A DIRECT ON-LINE ULTRASONIC SENSING METHOD TO DETERMINE TOOL AND PROCESS CONDITIONS DURING TURNING OPERATIONS

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Taysir H. Nayfeh

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APPROVED:

Osama K. Eyada, Ph.D. Advisor

Wolter J. Fabrycky, Ph.D.

Robert D. Dryden, Ph.D.

John C. Duke, Jr. Ph.D.

Subhash C. Sarin, Ph.D.

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Taysir H. Nayfeh

O. K. Eyada, Chairman

Industrial and Systems Engineering

(ABSTRACT)

Machining operations in automated manufacturing centers are under-performing by 20-80%. Optimizing these machining operations requires on-line knowledge about the cutting tool's condition and the process state. Currently, this information is either not reliable or not available in a timely manner. This is due to the lack of suitable sensors, which must measure on-line directly and accurately one or more of the relevant tool and process information sources in the hostile machining environment.

A direct, active, ultrasonic method for on-line sensing of the tool condition and process state in turning operations was developed. Sensing is acheived by using an ultrasonic transducer operating at 10 MHz in a pulse-echo mode to send pulses through the tool. The amplitude and propagation time of the reflected pulses are modulated by the tool nose, flank, temperature, and by the material in contact with the tool. The reflected pulses are received and processed by a high speed digital signal processing system.

This method has the potential to directly and accurately measure on-line several relevant processes and cutting tool parameters through the use of a single sensor. These parameters are tool-workpiece contact, tool wear, tool chipping, temperature and chatter.

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1. INTRODUCTION

1.1 Background and Importance

Machining operations, conventional or numerically controlled, present many opportunities for productivity improvements including maximizing the metal removal rates, reducing tool failures, and improving the quality of the finished product. In either form of machining, the condition of the cutting tool and the dynamics of the overall machining process are two dominant unknowns that must be determined in order to optimize the operation. These parameters are essential inputs to either manual optimization, in the case of conventional machining, or automatic adaptive control in the case of Computer Numerical Control (CNC) machining.

1.1.1 Conventional Machining

In conventional machining, the responsibility for optimizing the operation rests mostly with the operator. The operator uses his/her expertise and standard parameter tables to select the initial cutting parameters such as feed, speed, and depth of cut and then observes the performance of the cutting process. The color and the curl of chips, surface finish, dimensional accuracy, vibration and chatter are indicators that give the operator valuable information regarding the process's performance. Operational parameters such as excessive speed, feed, and/or depth of cut or a poor performing cutting fluid could influence any of the above indicators. The operator adjusts the cutting parameters accordingly to eliminate or reduce the effects of poor cutting, to improve part quality, and to optimize the metal removal rate.

In addition to indicating the cutting process performance, the above cutting indicators give the operator valuable information regarding the cutting tool's condition.

This information combined with direct visual inspection or actual measurements of the tool wear, gives the operator sufficient data to evaluate the overall tool condition and signals if corrective action is needed for tool replacement. Essentially, a manual adaptive control system is formed by the operator and his/her expertise. The operator's eyes and ears provide some of the sensory information regarding process performance. The operator uses this information and his/her expertise to choose the necessary corrective actions, which are then implemented manually.

The level of quality delivered by conventional machining is directly dependent on the machinist's skills and capabilities. Machining complex parts in small lots is a slow process that requires the operator to be skilled in blue print reading, the use of precision measuring instruments, planning the sequence of operations, and to have a good feel for the cutting process. In addition, repeatability is highly dependent on the individual machinist's skills. These factors, among several others, were the driving force behind the development of CNC machines.

1.1.2 CNC Machining

CNC machines are computer controlled, which can perform a multitude of operations on a workpiece, and in most cases, without the need for setup changes. CNC machines are able to exchange tools automatically to suit the required sequence of operations. They are also able to follow a programmed tool path along a single or multiple axis and maintain the programmed speeds, feeds, and depth of cuts. Automatic sensors monitor the current tool speed and position, the part's position, and the speed of motion along the various axes. This information is continuously updated and fed into the controller which issues the appropriate corrective actions, if needed, to maintain the current parameters within the programmed limits.

CNC machines offer many advantages over conventional machining, some of which are:

1. Flexibility of part change over
2. Ability to perform complex operations
3. Ease of replications of any geometry
4. Reduction of jigs and fixtures cost
5. Elimination of variations due to human skill levels

The benefits of CNC machining are clear and abundant; consequently, their use is spreading rapidly throughout industry. Unfortunately, the inherent limitation of the machines is the lack of an on-line cutting optimization function. The controller follows the prescribed cutting parameters without regard to the current process performance. This is due to the lack of sensory capabilities about the process performance, some of which was provided by the eyes, ears, and the experience of the machinists.

Today's machining environment involves the wide use of CNC machines and manned machining centers seemingly eliminated the need for the machinist or changed his/her role from an adaptive machine controller to a standby function. In most cases, the adaptive control function of the operator has not been replaced, and as such, part programmers, detached from the actual cutting, are in control of the process. In these cases, the cutting parameters are pre-determined and specified for the overall operation. The feeds, speeds, and depths of cuts are conservatively selected in order to reduce catastrophic tool failures and to explain the tool condition and work material variations. This causes the operation to under perform by 20-80% depending on the material and part complexity [1].

In order to optimize CNC and unmanned machining operations, the machining parameters have to be adjusted on-line, i.e., adaptively controlled. Optimizing the machining operations implies that the metal removal rate is to be maximized while minimizing tool failures and maintaining the required dimensions and surface finish. This task has to be accomplished within the hostile machining environment. The environment consists of non-uniform work materials, changing process dynamics, and variable tool conditions, such as wear and chipping. In order to achieve these objectives, the adaptive controller has to continuously be able to:

1. Sense the relevant features or indicators of the cutting process
2. Relate the indicators and or the features to the controllable variables, such as speed, feed, depth of cut, etc.
3. Decide on the corrective actions based on the control strategy of the machine
4. Execute the corrective actions

As can be seen from the previous discussion, optimization of the machining process through adaptive control requires the on-line knowledge of the relevant features and indicators of the process, i.e., on-line tool and process condition monitoring.

1.2 Tool Condition Monitoring

The needs for on-line tool and process state monitoring are becoming critical with the widespread use of CNC and the move toward unmanned machining centers. In these settings, it has been shown that 6.8% of all the down time is attributed exclusively to tool failures [1]. In our age of expensive tooling, such as, carbide, ceramics, and industrial diamonds, the cost of the tooling itself becomes a major factor in the economics of machining.

Tool condition monitoring has been and continues to be, of great importance to industry and researchers. The needs in tool condition monitoring have long been recognized, and as such, significant amounts of research of various sensing methodologies have been conducted. Of the many methods researched and systems developed, few have made it to the shop floor. This is mainly due to the complexity of the machining operations and the lack of robust sensors.

Although there are many factors which affect the machining process, most machining problems are either directly related to the cutting tool's condition, or manifest themselves by a change in the tool's properties. For example, the tool's temperature, is an indicator of too high of a cutting speed, feed, depth of cut, or a poor performing cutting fluid. Although, built-up edge, vibration, and chatter, may not be directly caused by the tool's condition, they are unmistakably caused by improper settings of the machine. Therefore, the tool condition and the process state are generally referred to as tool condition monitoring, in most cases.

Tool condition monitoring can be performed on-line or off-line by either direct or indirect means. The on-line designation for a sensing method refers to the fact that it is performed while metal is being removed without the need for interrupting the process. Off-line methods can be performed on the machine or away from the machine. In either case, these methods require either scheduling idle time for the measurements or actually interrupting the process.

The direct methods refer to systems that can measure a property of a tool, such as the actual tool flank wear and/or the depth of crater wear. The indirect methods measures one or more of the indicators and/or parameters associated with the cutting operation, such as tool forces, acoustic emission, vibration, etc. The tool condition is then inferred from the values of the parameters. Due to the complexity of machining operations, there are no exact mathematical models that relate the cutting parameters to the actual tool condition. For example, tool forces, temperature, vibration, etc., may be changing due to tool wear, harder material, improper feed, speed or depth of cut.

Direct on-line methods for tool and condition monitoring have been difficult to develop and implement since the tool nose and flanks are obscured from vision during cutting. Furthermore, the debris and cutting fluids makes it difficult to conduct measurements while the tool is idle. Several methodologies and systems have been explored for sensing the tool condition on-line directly [3]. Some of the methodologies explored are radioactivity tracers, optical scanning, electrical resistance, probes to measure the workpiece dimensions, and measurements of the distance to the tool post, etc. However, none of these systems is practical for the shop floor.

In a recent development, an ultrasonic on-line direct sensing methodology was developed by Reed [76] to measure the part diameter and surface finish in turning operations. The method was shown to be accurate and robust. The major drawback to the system is that the measurement lags the actual cutting by 1/16". As such, catastrophic tool failures cannot be detected in time. In addition, the cost of the system is prohibitive and on the order of $250,000.

Indirect methods are much easier to implement on-line, due to the required sensor location and the type of parameters, which are usually measured. The sensors are generally placed at or near the tool post away from the cutting action or on the machines spindle. Although the indirect measurements are generally reliable, the correlation between the actual pertinent parameters and the measured indicators is questionable, since there are no exact mathematical models representing the relations. Some of the popular indicators measured are, cutting forces, vibration, power consumption, acoustic emissions, etc.

Currently, there are no commercial direct on-line tool and process condition monitoring in application on the shop floor. However, there are several varieties of indirect measurement systems in operation [1,2,3] such as:

1. Tool presence sensing probes
2. Vibration and acceleration sensors
3. Load and power sensors
4. Acoustic emissions
5. Force sensors

Most of these systems measure on-line a single property such as force, torque, current, etc. Although catastrophic tool failures can be predicted reasonably well by some of the methods, the level of reliability and accuracy of predicting gradual wear is certainly well bellow industrial expectation. The state of on-line tool and process monitoring was best summed up in January of 1993 by Owen [2] in an article in Manufacturing Engineering as follows:

> **"Automated high-volume machine tools like multi-spindle screw machines, mid size rotary transfer machines, and transfer and trunnion machines are well-suited for tool monitoring. Yet tool control systems are a tough sell. Everyone seems to have a story of malfunction, frequent false alarms- or real alarms followed by crashes seconds later, and the systems disconnected in disgust."**

1.3 The Research Problem

Metal removal is a hostile, complex, and dynamic process in which many interactions take place. Furthermore, the mechanics and/or interactions between the parameters are not well known or defined. Because of these conditions, tool and process condition monitoring whether direct or indirect, on-line or off-line, has been extremely difficult. The hostile machining environment, obscured vision of the tool, limited space for sensor placement, and high mechanical impacts make it nearly impossible to implement most of the current monitoring methodologies. Despite the obstacles, the need for direct on-line tool and process condition monitoring in today's operating environment is greater than ever. As such, the choice of parameters to monitor has to be prudent, i.e., a minimal set, which represents or predicts the true condition of the tool, workpiece, and machine.

In order to determine the minimum set of parameters, which must be monitored, we must first define efficient machining. In turning operations, the objective is to maximize the metal removal rate while maintaining the part's dimensions and surface finish within the required specifications. This has to be accomplished while (1) minimizing catastrophic tool failures, (2) maintaining the tool life within an acceptable range, (3) minimizing vibration and chatter, and (4) maintaining the cutting forces or power requirements within the machine's capabilities.

Based on the above, the areas and/or parameters of concern are:

1. The workpiece dimensions and surface finish
2. Tool wear rate and condition
3. Vibration and chatter
4. Tool forces or power consumption
5. Built-up edge (BUE)
6. Cutting temperature

Of the five areas presented, some are currently measured successfully on-line. These are vibration and chatter, catastrophic tool failures, and tool forces and power consumption. The other areas of observation, which are not commercially monitored on-line are tool wear rate and condition, BUE (accumulation of cutting particles that's welded on the tool due to intense heat and pressure), and the workpiece dimensions and surface finish. The part dimensions and surface finish can be accurately predicted if the tool condition is known, and in the absence or minimal presence of vibration, chatter, and BUE. Under these conditions, the part dimensions can be maintained by compensating for tool wear automatically. Therefore, under these circumstances there will be no need to monitor the workpiece on-line.

The two remaining areas, BUE and tool condition, are critical to the performance of the machining operation. Although BUE can be minimized, its presence is detrimental to the surface finish and in some cases to the dimensional accuracy. Currently, BUE is not predicted by independent or direct means, it is unreliably and/or untimely inferred from the quality of the surface finish or from changes in the cutting forces.

There are two modes of tool failure, which are gradual and catastrophic. Catastrophic failures are caused by chipping, breaking, and/or plastic deformation. Catastrophic failures are, in general, due to improper machining conditions. High vibration and/or chatter causes tool chipping or breakage. Plastic deformation is due to very high cutting temperatures. Although gradual wear is inherent in normal machining, the rate of wear can be effected by several factors, such as, the cutting speed, feed, temperature, work material, etc.

Monitoring the cutting temperature is imperative since it plays a major role in the formation of BUE and is one of the factors effecting the rate of gradual tool wear. In addition, high temperatures can cause catastrophic plastic deformation of the tool's cutting edges. Currently, there are no direct on-line tool temperature sensors. Instead, the temperature is unreliably predicted from the cutting forces or empirically computed.

Therefore, in order to optimize the machining process, the minimal set of parameters that is imperative to monitor is:

1. Gradual wear
2. Tool chipping, and breakage
3. Cutting temperature
4. BUE
5. Cutting forces or power consumption.
6. Vibration and chatter

Currently, there are no reliable sensors for determining on-line gradual wear, cutting temperature, tool probing, and BUE. Furthermore, due to the space and economic restrictions, the number of sensors must be limited to a minimum. Therefore, the need still exists for reliable integrated sensors capable of providing accurate, fast, and robust measurements of more than one of the relevant machining parameters economically. In addition, the format of the sensor's output has to be compatible with that of CNC machines and other types of industrial controllers.

1.4 Research Objectives

The objective of this research is to explore the use of ultrasonic nondestructive methods for on-line tool and process condition monitoring in turning operations. Ultrasonic methods are used successfully in the medical and industrial applications for gauging, imaging, and stress crack detection. This approach was chosen since the ultrasonic waves can be induced in the tool from a safe distance and the waves are able to penetrate the length of the tool to the obscured nose and the flanks of the tool. As such, this sensing method can be implemented on-line. If successful, this sensing method has the potential of capturing several relevant machining parameters through the use of a single sensor. Some of the parameters are: gradual tool wear, tool-work contact, tool temperature, chatter, and tool chipping.

The research procedure consists of two phases, the first is determining the feasibility of the methodology in the form of static, which included a set of GO/NOGO tests, and the second is the validation of the methodology on-line in actual machining operations.

The first phase consisted of verifying a set of concerns and objectives, which were:

1. Inducing ultrasonic waves into a carbide cutting insert and isolating the wave form echo returning from the nose and flanks
2. Verifying the sensitivity of the changes in the wave forms due to simulated cutting conditions such as probing, gradual wear, tool chipping, etc.
3. Designing a robust thermal shielding and positioning mechanism to position and protect the ultrasonic transducer
4. Developing a new style tool holder that's capable of accommodating the transducer assembly and cutting tools
5. Determining and developing the required data acquisition and processing electronics and computer software for on-line operation

The second phase of the research, which is the validation of the methodology, consisted of the following steps:

1. Conducting on-line experiments to determine the system's capabilities in acquiring the proposed parameters.
2. Evaluating each phase of experiments to determine the accuracy, repeatability, and sensitivity of the methodology.

3. Determining the feasibility, limitations and/or short comings of the system.

The results of the pilot study indicated that it is possible to measure several relevant tool and process cutting parameters directly and on-line in turning operations. The study further showed that these parameters can be measured efficiently by a single active ultrasonic sensor. Most of the required acquisition hardware is available commercially. However some engineering and wave mechanics issues remain to be resolved in future work.

1.5 Document Organization

A short description of turning operations and the previous work on on-line tool condition monitoring is presented in Chapter Two. Chapter Three is organized into two sections. The first contains a brief description of the nature and the mechanics of ultrasonic waves, and the second section contains a description of the proposed sensing methodology and the experimental design. The tests and test procedures are discussed in chapter 4 along with the results. The final conclusions, recommendations for future work, and the application areas are discussed in chapter five.

2. LITERATURE REVIEW

The output of a machining operation is highly dependent on a set of input parameters that can act either collectively or independently. In addition, the performance criteria of machining operations are in direct conflict with each other, for example, a faster metal removal rate result in an increase in the tool wear rate. In order to optimize the overall operation's performance, a thorough understanding of the causes and effects is necessary.

