce holes. Higher quality holes(surface finish and dimensional accuracy) are produced at lower thrust forces (e.g., less cutting edge wear). A "C" computer code is developed to handle:

1. acquire the raw data and process the data

2. set threshold value(tool failure definition) and refer to the standard cutting force hole by hole bases and maintain tool performance database.

3. calculate the conditional tool reliability, predict failure-free operating period, and indicate the usable period of tool given the current operating condition.

4. If the cutting force point is out of control limit, send operator an alarm signal or send emergency stop signal to stop the feed moter.

The real-time conditional reliability structure is shown in 〈Figure 10〉.

8. Conclusions

Although certain aspect of tool monitoring have been around for some time, recently, with the help of microprocessor and reliable sensors, tool monitoring systems have been possible to incorporate tool breakage, collision and wear protection and so forth. Since tool monitoring system is very much dependent on multisensory system and control algorithms, a lot of work need to be done on integrated sensor based systems and suitable control algorithms to provide intelligence to the cutting tools.

A system of tool management has become of critical importance as componies spend more monies to control tooling resouce within economical environment. When company introduces the monitoring related module to their manufacturing system, they need not invest heavily in a large-scale system in one go, but have to gain experience in a step by step approach, while establishing the short and long term goal of implementing condition monitoring system for their production system.

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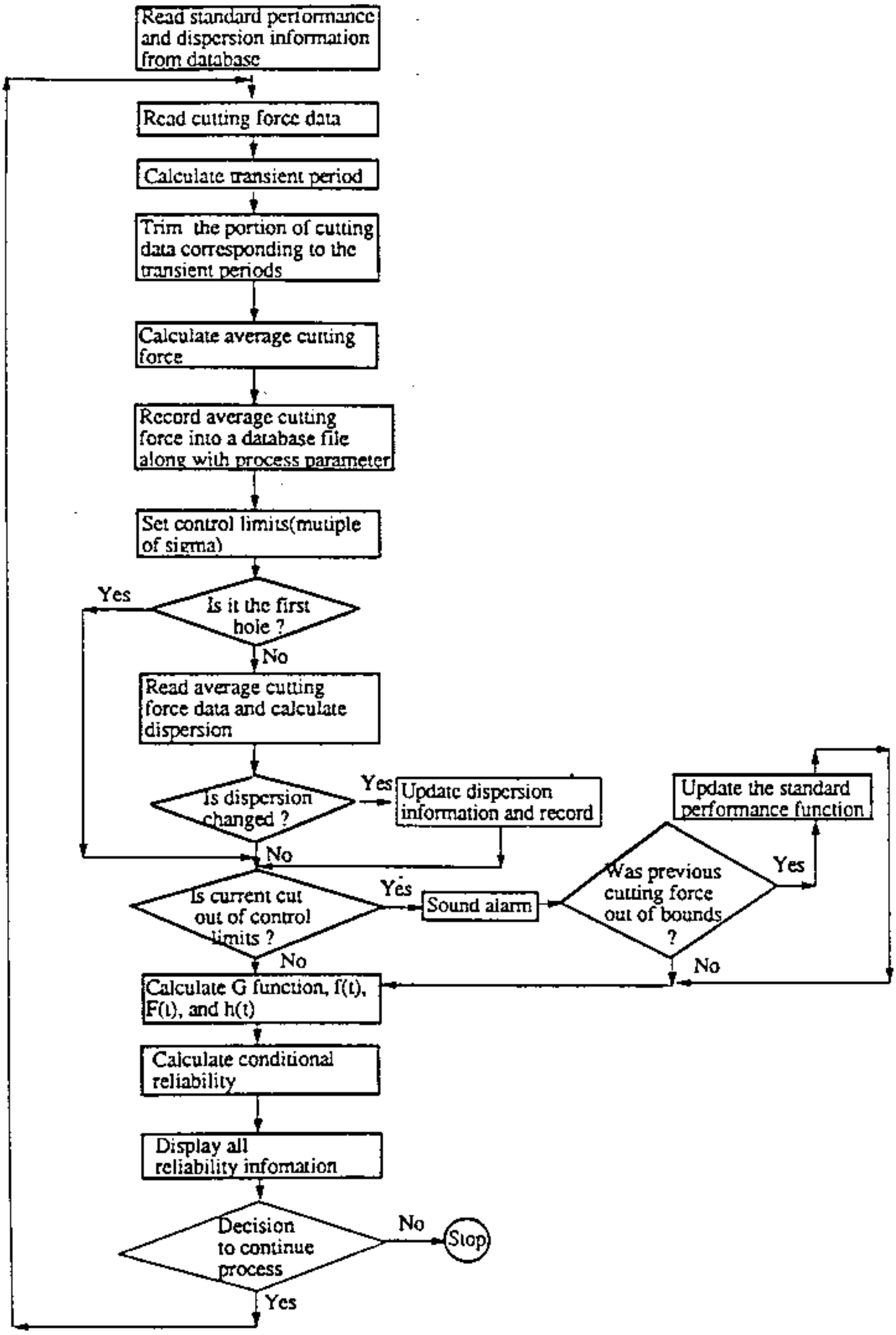

〈Figure 10〉 Real-time Conditional Reliability Structure.

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