A list of the major dependent and independent variables of a machining operation was provided by Kalpakjian [77]. The dependent variables are:

1. The surface finish of the work piece
2. Wear and tool failures
3. The rate and overall energy consumption
4. Temperature rise in the workpiece, chips, and tool
5. Type of chips produced

These variables are dependent on a set of input variables that are:

1. Tool material and its condition
2. Tool shape, surface finish, and sharpness
3. Workpiece material, condition, and temperature
4. Cutting conditions, such as speed, feed, and depth of cut
5. Cutting fluid, type and application
6. The machine tool dynamics

A change in one or more of the input variables has a direct impact on the state of one or more of the dependent variables.

The objective of this work is to explore the feasibility of a direct on-line active ultrasonic sensing method for turning operations. To achieve this goal, the current methodologies are reviewed and critiqued. In order to provide a meaningful critique of the current sensors, it is necessary to discuss them within their application environment. A limited review of the mechanics of turning operations, the tools involved, and the problem areas are presented. A literature review is then presented of on-line sensing methods.

2.1 Turning Operations

Turning parts on a lathe is accomplished by the use of a single point tool, in oblique or orthogonal configuration to the workpiece. Orthogonal cutting refers to the overall cutting edge of the tool being perpendicular to the direction of the relative work-tool motion. Consequently, oblique cutting is the general case in which the tool is not perpendicular, (Figure 2.1). The general case of oblique cutting is a three-dimensional cutting problem, while in orthogonal cutting the problem reduces to a two-dimensional case.

The mechanics of machining operations through chip removal are mostly the same. In all cases, the cutting action is accomplished by the cutting tool's motion across the surface of the work material at some speed, feed, and a depth of cut. The tool motion forces the material ahead of the tool into compression, and small amounts of material (chips) are continuously sheared along what is called a shear plain. The chips can be continuous, discontinuous, irregular, and some with built-up edge. The type of operations, machine selection, and cutting tools used depends on the original geometry and mechanical properties of the work material, along with the final requirements for the workpiece, such as shape, tolerance, surface finish, complexity, and the cost.

2.1.1 Single Point Tools

The traditional cutting tool on a lathe, shaper, and boring mills, is called a single point tool. This type of tool consists of two parts, a cutting part and a shank. The shank of the tool is the part that is clamped in the tool holder to provide a rigid support. Figure 2.2 illustrates the geometry of a single point tool, along with the major surfaces surrounding it.

The cutting part consists of a major and a minor flank. The corner of the cutting tool is formed by the face and the intersection of the major and minor flanks. The flanks are the surfaces over which the newly machined part surface passes. The face is the surface over which the chips flow. The tops of the major and minor flanks are called the major and minor cutting edges respectively, with most of cutting being performed by the major cutting edge. The corner, which is the intersection of the major and the minor cutting edges, is a small portion of the overall cutting edge, it may be curved, round or the actual intersection of two lines.

There are five principle angles associated with cutting edge of the tool as illustrated in Figure 2.3. These angles play a major role in the performance of the cutting process. The angles are, clearance or relief α_0, rake γ_0, inclination λ_0, principle cutting edge angle (PCEA) ϕ_p, and the auxiliary cutting edge angle (ACEA) ϕ_e.

The forces associated with the cutting process can be broken into three components as illustrated in Figure 2.4. The forces are:

1. Feed force (Px), in the direction of the tool travel along the work X axis
2. Thrust force (Py), in a direction that's normal to the machined surface
3. Main cutting force (Pz), acting in the direction of the cutting velocity vector

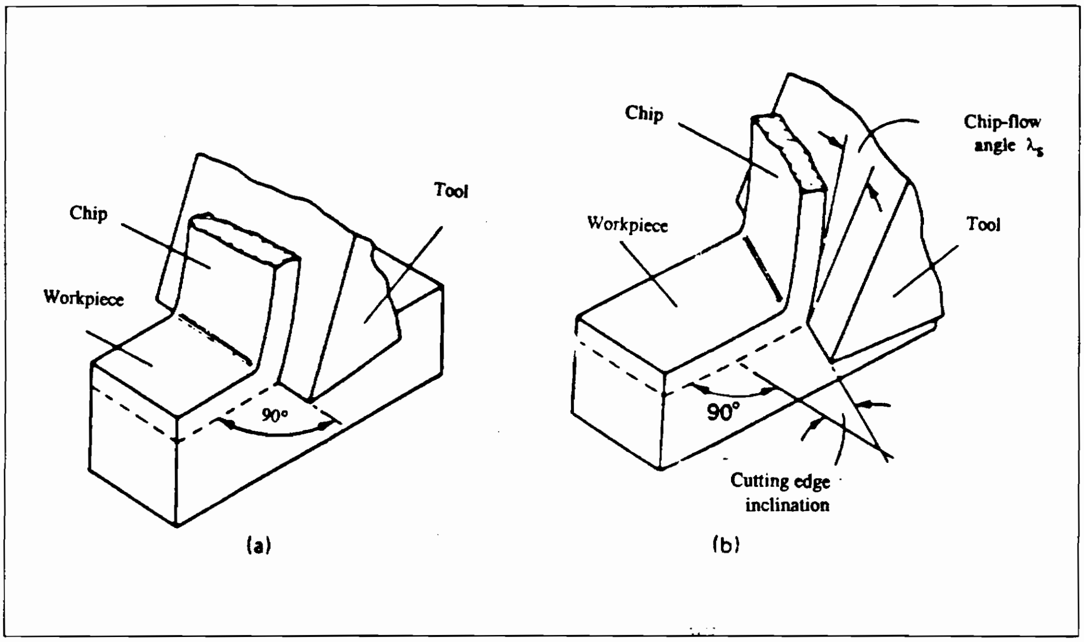

Figure 2.1. (a) Orthogonal Cutting, (b) Oblique Cutting [79]

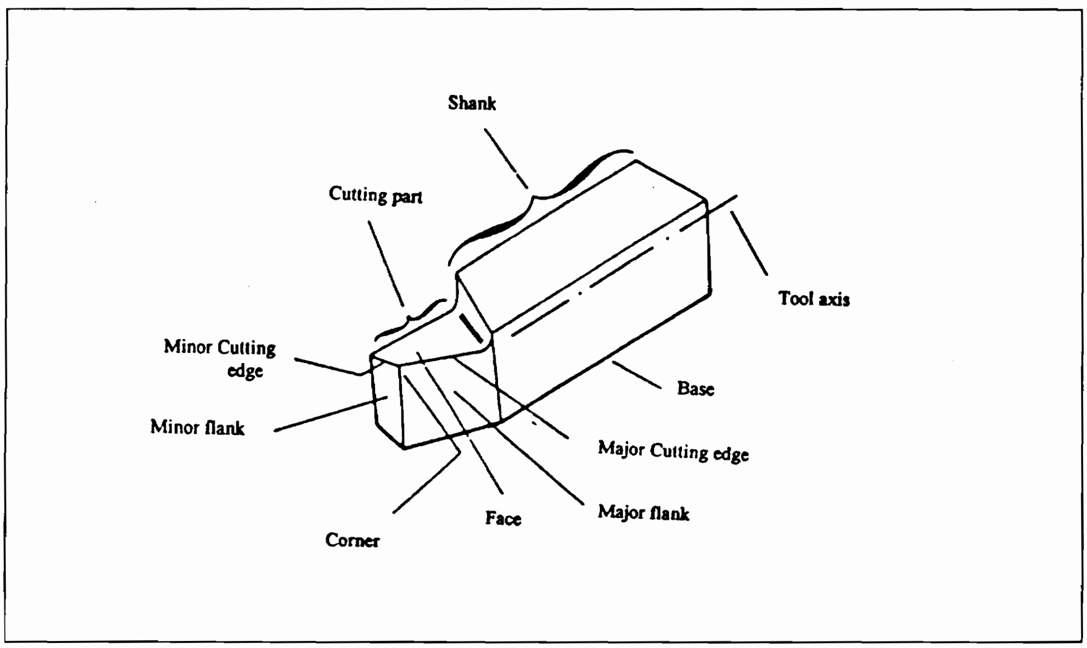

Figure 2.2. Single Point Tool [79]

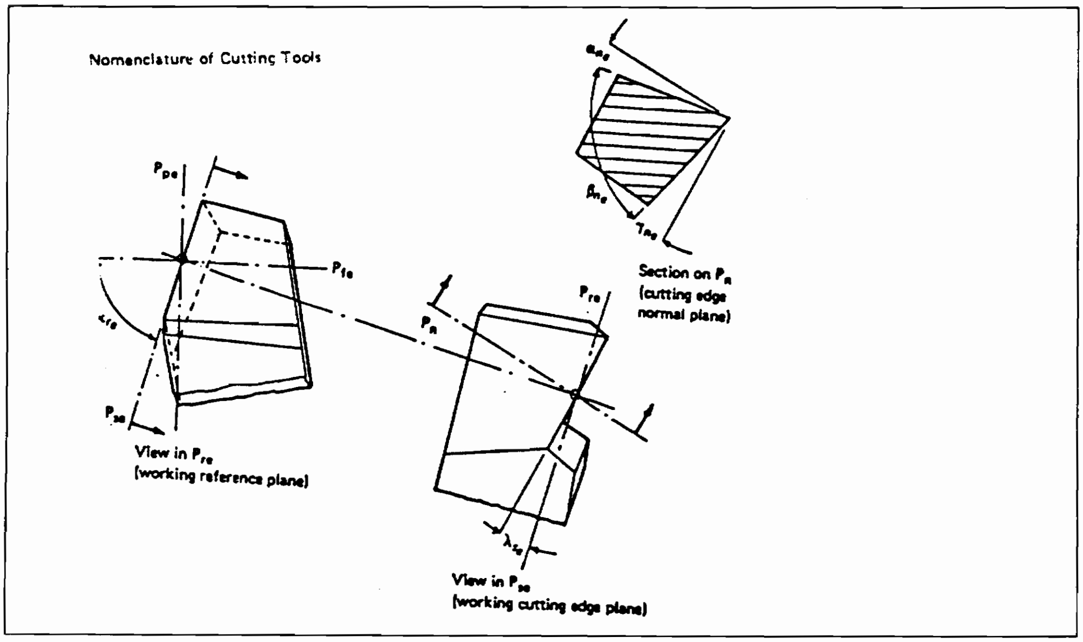

Figure 2.3. Angles Associated with Single Point Cutting Tools [78]

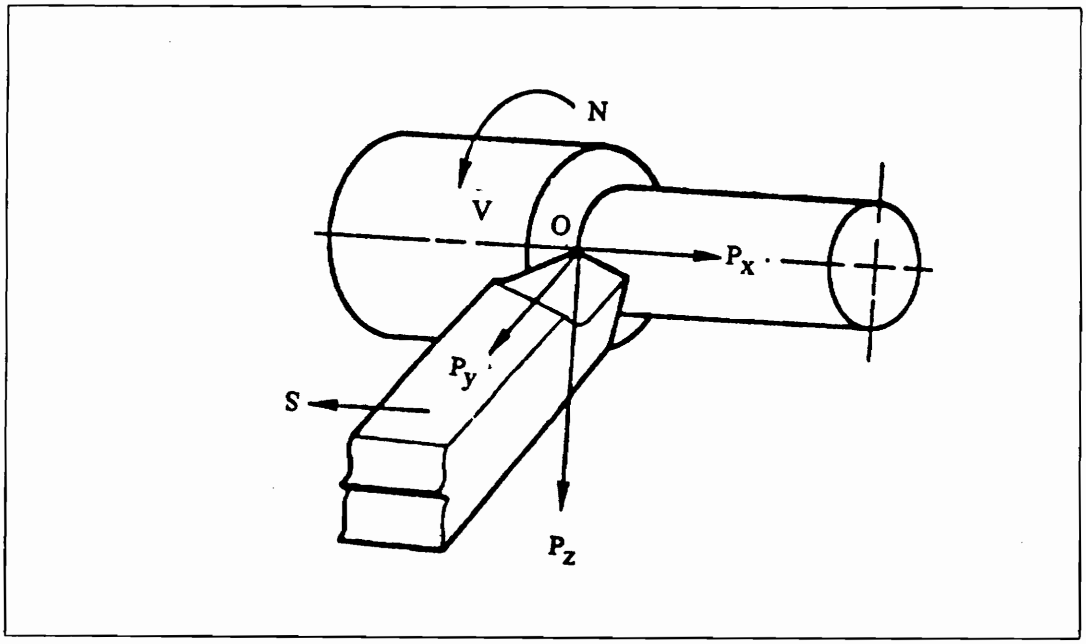

Figure 2.4. Forces Orientation in Turning Operations [79]

2.1.2 Heat Generation During Cutting

Most of the energy involved in the cutting process is converted into heat. This conversion occurs in two primary regions of the plastic deformation, the primary and the secondary shear zones. Another source of heat generation, due to the cutting action, is caused by the friction between the tool and the work. This becomes a factor only in cutting with worn tools, and is mostly neglected. The rise in the cutting tool temperature is mainly due to three sources, which are:

1. Some of the heat generated in the primary and secondary shear plastic deformation zones is conducted to the tool
2. Heat is conducted to the face of the tool by the chips flowing over it
3. Friction between the chips and the face of the tool, and the friction between the tool-work interface

Counter to the intuitive notion that the nose is the hottest part of the tool, the temperature behind the nose, on the face of the tool and directly below the chip flow, can reach 100-200^0 C above that of the nose as can be seen in Figure 2.5. The cutting temperature in some circumstances can reach upwards to 1000^0 C especially during high speed machining.

Built-up edge is formed by layers of material from the workpiece that are gradually deposited through heat and high pressure on the tool. This layer grows in size until it becomes unstable and eventually breaks off to be carried away by the chips and the workpiece. In addition to the damage already caused by the deposits of the broken built-up pieces, the non uniform layer of the built-up edge on the tool is what actually performs the cutting, thus, damaging the dimensional accuracy and the surface finish of the

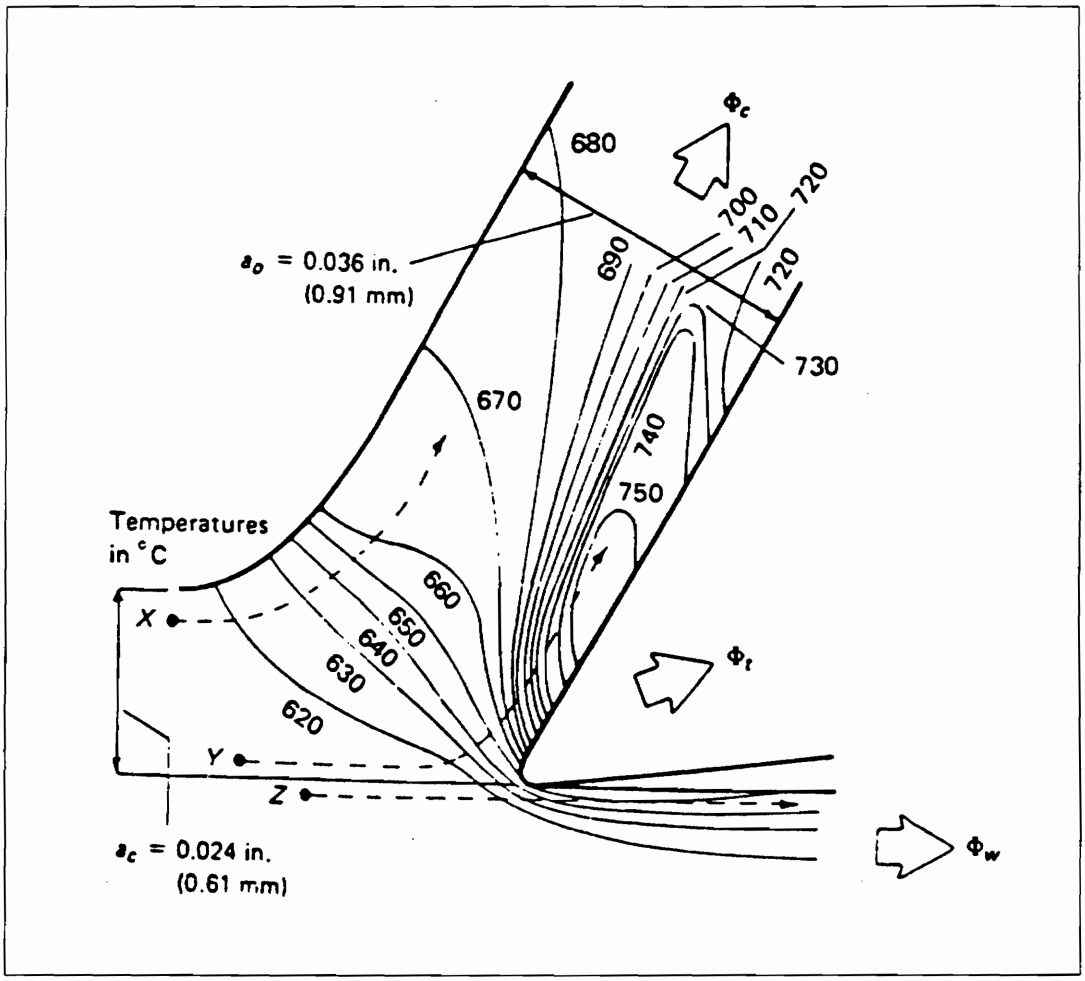

Figure 2.5. Temperature Profile During Cutting [79]

workpiece. Built-up edge commonly occurs at low cutting speeds, and by increasing the cutting speed the built-up edge is reduced or may be eliminated completely.

2.2 Tool Life and Failure Modes

2.2.1 Modes of Tool Failures

A very important consideration in metal cutting is the life of the cutting tools. The cost and time involved in changing or regrinding tools are a major economic consideration in machining operations. The cutting speed, feed, the tool's angles and the cutting fluids, are generally the most influential factors in determining the tool life. Also, the cutting speed and the feed along with the depth of cut are the determining factors of the metal removal rate, i.e., the time to machine a part, therefore, generally a compromise is used which maximizes the life of the tool while minimizing the overall machining time, along with using the appropriate tool angles and cutting fluids.

There are three main modes of tool failure, (1) plastic deformation, (2) abrupt failures in the form of breaking, chipping, and pitting, and (3) gradual wear of certain parts of the face and the flanks.

Plastic deformation. During cutting the stresses and temperatures generated are very high. This could cause the tool to lose its hardness and become deformed, thereby losing its ability to cut.

Abrupt failures. In this mode of failure, the varying mechanical loading of the tool, resulting from vibration, chatter, and or intermittent cutting weakens the tool, thus generating small stress cracks, which could generate small chips or pits on the tool's nose that results in a degraded surface finish. In some cases, catastrophic failures can be caused by the action of very large stresses breaking a chunk of the tool, or a piece of an unstable built-up edge breaking away and ripping with it part of the tool nose. In either case, catastrophic failures cause great deal of damage to the workpiece and possibly the machine.

Gradual wear. This form of wear is inherent in metal cutting and is attributable to mechanisms. The first is adhesion wear, the second is abrasion, and the third is solid state diffusion. This form of wear is unavoidable and is a part of the cutting process. Choosing the correct input cutting parameters can slow down the wearing process. The following is a short description of the three forms of gradual wear:

1. **Adhesion wear.** Junctions between the tool and the work are welded together through the friction mechanism. When these junctions fracture as part of the cutting process, small segments of the tool are carried away along the underside of the chips or by the newly machined surface.

2. **Abrasion wear.** Hard particles on the underside of the chips, mechanically remove particles from the tool face much like the action of sand paper. The hard particles can be either, highly strain-hardened segments of an unstable built-up edge, fragments of the hard tool material, or hard inclusions in the workpiece.

3. **Solid-state diffusion.** The movement of atoms in a metallic crystal lattice from regions of high to low atomic concentration is called solid-state diffusion. The effect is greatly enhanced by temperature and intimate contact between the tool and work. This occurs in a very narrow reaction zone at the interface of the two materials, thus weakens the surface structure of the tool.

Gradual wear is manifested on the tool in two forms, the first is crater wear and the second is flank wear. Crater wear is the wear on the tool face, a short distance in the back of the tool's nose and is shown in Figure 2.6. This form of wear is the result of the action of chips flowing over the face of the tool and coincides with the area of maximum temperature. At high cutting speed, the temperature in this region can reach upwards of 1000^0 C. The combined action of chip friction and solid state diffusion cuts away at the tool surface, thus forming a crater in the face of the tool. Normally, crater wear is not the primary reason for ending the tool life, but under some severe conditions, the crater wear becomes severe, and because of the close proximity of this zone to the tool's cutting edges, the cutting edge weakens and the tool fails.

Flank wear, termed wear land, is caused by friction between the newly machined surface and the contact area on the tool (see Figure 2.6). It forms on both the major and minor cutting flanks. The mechanism of wear acts in such a way as to grind away parallel layers of the tool's major and minor flanks, much as the wearing action of a lead pencil while being dragged along in a constant orientation. The surface of the wear land area is parallel to the direction of the cutting.

There are three phases associated with flank wear:

1. The sharp new tool edge is broken-in very rapidly and a finite wear land is established.
2. A progressive and predictable wear continues in a linear fashion for some period of time (the useful life of the tool).
3. The wear becomes extremely rapid, unpredictable and is accompanied by more heat generation due to increased friction. As a result, the tool then breaks down very quickly ending its life in a somewhat catastrophic fashion.

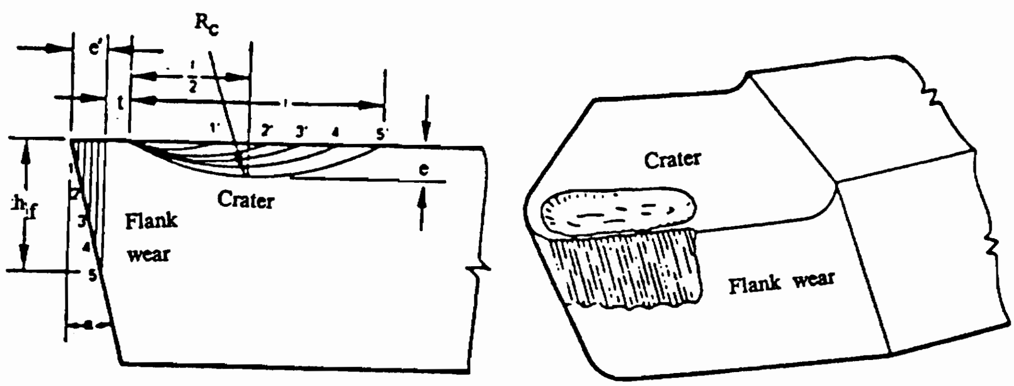

Figure 2.6. Location and Shape of Crater and Flank Wear [79]

The surface finish of the machined part during the breaking-in process is not optimal, which then improves considerably and is maintained for the duration of the second stage, and finally deteriorates in the third stage. Considerable damage could be caused to the workpiece during the third stage of the tool life.

2.2.2 The Criteria for Tool Life

Tool wear is generally not uniform across the flanks, and the depth of the crater wear varies along the area of the crater. In addition, the degree of acceptable wear varies with the location, thus, it is necessary to specify the amount of acceptable wear for each of the primary locations.

Flank wear. The major flank wear zone is divided into three locations, two at the extremities and a central zone as illustrated by Figure 2.7a. The width of the flank wear land at the tool's corner, zone C, is designated VC. In zone N, the other extreme region of flank wear, VN is used for the wear designation. Wear in the central zone of the flank is generally uniform, but in order to allow for variations, two terms are used; VB is used for the average wear and VB_{max} for the maximum wear.

Crater wear. The common criteria used to designate crater wear is the maximum depth of the crater KT, as illustrated by Figure 2.7b. The following are the cutoff values for the useful tool life that's recommended by ISO [78] for centered-carbide tools:

1. VB = 0.3 mm, or
2. VB max = 0.6 mm, if the flank is irregularly worn, or
3. KT = 0.06 + 0.3f, f is the feed

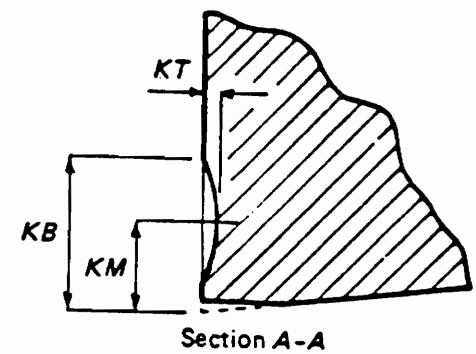

Figure 2.7. (a) Nomenclature of Crater Wear [79]

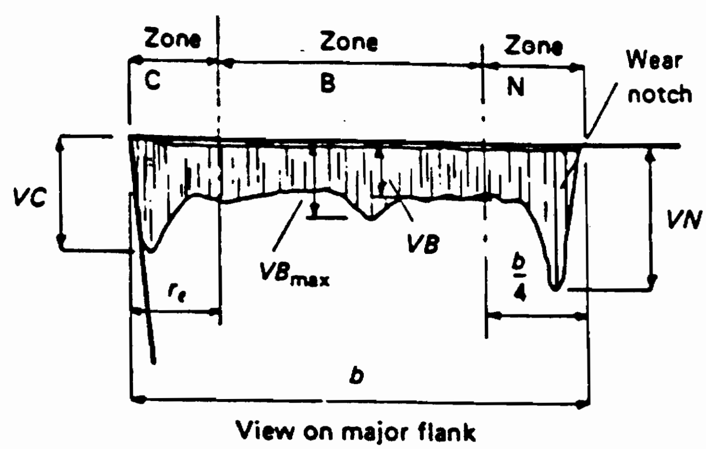

Figure 2.7. (b) Nomenclature of Flank Wear [79]

2.2.3 Predicting Tool Life

Currently, there are no reliable analytical methods for predicting tool life [1,2,3]. The complexity of the machining operation along with the variations in the work materials makes it very difficult to develop a generalized model of tool wear; therefore, empirical tool life tests have been traditionally used and continue to be used throughout the industry.

Under normal cutting conditions, gradual wear of the flanks is the most dominant form of tool wear. As noted earlier, gradual wear is highly dependent on the cutting speed, therefore, under these cutting conditions, Taylor [76] pioneered tool life testing and developed the following empirical equation relating tool life to cutting speed, i.e., the time it takes to develop a certain flank wear VB:

$$\frac{v}{v_r} = (t_r/t)^n$$

where:

- v is the cutting speed
- t is the time to develop a flank wear VB
- n is a constant, a function of the tool material
- t_r is the measured tool life for a given cutting speed v_r

The Taylor equation can be written in the following form

$$VT^n = C$$

where: V is the cutting speed in surface feet/min, T is the tool life in minutes, and C is the cutting speed for 1 minute tool life, in feet/min

The values of symbol n for carbide tools are generally in the range of $0.25 < n < 0.3$, for high-speed steel tools $n \approx 0.125$, and for ceramic tool material $0.5 < n < 0.7$. The value of t_r or C can be determined experimentally, or may be found in tables for a specific workpiece-tool material combination at a specified feed.

2.3 Tool and Process Monitoring

There has been considerable amount of research and experimentation of tool and process condition monitoring in turning operations. Since there is not a single or a multi set of features that are readily accessible, which reflect the state of the process in the various turning environments, many specialized areas of research have emerged along the application, features, and or environment lines. Although the objectives are the same, the monitoring problems have been approached in many different ways.

Traditionally, tool and process state monitoring are referred to as tool condition monitoring to encompass the tool condition, the process state, and the machined part features. Thus, there are several ways of classifying tool and process condition monitoring techniques. The traditional approach is to classify them into direct or indirect methods. The direct methods refer to, for example, measuring tool wear with some type of a sensor, and the indirect methods refer to measuring a feature from which tool wear can be inferred, such as measuring the cutting forces.

Either form of measurement can be performed on-line, off-line, or on-line while the tool is idle; furthermore, some of the measurements can be performed by contact or non contact with the tool or machine. An additional classification is based on the environment of whether wet or dry, i.e., with or without cutting fluids. For the purpose of this work, a distinction is made between monitoring the tool condition and monitoring the process state. Strictly speaking, monitoring the tool condition is the act of determining the presence, geometry, position, and mechanical integrity of the tool; consequently, process monitoring is the determination of the cutting states' performance measures of forces, vibration, chatter, power consumption, torque, temperature, the machined part's dimensional accuracy and surface finish, given a set of inputs of a cutting tool, work material, cutting fluid, specific machine tool, and a set of machining parameters (cutting speed, feed, and depth of cut).

Although the tool condition is effected by the machining process, any direct measure of it, is exclusively attributable to the tool itself. The process state measures are attributed to all the process inputs, with the tool being one of the inputs. On some occasions the tool condition has been shown to be the dominant factor contributing to the process state; therefore, in these circumstances the tool condition can be inferred indirectly from the process state features. For the purpose of the literature survey, the classification used by Dan and Mathew [3] is followed (see Table 1).

Table 1. On-line Tool and Process Condition Monitoring Techniques

	Procedure	**Transducer Used**
Direct	1. optical	TV camera, fiber optics, laser
	2. wear particles & radioactivity	radiation detector
	3. tool/work junction resistance	voltmeter
	4. tool/work distance	displacement transducer, pneumatic gauge
	5. tool geometry measurements	micrometer, optical comparator, microscope
	6. tool presence	contact probes, cameras, many other sensors
Indirect	1. cutting forces	dynamometer (string gauge, piezoelectric)
	2. acoustic emission	acoustic emission transducer
	3. sound, vibration, & chatter	microphone, accelerometer
	4. temperature	thermocouple, work/tool thermocouple, thermo-paints, infrared cameras
	5. part geometry & finish	micrometer, laser, camera, ultrasonic, stylus
	6. current & torque	power and current meters

2.3.1 Direct Methods

2.3.1.1 Optical Measurements

Optical methods are probably the most accurate means of determining tool wear. Accuracy in the range of nano-inches (10^{-9}) can be theoretically achieved depending on the sensor used. The problem, as always, with tool wear in turning operations is that the tool is hidden from view while cutting. The view is obstructed by the cutting fluids and chips (as if the camera or the laser is looking through fog) most of the time, thus, optical measurements are used during idle time or off-line.

The sensor used for optical measurements is typically a camera with either ambient lighting or a coherent laser light. There are three types of methods and/or sensors used in the optical evaluation of the tool and the workpiece while the machine is idle, they are: TV cameras, fiber optics, and lasers. In off-line mode the above sensors can be used in addition to the tool makers' microscope and the optical comparator. They are all direct non-contact measures of the tool and part's geometry. The surface finish can be quantitatively and accurately determined by roughness meters and laser interferometers.

A tool management system using CCD cameras (charged couple device) has been used by Levi et al. [4] to detect tool wear under idle conditions. The camera was coupled to an expert system for the image analysis. Jeon and Kim 1988 [5] used a vidicon camera to image the cutting tool illuminated with coherent laser light. They were able to achieve a 0.1mm resolution in determining the average and peak wear of the flanks. A more recent work by Pedersen, in 1989 [6], demonstrated the capabilities of cameras and digital signal processing in determining tool wear. Pedersen remarked that two major drawbacks to his system were the processing time and non-uniformity of the lenses. Each frame of data required seven seconds of processing time. In addition, he also noted that his system could not resolve the flank areas from the wear notch next to it. Pedersen predicted that with faster processing, better imaging methods, and better optics the system could be viable in determining tool wear in the idle state of the machine.

Giusti & Santochi [7], in 1979, used fiber-optics to detect a threshold level of VB wear. A fixed window containing pre-arranged fibers to carry both the source and the reflected light was used. A simple circuit of threshold detectors matches the reflected light intensity to an original preset level for all the fibers. When the threshold reaches or slightly exceeds the preset levels, the system gives an indication that the tool is worn. It is obvious that this type of system has very limited applications. In order for this system to discriminate, the flank has to undergo wear in the same manner every time and in addition, it cannot evaluate gradual wear. It only gives an indication of one state of wear.

2.3.1.2 Wear Particles and Radioactivity

This type of measurement attempts to determine the overall volumetric wear of the tool. The problems with such systems are the exceptional complications that arise from radioactivity measuring equipment; in the case of chemical analysis, the photo spectrometers are very difficult to operate in the factory setting. Currently there are no commercial systems in operation that are based on any of these methods.

Wear particles' methods are based on the fact that most of the tools' worn particles are carried away with the chips and theoretically the amount of tool wear can be determined by chemical analysis. Uehara [8,9] 1973, in 1974, developed a methodology by which he detected the tungsten particles that were carried away by the chips. The cuttings were chemically treated and filtered by a 0.1 μm filter, leaving the tungsten derivatives suspended in the solution. Spectroscopy is used to determine the concentration of the tungsten derivatives and thereby determines the tool wear.

The underlying assumptions for this method are:

1. That the chips carried all the worn tool particles
2. That all the chips were recovered
3. That all the tungsten derivatives were separated and suspended in the solution by the chemical process, and removed by the chemical process
4. That in the presence of many elements in the solution spectroscopy is capable of accurately measuring the tungsten derivatives

If one can be assured of all the above, the final problem would be identifying the location on the tool of the recovered wear particles.

Fluoroscopy is another method used to determine the overall volumetric wear. Ham et al. [10] in 1968, and Uehara [11] in 1972, used fluorescence to determine the concentration of the wear particles carried by the cutting debris. The cutting debris samples were bombarded by an electron beam, thereby causing the wear particles to fluoresce in the X-ray region. A spectrometer is then used to determine the intensity of the radiation emitted by the worn particles, which is translated to a volumetric tool loss.

Radio activation was used by Cook [12] and Arsovski [13] in 1980 to determine the volumetric wear loss. The method involves activating the tool by bombarding it with neutrons or charged particles. In such a case, the wear particles will become radioactive. The particles' radioactive concentration can be determined by surveying the cutting debris with radiation detectors, and thus the volumetric wear is determined.

Another method of determining the tool life is achieved by attaching radioactive tracers to the tool [12]. At each cycle stop, the tracer's level of radioactivity is measured. The tool is considered worn when the radioactivity ceases.

2.3.1.3 Tool/Work Junction Resistance

The tool /work contact area is used in this type of methods. It either measures the conductivity or the resistivity of the contact area. The assumption is that the contact area is a direct function of tool wear; thus, the measurements can be correlated to tool wear. Variation of the feed and the thrust force can alter the contact area, thereby confusing the overall measurement. In addition, this process cannot evaluate the crater wear and micro cracking.

2.3.1.4 Tool/Work Distance

The distance between the tool holder and the workpiece is constantly decreasing due to wear; therefore, by measuring this distance, one can infer the degrees of tool wear. Several types of sensors have been used to measure the distance between the tool holder and the work. An electric feeler micrometer was used by Takeyama [14] in 1967. Pneumatic gauges were used by Bath et. al. [15] and Stoferle [16] et. al. Suzuki and Weinamann used a stylus with a displacement transducer in 1985 [17]. Since the tool/work distance is effected by thermal expansion, vibration, part deflection, and the inherent machine motion errors, the overall effectiveness of these methods is at best shaky; furthermore, repeatability tests of device [17] showed a 10% variation in the final distance measured and in addition, none of these methods addresses crater wear.

2.3.1.5 Actual Tool Geometry Measures

Obviously the tool wear can be measured off-line by an optical comparator, tool makers' microscope, micro calipers or any other means. Tool wear can be determined precisely with this method, but it leads to considerable down time each time the tool is measured. Meanwhile the tool can suffer a catastrophic failure before the next measurement. Many tools with a small remaining tool life will be discarded since the tool's expected remaining lifetime may be shorter or close to the measurement cycle time.

2.3.1.6 Tool Presence and Breakage

Currently, in automated machining cells, the presence of or a broken tool can be determined by various methods. TV cameras can verify the presence of the tool and with reasonable processing can also see large chips or tool breakage. Contact probes are another type of sensor that is commonly used for this purpose. The down side of these systems is that they are difficult to operate and maintain in the dirty and hostile machining environment, along with the restricted applicability due to the obscured vision caused by the chips and cutting fluids. Generally, these measurements are conducted while the tool is idle, and if there is no dead time between operations, the process consumes valuable time. Verifying the tool presence after tool exchange is an important feature of these systems along with the detection of broken tools. Unfortunately, the detection process is after the fact, since the damage would have already occurred.

2.3.2 Indirect Methods

2.3.2.1 Cutting Forces

Cutting forces have been used extensively as indicators of tool wear. The attractiveness of cutting forces for wear estimation is the intuitiveness of the concepts coupled with the ease and reliability of the data acquisition. Many cutting force methods for estimating tool wear have been developed. One or more of the force components are either used directly or the ratio between the forces may be used.

The three components of the cutting forces are measured with a three-axis dynamometer. On a lathe, the dynamometer is typically bolted on the cross slide with the tool holder bolted to it. Sometimes the rigidity of the setup may be in question, but in most applications it can be made rigid enough. The classic dynamometer uses strain gauges for sensing the forces and more recent ones use piezoelectric materials in place of the strain gauges. In either case, the accuracy of the measurement has not been disputed exceedingly. The general assumption is that the dynamometer measurements accurately represent the cutting forces.

It is intuitively obvious that cutting with a sharp tool takes less energy than cutting with a dull tool. In turning operations, this notion certainly holds true. As was pointed out earlier in this chapter, the cutting forces during turning operations are a function of several variables, some of these are:

1. Prescribed tool geometry
2. Work material (type and uniformity)
3. Depth of cut, along with the size effect
4. Feed and cutting speed
5. Cutting fluid type and application
6. Temperature
7. Tool wear

In order to predict tool wear or fracture from the cutting forces, one must be able to isolate its effect from all the others; as such, the literature is rich and abundant with methodologies for achieving this goal.

Prior to 1965, the general accepted thought was that the cutting or tangential force was influenced most by tool wear. The experimental results of Takeyama [14], in 1967, showed that the feed and thrust forces are influenced much more by tool wear than the main cutting force. Additional experimental work [18,19-22,23] has also demonstrated this phenomenon. In 1976, Langhammer [19] claimed, that in some regions a linear relationship existed between the feed and thrust forces with tool wear. The prominence of the feed force was highlighted in another form by Uehara [20] in 1979. The results of this work showed that the curve of the feed force Vs the feed rate/revolution was strongly influenced by tool wear. The two modes of wear, flank and crater, had to be isolated and each represented by a separate curve. The initial wear components were determined in pre-cut tests. By measuring the peak height of the curve in the wear region, the values of VB and KT were determined from their respective curves with .15 mm and 20 μm resolution respectively. Uehara also noted that his method was effective in detecting chipping of the cutting tools.

The normal force component was used in 1987, by Koren et al. [24] to develop a parametric based model approach for on-line tool wear estimation. The model uses the normal force as the standard measured variable. This is used to drive the on-line parametric model for tool wear estimation. The model's accuracy was tested by simulations and cutting tests. The authors reported that the estimated and the actual wear data were in close agreement, however, the estimated results were consistently higher in value. It was also noted that early stages of tool wear could not be predicted and that the model fails to identify tool breakage.

Lindstrom and Lindberg [25], in 1984, used a piezoelectric sensor to measure the cutting forces. The piezoelectric material was placed directly under the insert and a conventional accelerometer was placed on the tool holder. After conducting more than 400 different cutting tests, the authors concluded that the force signal is much better than the accelerometer signal for representing chip formation mechanism and for the detection of tool wear. The authors presented several samples of their work that showed correlation between the force signal and major flank wear.

In 1986, Lister and Barrow [26], disputed the values of the thrust and feed force in detecting tool wear. They claimed that the main cutting force was the most reliable component for estimating tool wear. Their experimental work showed that below an average flank wear of 0.508 mm the feed force is linearly related to the wear and in addition, this relationship was heavily influenced by the feed rate. In the case of finish turning, at low feed rates, the increase of the feed force due to wear was negligible at low feed rates.

Colwell [27] used a ratio of the feed force to the main cutting force to derive an index of tool dullness. He reported that this ratio was sensitive to dullness (tool wear) at all force magnitudes, and that it was much more pronounced at the start and the end of cuts. Furthermore, the dullness ratio appeared to be insensitive to the depth of cut.

In 1986, Mackinnon et al [28] developed a wear index called ω_{index} for the flank wear land. The index was derived from the ratio of the cutting force over the feed force and ω was dubbed as a percentage wear index of a new tool, i.e., with ω =100% for completely damaged tools. The authors reported good results for detecting damaged or broken tools, but the accuracy of detecting intermediate wear was not demonstrated.

Another major aspect of cutting forces is tool breakage or fracture detection. Tulsty and Andrews [22] reported, in 1983, that an interrelationship exists among the three components of the cutting forces. It was reported that when a tool breaks, the magnitude of the three forces increases suddenly, followed by a large drop to zero, and increased again beyond the original values. This pattern of change in the forces can be used as a reliable indicator of tool breakage.

Lan and Dornfeld [29], in 1984, presented a summary of competitive views. The summary addressed the behaviors of the cutting forces during tool breakage or fracturing. The first view postulates that cutting forces initially increase due to the squeezing of the chipped or broken particles between the cutting edge and the work and the forces decline to zero as the fragments move out of the way. In the case of micro chipping, there is a noticeable sudden and permanent increase in the feed force. The second view claims that both the tangential and the feed force are sensitive to tool fracture. In the case of broken tools, the tangential force is the only one that exhibits consistent change in magnitude. The magnitude of the tangential force consistently decreases proportionally with the fractured length along the tool edge. The magnitude and sign of the change in the feed force during tool chipping are unpredictable.

2.3.2.2 Acoustic Emission (AE)

Acoustic emissions are caused by the release of stresses during the cutting process. Plastic deformation and fracture are the most significant sources of AE. The frequency spectrum and the amplitude of the stress waves are a function of the metal removal rate. Since the source of these waves is the tool-work interface, and in most cases, the detection transducers are some distance away from the source, the received signals are highly dispersed and cannot be analyzed by the normal time-domain or frequency-domain analysis. Instead, statistical analysis methods are used.

The most commonly used methods of analysis are:

1. The number of counts and the count rate: the record of the signals with an amplitude that exceeds a preset threshold

2. Amplitude distribution analysis: a count of the number of acoustic bursts with an amplitude that falls within a range
3. Frequency domain analysis: the over all power distribution in the various spectrum regions
4. Auto correlation analysis: the comparison of two similar signals shifted in time by Δt
5. RMS evaluation: the root mean square of the signal amplitude

One of the first studies that attempted to derive a statistical model of acoustic emissions was conducted by Kannatey-Asibu, Jr. ȧnd Dornfeld [30] in 1981. The r.m.s. emission values from cutting were modeled as a β distribution. The skew and kurtosis of the assumed distribution were sensitive to the stick-slip transition for chip contact along the tool rake face and to progressive tool wear on the flank of the cutting tool.

In earlier work by the same authors in 1981 [31], attempts at deriving a quantitative relationship for AE in orthogonal metal cutting were made. The energy content of the AE signal was related to the plastic work of deformation that's generating the emissions. The r.m.s. signal value was expressed in terms of the basic cutting parameters. The relationship was developed for emissions generated by sharp tools. The shear zone and the chip-tool interface were the only two sources of emission considered. The stressed zone was discounted as a source of emissions since, in their opinion, this zone would have already been deformed and rigid, thus unlikely to produce any emissions. A methodology was presented for isolating the shear zone generated emissions and the chip-tool interface. Results of the experimental work were presented to verify the proposed theoretical model. The authors concluded that their method was capable of monitoring tool wear, on the tool face or the flanks by emissions.

An analytical model was developed by Chryssolouris and Domroese [32] to correlate the RMS value of the AE signal with the total power expended in the cutting process. In this model, the proportion of total power expended in generating AE is considered to be dependent on whether the power increase was due to an increase in the cutting forces or due to an increase in the cutting velocity. The authors reported that in this model the cutting forces and cutting velocity are much better represented by the RMS of AE than any previous models. The model indicates that the amount of energy that goes into producing acoustic emissions is not constant, instead, the proportion is larger if the power increase is due to an increase in the cutting speed rather than an increase due to the cutting forces. The authors cited that with this model it is more feasible to develop an on-line approach for detecting tool wear from acoustic emissions.

A more recent attempt in 1988 [33] at detecting tool wear and breakage was based on pattern recognition of the emission spectra. Base pattern spectra of a variety of worn tools were acquired under controlled conditions, and later used by an expert system for pattern match recognition. The results of the analysis showed that the most reliable band of spectra for AE evaluation of tool wear is in the range of 100 kHz-1 MHz. Normal wear was shown to have emissions in a narrow range between 400-700 kHz, whereas catastrophic tool failures tended to have a much broader range. The accuracy of this method was reported to be in the range of 84-94% for detecting total tool failures, with no predictions given for progressive tool wear.

The gradual increase in the AE signal level was used by Innsaki and Yonetsu [34] in 1981 to measure gradual flank wear. The authors reported that the amplitude level of the acoustic signals increased almost proportionally with the cutting speed and was not effected by the feed or depth of cut. The level was also reported to depend strongly on the flank wear. The regions of the spectra that responded to tool wear were in the 120, 170, and the 210 kHz bands.

Iwata and Moriwaki used event counting to detect flank wear [35]. The authors reported that the total count of acoustic emission events correlated with flank wear, and can be used as an index for on-line tool wear sensing. The spectra as a whole was reported to increase with wear, but the frequency band of 100-250 kHz exhibited the largest increase. The major obstacle reported by the authors was selecting the correct discrimination level of the signal for the various setups.

In a similar study conducted by Dalpiaz [36], in 1988, the spectra were reported not to exhibit a definite trend with tool wear but increased, in general, along with sudden variations related to the deformation process. The author later proposed [37] a monitoring method based on the cumulative energy count. The counts were reported to correlate well with flank wear under different cutting conditions and tools. Thus, the method could serve as an early warning of tool deterioration.

Tool chipping and fracture were also studied extensively by several authors with some promising results. Lan and Dornfeld [38] in 1984 investigated the acoustic emission generated by tool fractures. They concluded that during fracture, the amplitude of RMS energy of burst AE due to tool fracture is dependent on the fracture area, while the peak amplitude was insensitive to chip formation. It was further concluded that chipping produces substantial changes in acoustic emissions RMS level, rather than the burst types produced by fracturing. Thus, it was concluded that AE is sensitive to tool fractures and AE analysis is a viable method for on-line detection of tool failures.

Inasaki et al [39] in 1987, defined the amplitude level of the AE signal as the mode of the probability distribution function of the signal, and used this method to detect tool chipping. The values obtained at the beginning of the cut were used to normalize the calculated AE amplitude modes. The ratios of the modes increased in steps immediately after chipping. Marked reductions in the ratios were observed in situations where the chip was large enough to effectively reduce the depth of cut. The power of the spectra in the 0-300 kHz region undergoes noticeable increase when the cutting tool chips. It was reported that a 90% success ratio of tool fracture detection could be obtained if the appropriate discrimination levels were set for the ratios.

A more recent study conducted in 1989, by Ramalingam and Frohrib [40] used a wide band, acoustic emissions, thin film transducer for on-line detection of tool chipping. To avoid interfering with the cutting operation, the transducer was bonded to the bottom of the insert for protection. The authors reported that they were successful in detecting tool failures in both milling and turning operations in approximately one millisecond.

In one of the latest efforts of AE analysis, in 1992,[in press] Diniz et al. reported that the surface finish of the workpiece, tool life, and tool wear can be correlated to the acoustic emissions during machining. The authors reported a good potential for monitoring the surface roughness growth in finish turning when zero crossing rates, RMS signals' standard deviations in the frequency band of 50-500 kHz, and with RMS signals' standard deviations in the frequency band of 200-300 kHz. For this form of processing to be viable, on the factory floor, the authors noted, that the processing would have to be done by hardware.

2.3.2.3 Sound and Vibration

The cutting action generates low frequency noise due to the rubbing action of the tool and workpiece. Researchers [42] used this result to study the tool and process condition. A large increase was reported in the frequency band between 2.75-3.5 kHz. The noise level increased mostly during the tool breaking process followed by noise level saturation. The overall noise level decreases with a decrease in cutting speeds, and increased for longer overhang of the tool.

For a large variety of workpiece-material combination, the machine's base noise was restricted to the frequency band of 4-6 kHz [43]. Although this band of noise showed good correlation with tool wear in the lab, it would be very difficult to implement any acoustic type measurement on the shop floor, due to the large amount of background noise in this band

Generally, vibration measurements are measured with acceleration transducers. The measurements are generally reliable and their location on the machine tool is not as critical as the acoustic emission transducers. Vibrations from the tool's rubbing action and work can be easily measured and used for tool condition monitoring. A discrete model, data dependent system (DDS) was developed and used [44,45] for measuring tool wear. In 1969, Weller, et al., [46] constructed a vibration tool wear detector. The transducer was placed on the machine's tool block. It was determined that regardless of the variation of the speed and feed the total amount of vibration energy in the 4-8 kHz band increased as the wear land of the tool increased.

Earlier, in 1967, Del Taglia, et al., [47] studied the mutual relationships between tool wear and the vibration power spectrum of the tool. The authors noted that small increases of tool wear (1.3~1.5 mm) results in a seven-fold increase in the total power of the acceleration signal in the frequency band from DC-2.5 kHz. Further increase in tool wear resulted in the reduction of the power of the previous spectra. Thus, for wear of up to 1.5 mm, the DC-2.5 kHz band of spectra can be used for tool wear analysis.

In 1987 Jiang, et al., [48], divided the tool wear process into five stages and used spectral cascades in the lower frequency region of DC-1 kHz to identify these five stages of wear. The five stages are:

1. Initial wear
2. Normal wear
3. Micro-breakage wear
4. Rapid wear
5. Tool failure stage

This method was shown to be very sensitive to micro-breakage failures. The power of the vibration signal increased on order of magnitude as a result of micro-breakage over that observed for normal wear. This same mode of tool failures has very little effect on the tool's geometric shape, as well as on the cutting forces and temperature.

In 1993, Owen [2] summarized the state of vibration measurements on the factory floor as follows, "Accelerometers tend to be easy to install, but separating tool condition signals from process and machine vibration is a challenge for builders of these systems."

2.3.2.4 Temperature Measurements

As was noted earlier in this chapter, large portions of the work of plastic deformation during the cutting process are converted into heat. In addition, the friction between the chips and tool face along with the rubbing action of the tool flanks on the work generate additional heat and as a result of both actions, the tool's nose and face temperature can reach upwards to 1000^0 C. Under these conditions High Speed Steel (HSS) tools becomes soft, thus accelerating flank and crater wear. In addition, the tool's geometry may become deformed thereby contributing to more heat generation.

On-line monitoring of the cutting tool's temperature is a very important function for the life of the tool. Avoiding situations that lead to excessive heat generation can prolong the tool life and improve the product quality.

The methods of on-line temperature monitoring are classic, with very little advancements over the years. Basically, four methods are used, which are:

1. Tool-work junction thermocouple
2. Thermocouples placed on the tool
3. Optical thermometry
4. Thermochemical reactions

The measurements are either point wise, as in the case of the tool-work thermocouple and placing a thermocouple on the tool, or overall, such as in the case of making measurements of the tool's face temperature with an infrared camera.

Since the temperature of the tool is variable and is a function of the location on the face, it is very difficult to obtain an accurate estimate of the tool's temperature with a single thermocouple or with the tool-work junction methods. As was pointed out earlier in this chapter, the tool's nose and the crater areas are both covered with chips; therefore, infrared methods are not truly representative of the overall temperature.

The tool-work junction thermocouple method has been used by several researchers [49,50-54] to measure the tool temperature and predict the tool's condition. The hot junction is formed by the tool-work contact, and the cold junction is taken somewhere along the far end of the workpiece. Since the voltage level generated is extremely small, ordinary slip ring joints cannot be used; therefore, in order to minimize the electrical noise, a mercury bath, slip joint is used.

Calibration of this type of junction is extremely difficult since it is obviously a function of the workpiece and the tool's material. The calibration has to be performed statistically, and as such several concerns arise, such as duplicating the actual cutting conditions and the surface area contact of the tool-work junction; in spite of these, several calibration methods evolved, which are:

1. Heating furnace for the whole set up [55]
2. Induction heating of the tool and work [56]
3. Resistance heating of the junction [57]

The accuracy of the tool-junction method is questionable since the e.m.f measured is a collection of the e.m.fs generated by all the junctions in between the tool-connector side, the workpiece side and the rest; therefore, one must assume that this measurement is basically an average or can be considered as a differential type measurement [58].

Single point thermocouple measurements were made by several researchers [59-62]. The thermocouple can be embedded in the tool or placed on the surface. The resulting measurement is representative of the specific location where it was made. Several measurements can be made at various locations to obtain the temperature distribution of the exposed surface. Balint and Brown [63] traced the temperature of the exposed tool surface and used extrapolation techniques to predict the temperature of the tool nose and crater area.

Schwerd used a radiation pyrometer [64] to measure the surface temperature of cutting tools. The area of investigation was isolated to 0.2mm in diameter. The results were promising as a lab instrument, but clearly not feasible for the factory floor.

Boothroyd [65] and Mayer [66] successfully used infrared photography to image the tool surface and the chip temperature distribution. The calibration of such a system is fairly simple, and is accomplished by photographing a known hot source in the same view as the targeted area.

Finally, thermochemical reactions are used in the form of heat sensitive paints for monitoring the tool's temperature. The paint is spread over the visible areas of the tool and change colors at certain temperatures. The change of colors generally lags the temperature changes and small variations are difficult to detect.

2.3.2.5 Part Geometry and Finish

The standard methods for on-line part gauging and surface roughness measures on a lathe are techniques. Optical sensors have the advantage of high resolution and can be used in a non-contact mode. In wet machining, the cutting fluid flows over the part in a random manner, this makes it difficult, if not impossible, to perform optical measurements of the part geometry and surface finish. Since most of the turning operations are wet, this severely restricts the utility optical measurements.

The accuracy and resolution of optical measurements are a function of the processing, the type of light (coherent or incoherent), and the wave length. Defects, in the order of nanometers, can be easily imaged by the use of laser and interferometer techniques. Light can be shined directly from the source on the workpiece or can be carried from the source to the work via fiber optic cables. In either case, the methodology, resolution, and processing are the same.

TV cameras can be used for imaging, but the resolution and the field of view are highly restricted. To achieve micro-inch resolution, the camera would have to be equipped with a high power telescope and lighting becomes extremely critical; therefore, cameras are, in general, used for recognition and or inspection of larger features.

Spirgeon and Slater used a fiber optic transducer in 1981, to measure surface roughness during finish turning [67]. The transducer was used to trace the part along the same path the tool traced. With this method, the authors were able to achieve 1~3 μm resolution.

Other researchers [68] used a pair of optical reflectors to measure the surface roughness. A 40μm resolution was achieved with this method. The authors also reported, that this method could detect on-line the slightest change of the cutting edge due to chipping or wear.

On-line part gauging with lasers was demonstrated by several authors [69-74]. In 1981, Colding and Novak [74] reported that they were able to measure parts on line with an accuracy of 1μm, and for specific applications the accuracy could be improved further.

Another method for sensing or gauging the part diameter on-line was illustrated by Gomayel and Bregger [75] in 1986. The change of the received voltage from a pair of electromagnetic transmitter receiver pairs was used to measure the part diameter and tool wear. The use of two pairs of transmitter-receivers compensates for the part deflection and vibration. The device was reported to achieve high accuracy in determining flank wear on the order of μm.

An ultrasonic methodology for part gauging in wet turning was proposed in 1974 by Lemelson in the United States, Patent No. 4,118,139. Lemelson proposed that a fluid squirting system could be used to squirt cutting fluid on the part at the opposite end of the cutting tool. The ultrasonic transducer was to be placed at the back of the fluid squirter. Thus, the stream of fluid would provide a direct acoustical coupling mechanism of the ultrasonic waves and the part. This negates the effect of the free falling cutting fluid on the work. There is no evidence that Lemelson pursued the work further or developed a prototype of the system himself.

In 1990, Reed [76] built a commercial ultrasonic on-line part gauging system based on Lemelson's concepts. The two-way time of flight of the ultrasonic waves and the amplitude of the reflected waves is used to both measure the part diameter and surface finish. A 0.0002 of an inch accuracy in measuring part diameters was reported by Reed. No surface finish accuracy values were reported. Reed informed this author in a personnel conversation, that this system is in successful operation at the shop floor of United Technology's Aircraft Engine Division (Pratt and Whitney). The main drawback of Reed's system is that it lags the cutting tool by 1/16th of an inch; so, in the case of catastrophic failures the part would have already been ruined.

2.3.2.6 Current and Torque

During cutting, the current of the drive motor is related to the cutting force; thus, less current will be used when using a sharp tool. The power consumption increases with tool wear; as such, it can be used to predict the overall condition of the tool. The spindle induction motor's current of a CNC was monitored during tool breakage. The current dropped substantially when the tool broke and then recovered soon after to a level lower than the original current level. During normal cutting operations, current data was used to dynamically develop a lower cutoff limit for current consumption rate. Tool breakage was detected when the current level dropped below the established lower limits.

2.3.3 Systems and Methods on the Shop Floor

Of all the systems and methods that were described above, only a few are in application today on-line in industrial settings. The systems are typically rugged and generally give an overall indication of tool wear and machine tool vibration. In 1993, Owen provided a survey of the current applicable sensors and methodologies [2]. According to the survey and my detailed literature search, there are no direct on-line tool wear or temperature measuring systems in application on the shop floor to date. The methods, which are in use now, are:

1. Probes
2. Vibration and Acceleration
3. Load/ Power
4. Acoustic Emission
5. Force

Probes. The probes, which are generally used to check for the presence or tool breakage, swings into position to make contact with the tool. If contact is made, the tool is assumed to be in good condition. This is usually used for taps, reamers, and form tools. The probing function is conducted between cycles. The probes are subjected to dirty environments, fluctuating temperatures, hammers, cutting fluids, and dynamic changes, which cause them to get gummed up and or bent, thus causing them to malfunction.

Vibration and Acceleration. Absolute acceleration and vibration are measured in most machining operations. Sharp tools have a different signature than duller tools. So that, as the tool dulls, the vibration or absolute acceleration increases, thus indicating tool wear. This method is used for detecting dull or broken tools.

Load/ Power. This is the oldest method of predicting tool wear. The spindle component of the power consumption is measured and is related to the tangential cutting force. Increases in this force component indicate tool wear. The critics of this method claim that it is not sensitive to tool condition and is slow to respond to tool related events. None-the-less, it is still widely used.

Acoustic emission. AE is usually used to monitor tool breakage and chipping. The acoustic emissions in the 10-200 kHz range increases or spikes substantially when a tool breaks or chips. This method has the advantage of being able to monitor the emissions of several machines at once.

Force. The current commercial systems are mostly piezo-electric sensors of the three force components. These were discussed in detail earlier, and are generally used to detect large wear, tool chipping, and tool failures. Although the sensitivity of the feed force in detecting tool wear and chipping was greatly debated by several researchers, the feed and the radial forces were shown to be highly sensitive to tool chipping while it was completely missed by the tangential force component. This was demonstrated by a system built by Monotronix and is commercially available and is in use.

Force/Acoustic Emission. A combination of Force and Acoustic emission sensor is currently under development at the University of Minnesota. This sensor form is made into a flat small sheet, which is placed under the tool insert. This has the advantage of lowering the cost, reducing the noise associated with AE, and giving better rigidity for force measurements. The researchers claim that they will have a hardened version ready for the shop floor soon.

2.4 Summary

There have been several tool and process condition monitoring methods developed, yet, few if any, made it to the shop floor. The direct methods are inherently restricted to off-line or machine idle situations. The indirect methods by their nature are not capable of measuring the level and location of gradual wear. In addition, the reliability of indirect methods is well below industrial expectation.

As was stated in the introduction, currently, there are no reliable sensors for determining on-line gradual wear, cutting temperature, tool probing, and BUE. Furthermore, due to the space and economic restrictions, the number of sensors must be limited to a minimum. Therefore, the need still exists for reliable integrated sensors capable of providing accurate, fast, and robust measurements of more than one of the relevant machining parameters economically. In addition, the format of the sensor's output has to be compatible with CNC machines and other types of industrial controllers.

3. ULTRASONICS AND RESEARCH METHODOLOGY

3.1 Ultrasonic Waves and Methods

The use of ultrasonic waves in flaw detection and material characterization has been very successful and is well documented. Wide range areas of applications have been developed such as medical imaging and diagnostics, weld inspection, gauging and many others. The popularity and success of ultrasonic evaluation can be attributed to the fact that they are mechanical waves, which can penetrate through the various mediums and are harmless at moderate energy levels. In addition, the physical principles governing the generation, propagation, and analysis are well founded and understood.

The on-line tool and process evaluation, in turning operations, uses ultrasonic waves in a non-destructive mode (low energy levels) to determine several aspects of the cutting process and to determine the condition of the cutting tool. In order to describe the developed system, a general descriptive review of the nature of ultrasonic waves is presented along with the physical principles governing the generation, propagation, and analysis of the waves.

3.1.1 The Nature of Ultrasonic Waves

Ultrasonic waves are mechanical waves, which are generated by displacing a physical medium away from its rest position. The mechanical disturbance is then carried away from the source by the adjacent particles. Thus the disturbance travels through the medium by each disturbed particle giving away some of its energy to the adjacent ones, and converting the rest to heat. If the initial disturbance is repeated in a periodic fashion, a series of waves emerges corresponding to the period of the initial disturbances.

The particle displacement in a wave can be either normal or along the direction of travel of the overall wave. In the normal case, the waves are called transverse and in the second case they are called longitudinal. The spatial distance between the repetitions is called a wave length and is termed λ, and the distance in time between repetitions is called the period τ. The frequency f of the waves is defined as the number of repetitions (cycles or hertz) per second. The speed of propagation C of a mechanical wave in a medium is a function of the medium's mechanical properties. The wave length, frequency, and the speed of sound are related to each other by the following expression:

$$C = f\lambda \tag{3.1}$$

where C is the speed of propagation in the medium in unit length per time units, f is the frequency in hertz, and λ is the wave length in units of length.

Mechanical vibrations can travel through air and solids and thus are audible by humans up to a point. Waves in the frequency range that's audible to humans are called sound or acoustic waves, they range from below 1 hertz to a maximum of 20 kHz (20,000 hertz) and as such, vibrations with frequencies above this range are called ultrasonic waves. Their frequency ranges from 20 kHz to hundreds of millions of cycles per second (MHz).

3.1.1.1 Speed of Sound

The propagation speed (speed of sound) is a function of the stiffness and density of the material. In an isotropic elastic media, two constants are used to account for the stiffness. The two constants are known as Lame's constants (λ and μ). These are related to Young's modulus of elasticity E, and Poison's ratio ν by the following expressions:

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} \tag{3.2}$$

and

$$\nu = \frac{\lambda}{2(\lambda + \mu)} \tag{3.3}$$

In this work, we are concerned with two types of wave motion. They are the longitudinal and the transverse waves. The longitudinal and the transverse waves' speed of propagation are defined by the following expressions respectively:

$$C_L = \sqrt{\frac{(\lambda + 2\mu)}{\rho}} \tag{3.4}$$

and

$$C_T = \sqrt{\frac{\mu}{\rho}} \tag{3.5}$$

where ρ is the density of the propagation medium. Other names are generally used to designate the longitudinal and transverse waves, which are compressional and shear respectively.

Unlike elastic mediums, the types of waves that arise in non-elastic mediums, such as light fluids and gas, are mostly compressional. This is due to the nature of fluids, which cannot support shear displacements (transverse). Generally, the speed of compressional waves in solids is approximately twice that of shear waves, and as such, they can be easily distinguished.

3.1.1.2 Characteristic Impedance

The compressibility of a material, as a function of the density and wave propagation speed, can either impede or promote the formation of mechanical waves; the same holds true in the case of compressional or shear waves. The parameter that's generally used to designate this property is called the characteristic impedance. The term is used to represent how well mechanical waves can be formed in a medium and are defined as:

$$Z = \rho C \tag{3.6}$$

where Z is the characteristic impedance, ρ is the material density and C is the speed of sound in the medium. The units for the acoustic impedance are pounds/(in^2-seconds). In this work the impedance is used in 10^4 units. In the case of acoustic waves or ultrasound, the term characteristic impedance is referred to as the acoustic impedance.

3.1.1.3 Plain Waves and Beam Spread

Ultrasonic waves, generated from a point source, propagate in a medium in all directions in ever expanding spheres. In some cases, the wave motion can be directed or steered in a planner form depending on the shape and the design of the radiating source. The wave patterns can be restricted further by placing an absorbing material behind the source; thus the waves can be made to travel in the forward direction only.

In general, the source of the ultrasonic waves is not a point source, and the wave patterns are highly directed. Therefore, for small angles of the energy beam, the wave fronts can be approximated by straight lines as illustrated in Figure 3.1. In this case the waves are termed plain waves.

As noted earlier, and for the general case of a point source, the waves travel away from the source in expanding spheres. Therefore, the energy intensity of the beam decreases as the waves expand and the energy is spread over larger volumes. The intensity at any point on the wave fronts due to beam spreading is inversely proportional to the square of the distance away from the source as shown in Figure 3.2

In addition to the geometric spreading, the waves continuously lose some of their energy in the form of heat generated by friction as a result of the particle motion. Also, if the wave length of the traveling wave is comparable or smaller than the grain size of the material, the waves' energy is further reduced by scattering. The net reduction of the waves' intensity is referred to as attenuation and is designated by α.

3.1.1.4 Propagation of Ultrasonic Waves

Plain ultrasonic waves traveling through a medium continue to propagate in the same direction losing energy continuously by beam spreading and attenuation. When a wave encounters a boundary (a different medium), part of the wave is reflected and the rest is transmitted through to the new medium as shown in Figure 3.3 The transmitted wave is refracted in the new medium, its new direction is represented by Snells's Law, which is:

$$\frac{Sin(i)}{Sin(r)} = \frac{C_1}{C_2} \qquad (3.7)$$

where i is the angle of incidence, r is the angle of reflection, and C_1 and C_2 are the speeds of the sound in the two materials. For normal incidence, i.e., $i = 90^0$, the wave is not refracted and will continue to travel along the original path. If the angle of incidence is large enough, total internal reflection may result, and for even larger angles, surface waves are generated.

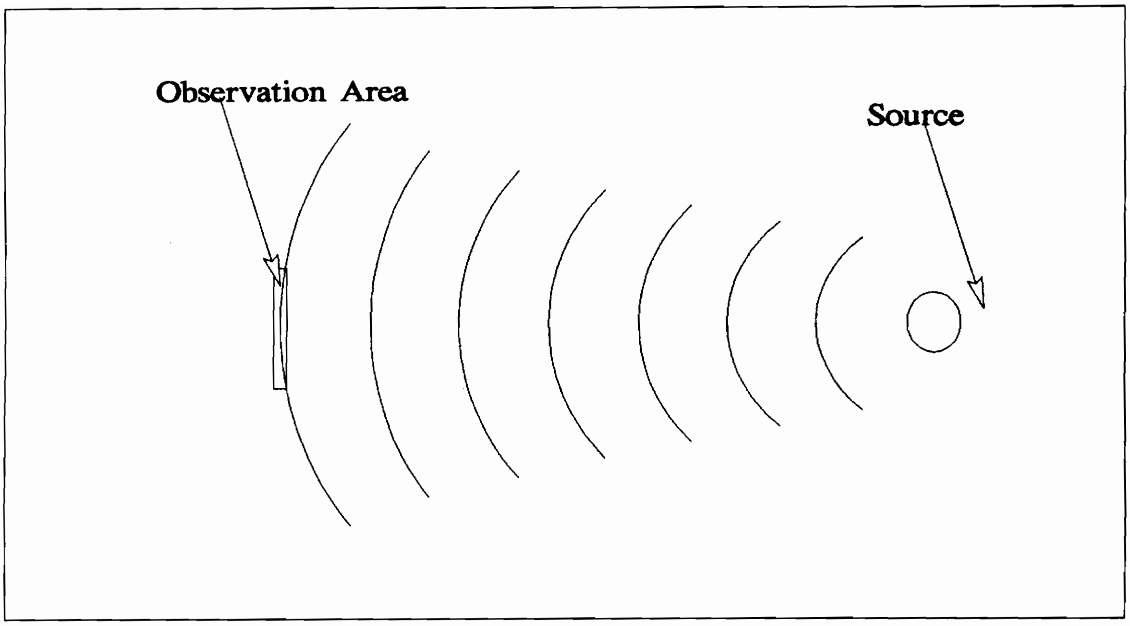

Figure 3.1. Ultrasonic Waves Generated From a Point Source

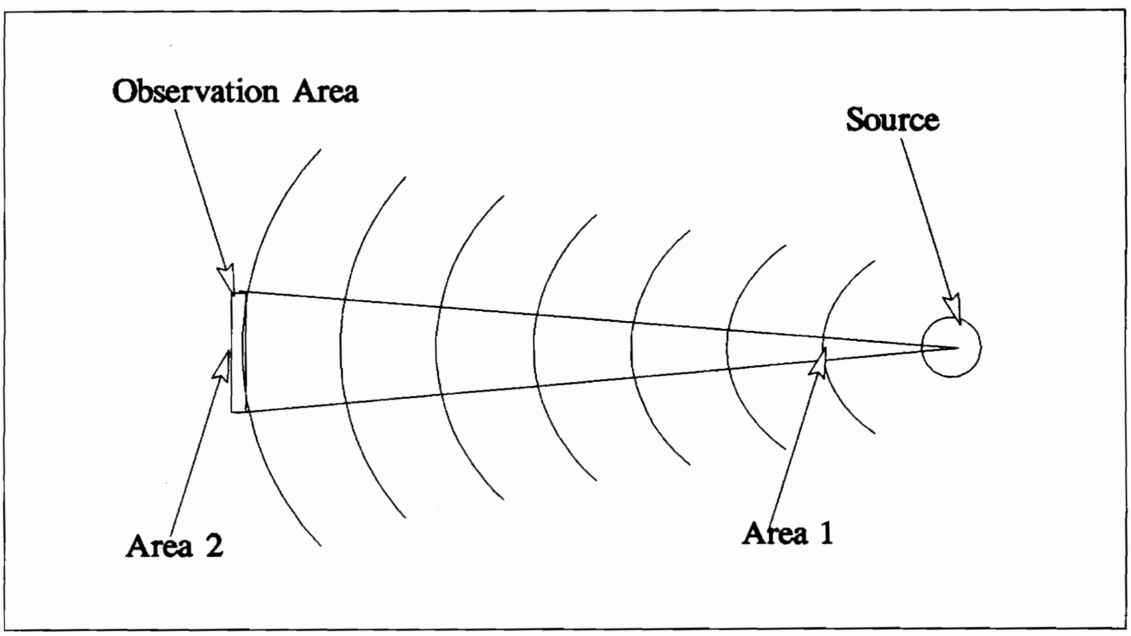

Figure 3.2. Energy Intensity as a Function of Beam Spread

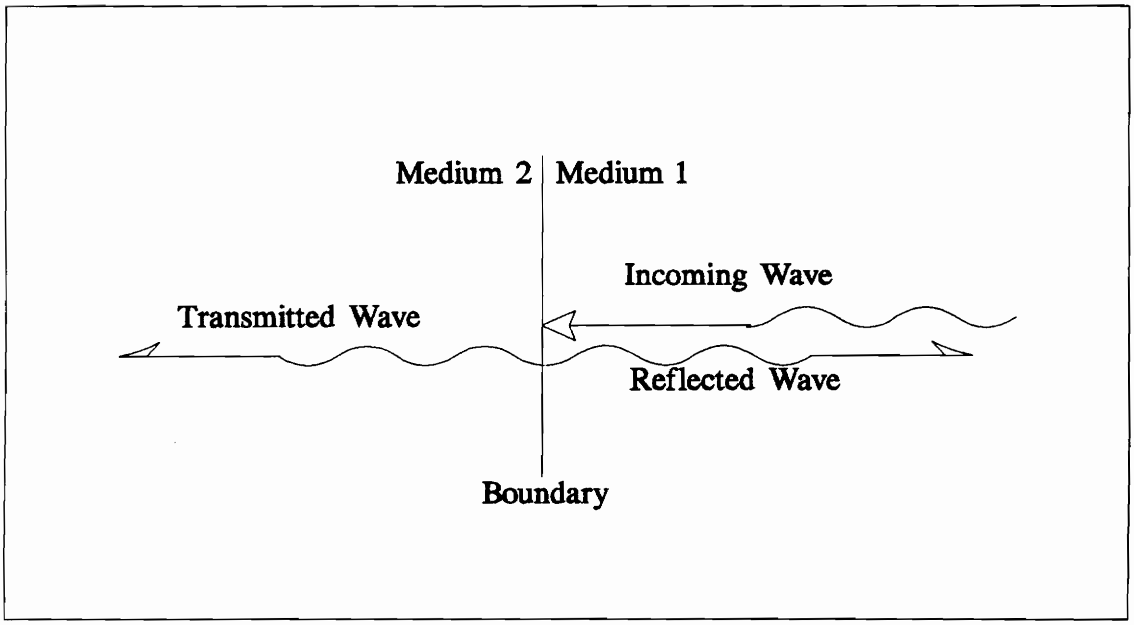

Figure 3.3. Reflection and Transmission at a Boundary

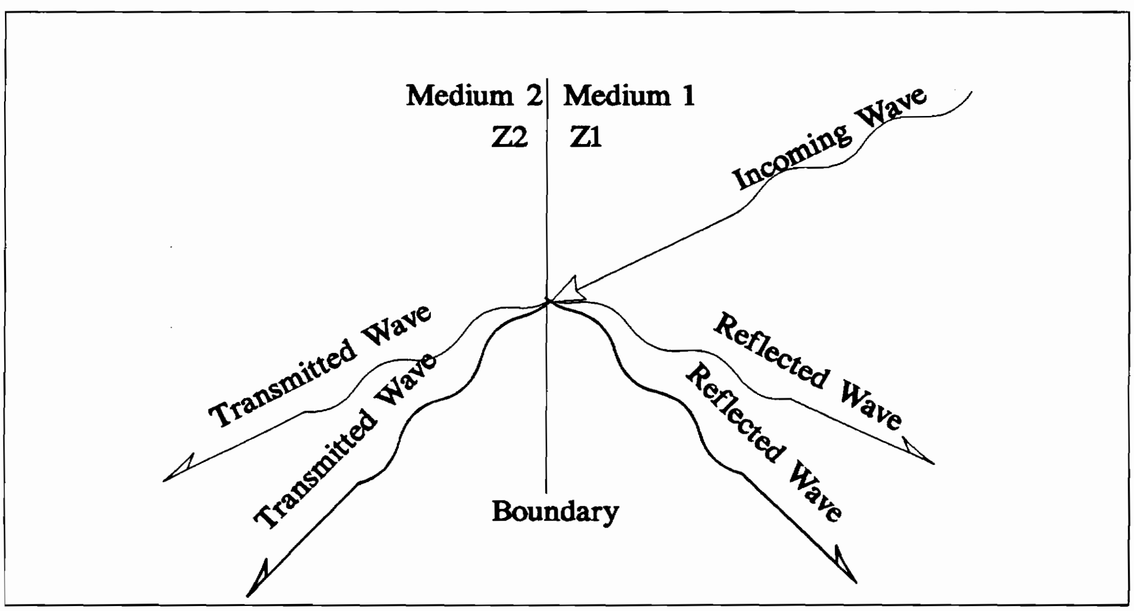

Figure 3.4. Wave Mode Conversion at Off-Normal Incidence

Whenever a wave strikes a boundary at off normal incidence, two types of waves are generated and are reflected back. Both shear and compressional waves are generated at the interface, regardless of the type (mode) of the original wave. This phenomenon is called mode conversion and is illustrated in Figure 3.4.

The amplitude of the reflected and transmitted waves at normal incidence is a function of the acoustic impedance mismatch between the two mediums and is represented by:

the reflected wave's amplitude:

$$A_r = A_i \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \tag{3.8}$$

and the transmitted wave's amplitude:

$$A_t = A_i \frac{(2Z_2)}{(Z_2 + Z_1)} \tag{3.9}$$

or

$$A_t + A_r = A_i \tag{3.10}$$

where A_t, A_r, A_i are the amplitudes of the transmitted, reflected, and incident waves respectively and Z_2, Z_1 are the acoustic impedance's of the two mediums. It can be seen from equation (3.8) that if the impedance of the two mediums is the same, i.e., $Z_2 = Z_1$, there will be no reflection as if the wave is traveling in a continuos material with no boundaries. In the case of a wave traveling from a high Z medium, such as steel, to a very low Z medium, such as air, or the opposite direction, the amplitude of the transmitted wave would be negligible and most of the energy is reflected back. The reflected wave is inverted whenever the wave encounters a lower Z medium.

3.1.2 Ultrasonic Tool and Process State Monitoring

Ultrasonic waves are used in this work to detect the condition of the cutting tool and some of the process dynamic parameters. The physical laws governing the generation, propagation, and transmission of ultrasonic waves are used to determine the following machining parameters in turning operations:

1. Tool-work contact (probing)
2. Chatter
3. Tool wear
4. Approximate tool temperature
5. Tool chipping and breakage

These parameters are measured by analyzing the amplitude, speed of sound and the two-way time of flight of the reflected component of the induced ultrasonic pulses in the cutting tool. The physical foundation and justification of each measurement's validity are presented in the following sections.

3.1.2.1 Tool-work contact (probing)

The induced ultrasonic pulses travel through the tool at a speed of sound C. When a pulse reaches the nose and the flanks of the tool, part of the pulse's energy is reflected, and the rest is transmitted into the medium surrounding the tool. The amplitude of the reflected pulse is a direct function of the acoustic impedance mismatch between the tool and the material surrounding it. The sum of the reflected and transmitted energy equals the energy of the incident pulse. When the tool is in the idle state, it is surrounded by air and or cutting fluid. The acoustic impedance of air is 0.00047, 0.214 for motor oil, and for most types of steel is approximately 6.5.

The amplitude of the reflected wave is determined by using equation (3.8), with medium 1 being the tool and medium 2 being air or oil.

$$A_r = A_i \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \ , \ A_r = A_i \frac{(0.00047 - 6.5)}{(0.00047 + 6.5)} = \ = -(0.9998) A_i$$

Therefore, most of the incident energy is reflected back and the wave is inverted.

The amplitude of the reflected wave with the tool in oil is 93.62% of the amplitude of the original incident wave. For thin layers of oil on the tool as in the case of turning operations, there will be multiple reflections between the tool-oil-air interfaces, which would appear as delayed low level noise on the baseline of the reflected signal. If the oil film thickness is less than one quarter the ultrasonic pulse's wave length in oil, i.e., the oil film is less than 1.7X 10^{-3} inches; then the reflected wave is not effected by the oil film.

When the tool touches the workpiece the amplitude of the reflected wave changes since the work material is solid metal with much higher acoustic impedance than air or oil. The level of amplitude change is a function of the acoustic impedance mismatch between the work piece and the tool. The Z value for most carbide or High Speed Steel tools is approximately 6.5, and the Z value for most work materials ranges between 2.45 for aluminum, 6.2 for steel and up to 14.2 for tungsten. These are orders of magnitude larger than air and oil, thus providing a measurable contrast.

The amount of energy reflected from the tool's nose is directly related to the area of the nose and the flanks. Since only a small portion of the tool actually makes contact with the workpiece, the change in the reflected wave's amplitude is a small fraction of the reflected signal and is a function of the degree and intimacy of contact. Although the change in most cases is small, it can be consistently detected to indicate tool-work contact. Figure 3.5 clearly shows a sequence of tool-work contacts.

3.1.2.2 Chatter

Chatter is manifested by intermittent breaking of contact between the tool and the workpiece during cutting. As was noted in the previous section, there is a change in the reflected wave's amplitude whenever the tool makes contact with the workpiece. Also sudden changes, in the degree and intimacy of contact cause sharp changes of the wave form amplitude. The wave form changes are in the form of spikes. Therefore, chatter is manifested by a succession of amplitude changes of the reflected wave. The frequency and severity of chatter can be determined by computing the period and magnitude of the spikes. Figure 3.6 shows tool chatter represented by the spikes in the amplitude of the reflected waves during cutting.

The change of the wave form's amplitude, due to temperature (discussed in the next section), will not impact or obscure the appearance of chatter since chatter is manifested by spikes in the base-line of the amplitude signal, i.e., fast variations on top of slow variations.

3.2.1.3 Tool Temperature

The speed of propagation of an ultrasonic wave is a function of the mechanical properties of the medium. Since a medium's mechanical properties change with temperature, the speed of sound will also change. As the temperature increases, the speed of sound decreases. This property is used to measure the temperature of objects and is called Ultrasonic Thermometry. Ultrasonic waves have been used to measure the temperatures of objects in hostile environments, such as nuclear reactors, on several occasions [78]. Although the phenomenon is well known, there is very little theoretical treatment of it in the literature.

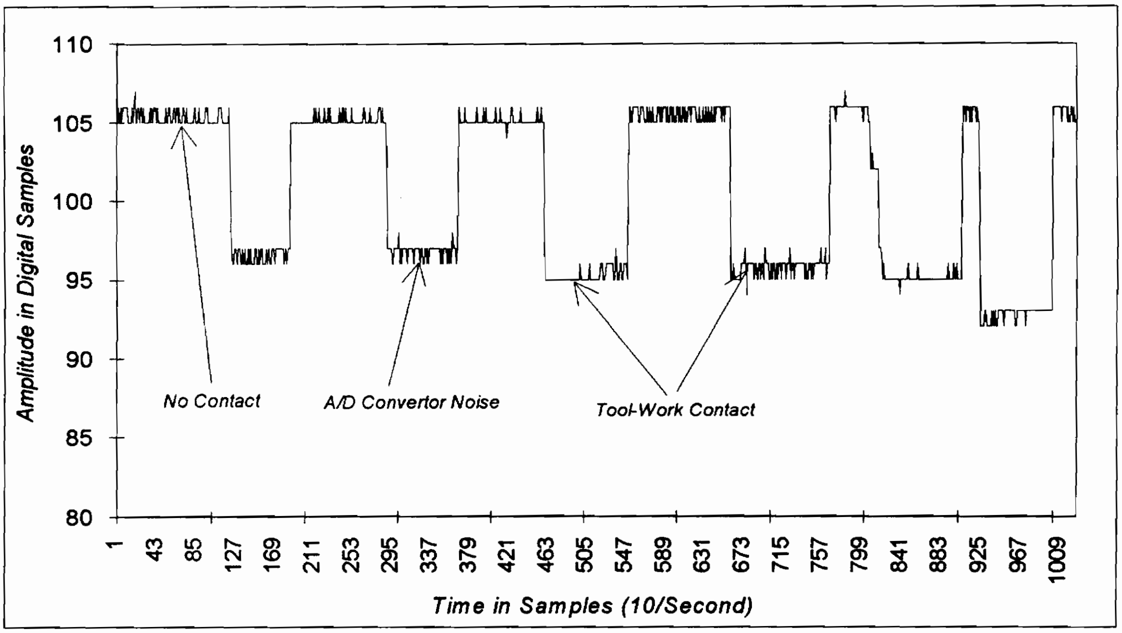

Figure 3.5 Change in the Wave Form Amplitude Vs the Contact Material

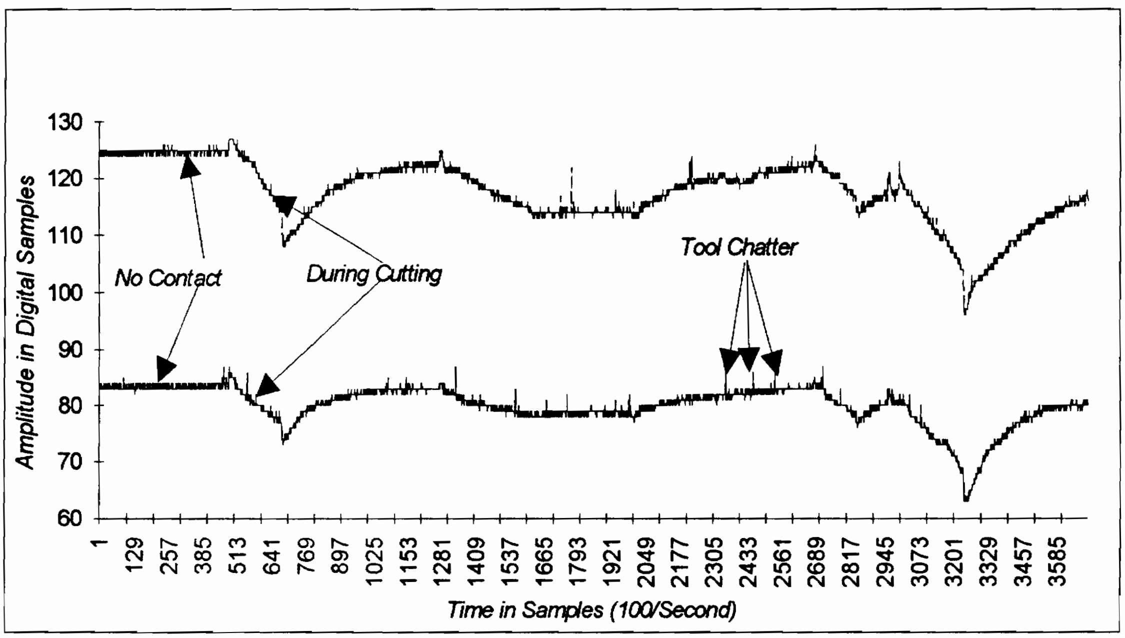

Figure 3.6. Dynamic Tool/Work Contact with Chatter

In the case of turning, high temperatures are developed and as such, the reflected ultrasonic echo's time of flight is altered due to the change in the speed of sound in the tool. The wave's overall time of flight represents the overall cutting tool's temperature since the wave would have traveled the length of the tool. Although there are large temperature gradients in the tool, i.e., the nose temperature and the crater areas are much hotter than the back of the tool (see figure 2.5); the TOF changes, due to these gradients, are conserved and are manifested by a correlation between the slowness of the wave and increases in the cutting temperature. Figure 3.7 shows the ultrasonic wave's time of flight changes during a sequence of tool engagements and disengagement.

The change in the value of the TOF in microseconds is scaled in units of temperature for wet and dry machining by comparing it to the readings obtained from a type K thermocouple. Two multipliers were used one for wet and the other for dry machining, which were 2800 and 1360 respectively. The multipliers were selected to achieve the best overall fit of the complete temperature curve, such as initial rise, maximum temperature, transients, and cooling off.

The thermocouple was positioned near the nose of the tool and directly below the tool clamp as illustrated by Figure (3.8). The distance from the nose of the tool to the thermocouple is 1/20". As such, the temperature measured by the thermocouple is less than the actual cutting temperature by approximately 40% (see Figure 2.5). Therefore, to reflect the true cutting temperature, the thermocouple's temperature readings must be multiplied by 1.667.

In addition to the TOF change, with temperature increases, the amplitude of the wave form is also decreased. This is due to the fact that the acoustic impedance of the tool decreases as its temperature increases; thus less energy is transferred from the

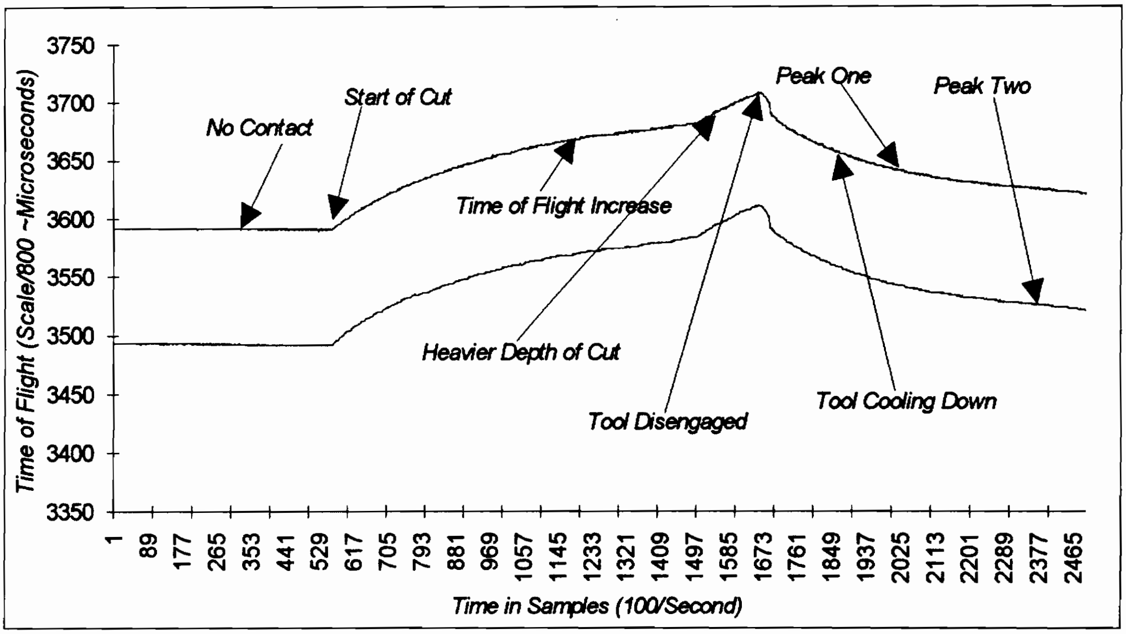

Figure 3.7. Change in the Time of Flight TOF with Temperature

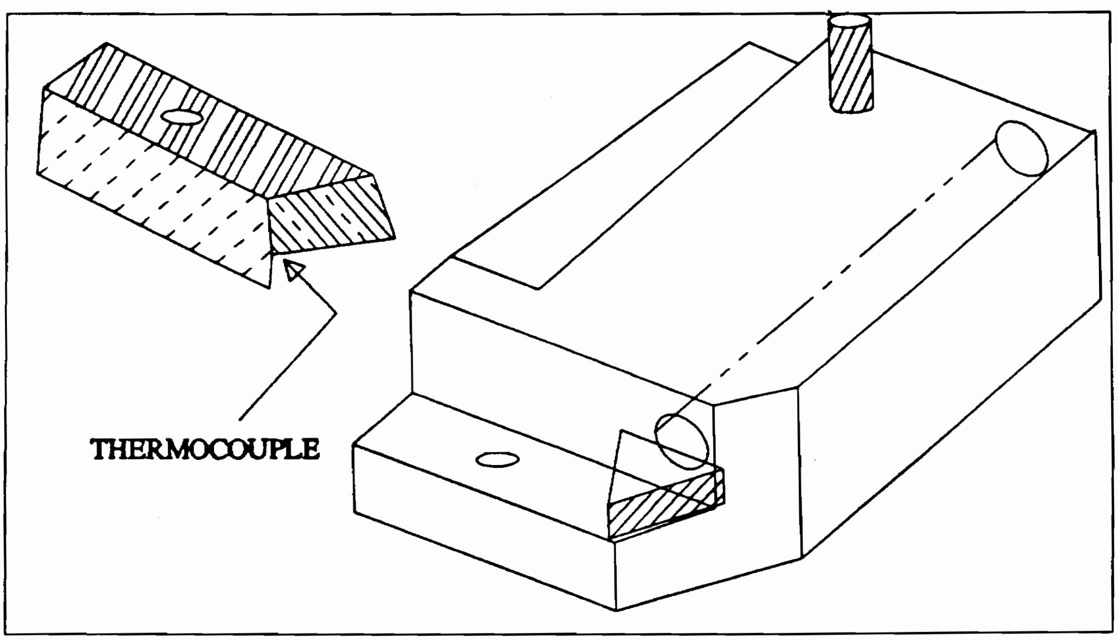

Figure 3.8. Location of the Thermocouple with Respect to the Tool

transducer to the tool. This effect has no impact on the temperature measurement since only the TOF is used in its computation. In order to neutralize the effect on amplitude measurements, the amplitude of the tool's signal has to be made either at the nominal temperature, or the signal has to be normalized first, to current operating temperature, before making any absolute amplitude measurements. The calibration and normalization procedure are outlined in section 3.1.2.4. on Gradual Tool Wear.

3.1.2.4 Gradual Tool Wear

Gradual tool wear manifests itself in three forms and is nose, primary and secondary flanks, and crater wear. The present tool-transducer configuration can detect the first two forms. The third form, crater wear, can only be detected when it is very severe. The cutting action chips away at the tool nose and flanks at an angle corresponding to the clearance angle of the nose and the main cutting edge's clearance angle as shown in Figure 3.9.

The contents of the ultrasonic wave returning from the nose and the flanks can be broken down into two wave packets as illustrated by Figure 3.10. The first is the direct reflection off the nose of the tool, and the second is an internally reflected wave, which corresponds to the energy that strikes the flanks at the point of the nose curvature. The wave, which strikes either flank is internally reflected to the opposite flank, which is then reflected back, along a different path to the transducer. The travel path in the second case is longer than the path for the nose signal, which is manifested by the longer time flight exhibited in Figure 3.11. As such, the flank wear may be isolated from the nose wear and independently determined.

In the course of cutting and due to wear, a flat spot begins to develop at the tool nose and the flanks. This change in the geometry of the tool serves to change the total

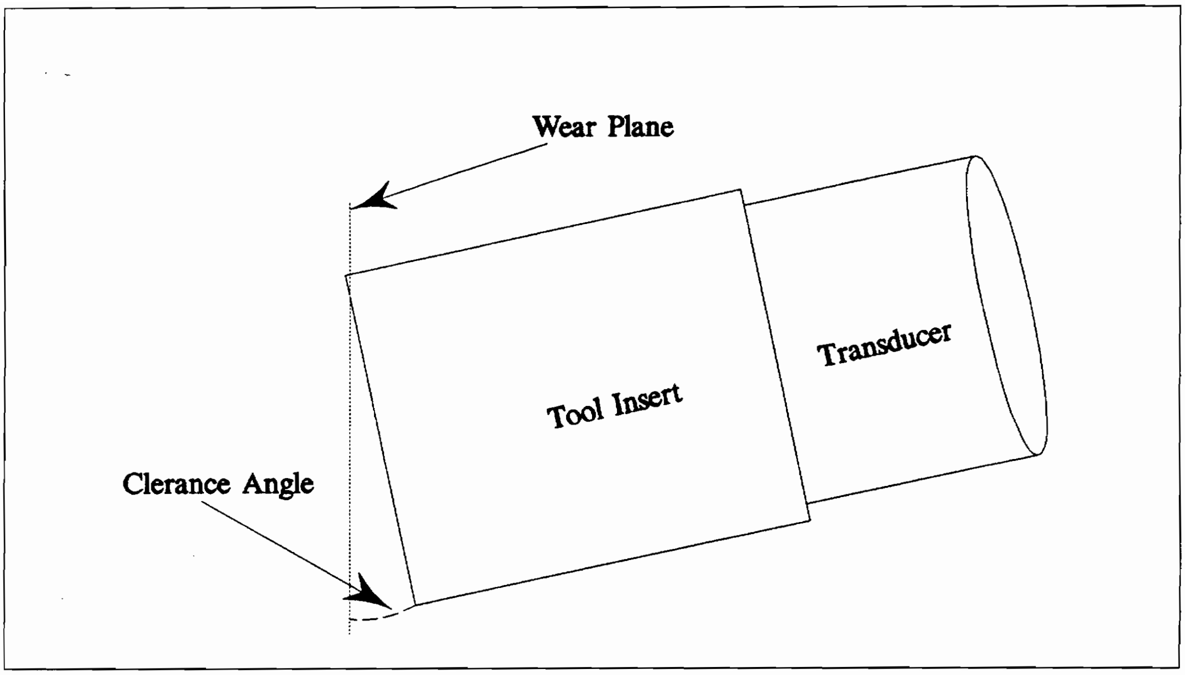

Figure 3.9. Gradual Wear of Nose and Flanks

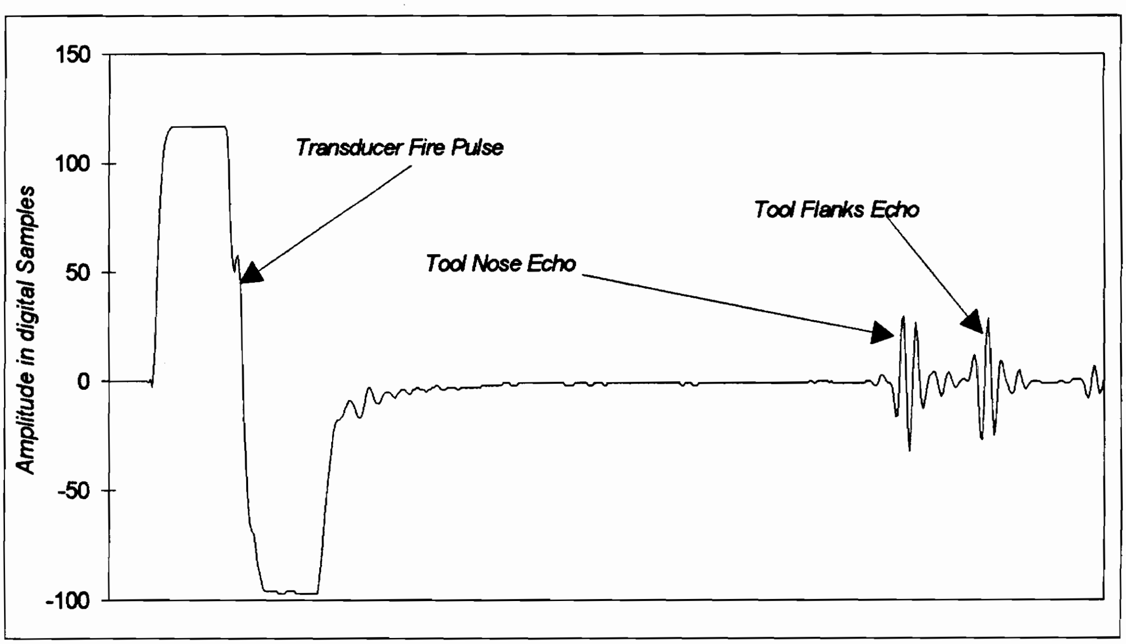

Figure 3.10. Wave Form of the Ultrasonic Tool Echo

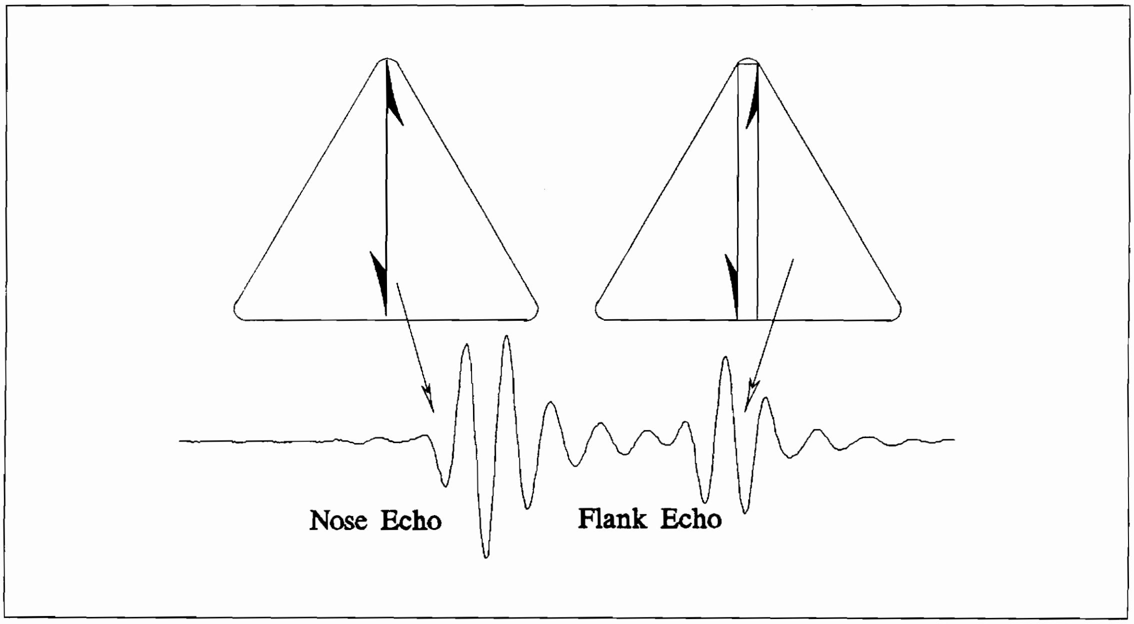

Figure 3.11. Wave Form Packets from the Nose and the Flanks of the Tool

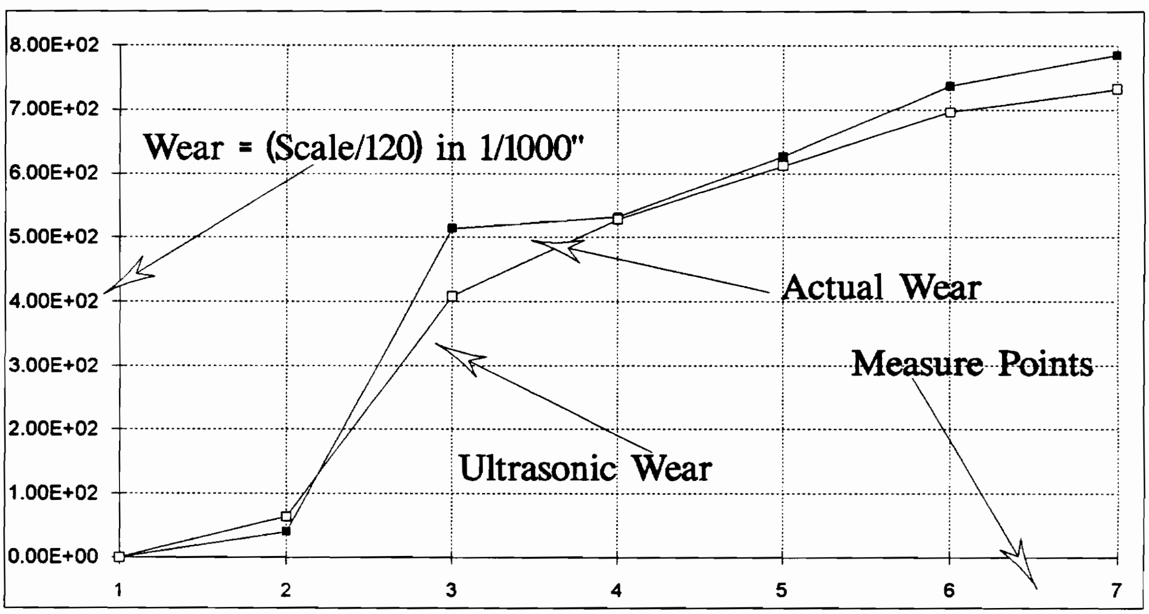

Figure 3.12. Gradual Tool Wear (Optical and Ultrasonic Measurements)

amount of the reflected ultrasonic energy. In this case, the flat area is a more favorable reflector. As such, the total amount of reflected ultrasonic energy increases with gradual wear for both components of the wave. In the ideal case, the increase in the amount of the reflected energy obeys the square law. In the case of turning, the principle does not strictly hold since the reflecting surfaces are marred and are at off angles from the normal to the transducer thus results in complex wave interactions. In spite of the complex interactions, an overall increase in the energy content develops with wear. Figure 3.12 shows the overall increase in the amount of energy at room temperature of the nose echo of a tool recorded during a sequence of successive static tool wear tests.

As was previously discussed in the section on Tool Temperature (section 3.2.1.3), the amplitude or wear measurements, have to be conducted at either a nominal temperature, or after the wave form has been normalized to the effects of acoustic impedance changes due to temperature. The relationship between the reflected wave's amplitude and the tool's temperature are related through the TOF measurement. This is due to an increase in the tool's temperature causes a decrease in the echo's amplitude and increases the two-way TOF simultaneously.

The two-way TOF was compared with the amplitude during actual machining while the tool was engaged and cutting fluid being applied, and also immediately after disengaging the tool and stopping the cutting fluid applications. The two types of test results are illustrated in Figures 3.13 and 3.14. It can be seen from Figure 3.13 that the relationship between the amplitude and the TOF is not well behaved during actual tool engagement and forced application of cutting fluids. However, the relationship is well behaved and is repeatable immediately after the tool is disengaged as illustrated by Figure 3.14. The relation between the amplitude and the Δ TOF was determined by a linear regression curve fit (see Figure 3.15) which is:

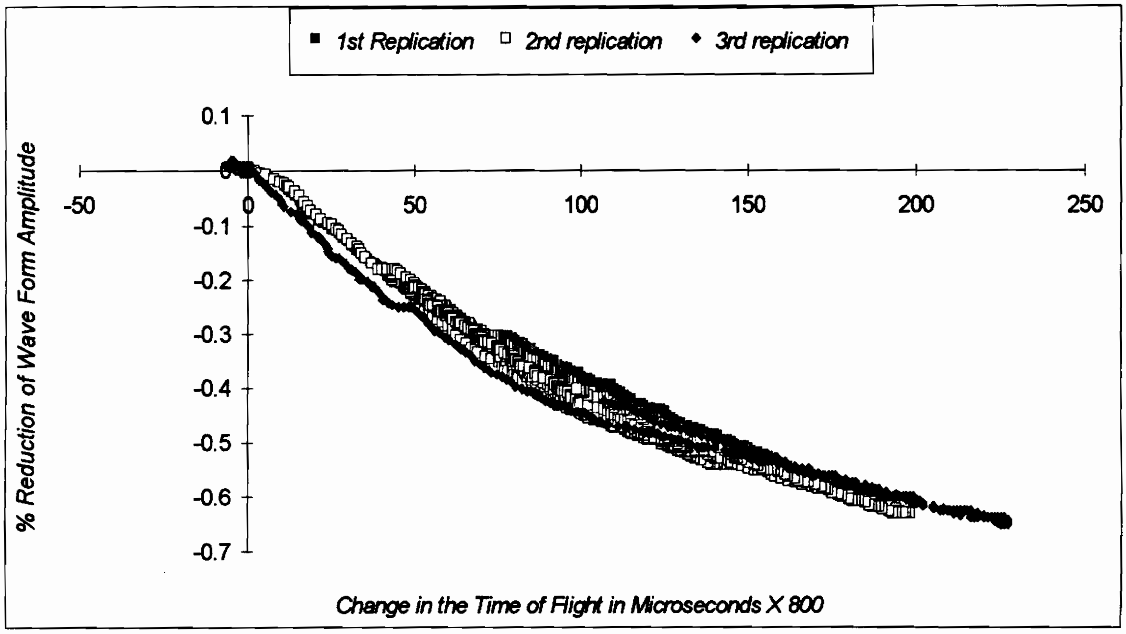

Figure 3.13. TOF-Amplitude Cross Plot While Cutting (Wet)

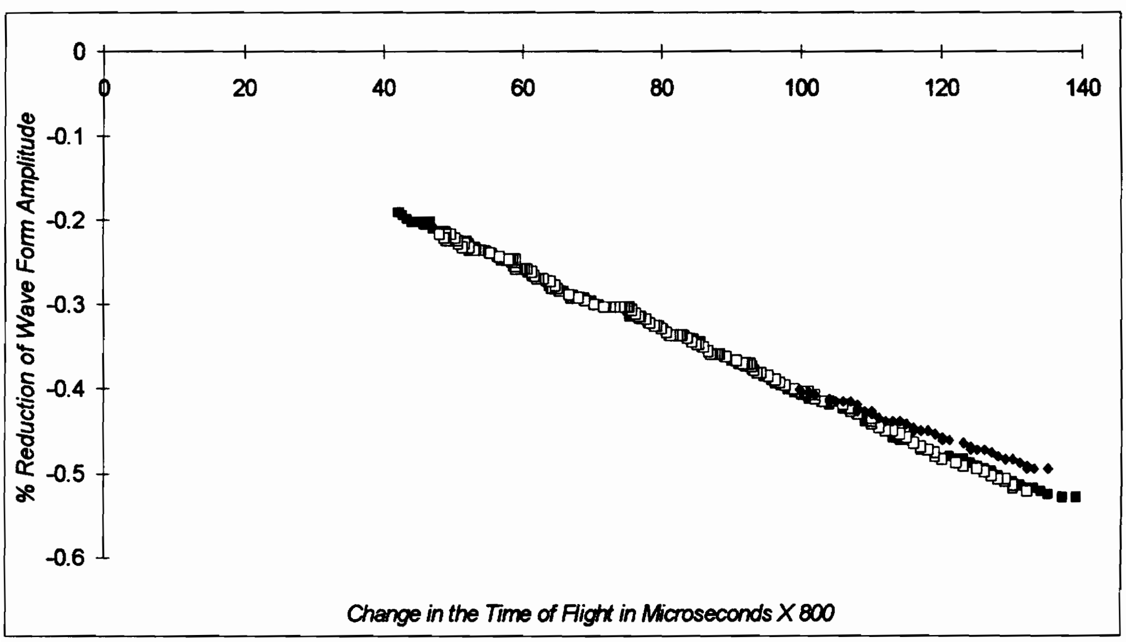

Figure 3.14. TOF-Amplitude Cross Plot After Disengaging the Tool

$$A^* = A / \{1-[(800/M)^* (0.00362^* \Delta TOF) + 0.04038]\} \quad (3.11)$$

where: A* is the corrected amplitude, A is the current amplitude, M is the MHz multiplier of the frequency sampling rate. So that if a wave is sampled at 1600 MHz, a Δ TOF of 60, and an amplitude of a peak in the wave form of 300mv, then the corrected amplitude is:

$$A^* = 300/\{1-[(800/1600)^*(0.00362^*60) + 0.04038]\} = 352.518mv$$

The reason for the poor correlation during cutting is that the amplitude of the reflected wave is a function of the temperature and the degree of contact between the tool and the workpiece, i.e., the depth of cut, tool wear, chatter, and contact with the metal chips. In addition, the flow of cutting fluid over the face of the tool is turbulent, which is due, in part, to the interaction with the cutting chips, this causes small erratic variations in the tool's temperature and thus the amplitude.

Gradual wear measurements can be made efficiently immediately after the tool is disengaged. The time required for making the measurement is on the order of 1~2 milli seconds. The current TOF is recorded along with a full wave form. The change in the TOF (Δ TOF) from that of the nominal value is computed. The corrected wave form amplitude A* is then computed from the Amplitude-TOF Equation (3.11).

3.1.2.5 Tool Chipping and Breakage

Tool chipping and breakage are catastrophic failures, which occur suddenly, and cause abrupt changes in the tool geometry. The magnitude and the shape of the change are unpredictable but are much faster and larger than gradual wear. The sudden change in the tool geometry causes a sudden change in the time of flight and the overall shape of the

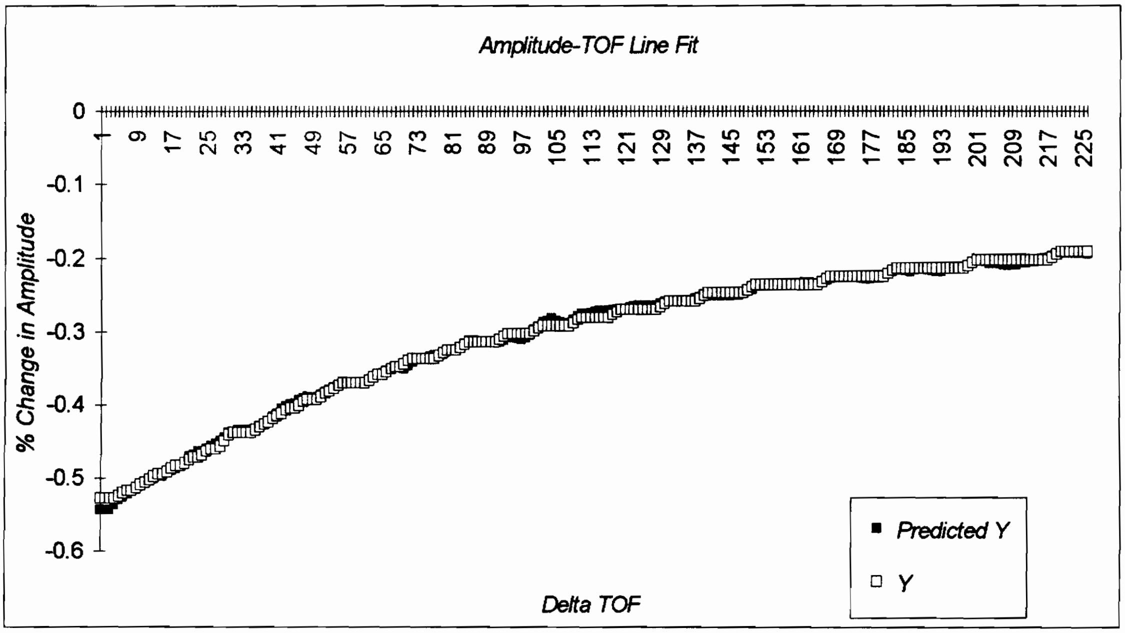

Figure 3.15. Linear Regression Curve Fit of Δ TOF Vs Amplitude Change

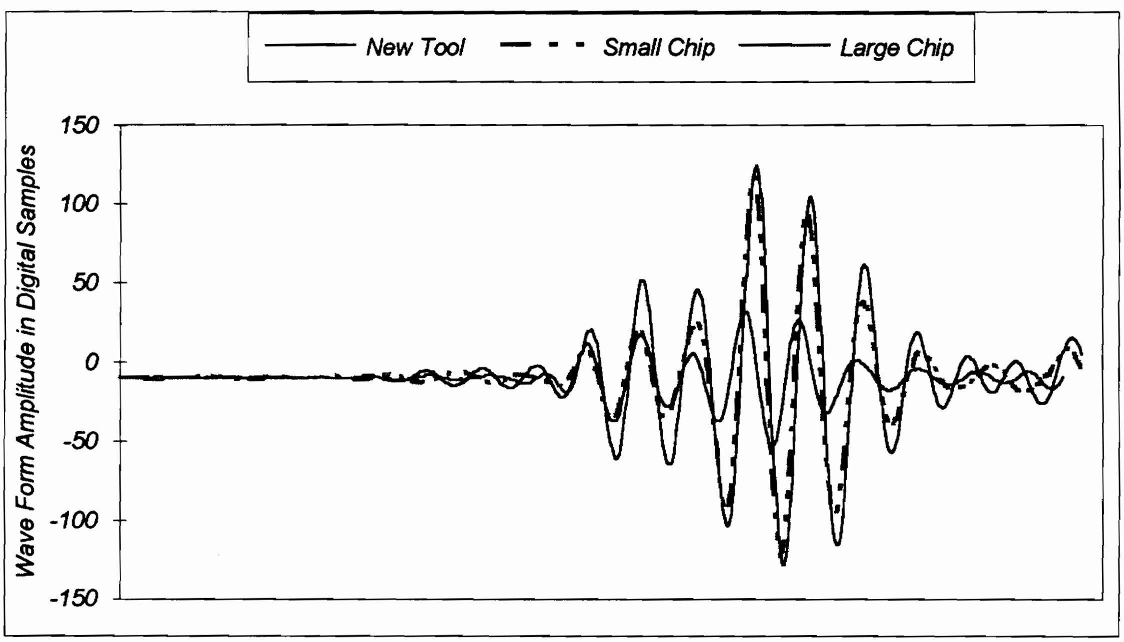

Figure 3.16. Examples of Wave Forms of Tool Chipping

nose and the flanks ultrasonic echoes. In some cases, the tool chips are large enough to cause an abrupt change in the signal's TOF, which can be easily recognized as shown in Figure 3.16. In other cases, such as small pitting of the tool face, small and sudden changes in the overall amount of the reflected energy would be observed.

3.2 Experimental Setup

The experimental setup consists of two major sections. One is associated with coupling the transducer safely to the cutting tool, and the other consists of the hardware and software data acquisition systems. The hardware used is available commercially, off the shelf and as such, certain limitations are imposed on the capabilities and performance of the experimental setup. Figure 3.17 is a schematic representation of the overall setup. The descriptions of each section's various components, capabilities and limitations are presented.

3.2.1 Tool and Transducer

3.2.1.1 Transducer

The shape and types of the commercially available ultrasonic transducers selected, for this research, dictated the cutting inserts' geometry. The transducers used are Panametrcis (V-203-RM) and (V-208-RM) flat face contact transducers operating at frequencies of 10 and 20 MHz respectively. Both have active elements of 0.125" in diameter and with an overall cylindrical package geometry 0.1875" in diameter. The recommended maximum direct operating temperature range for the transducers is 60^{o} Centigrade.

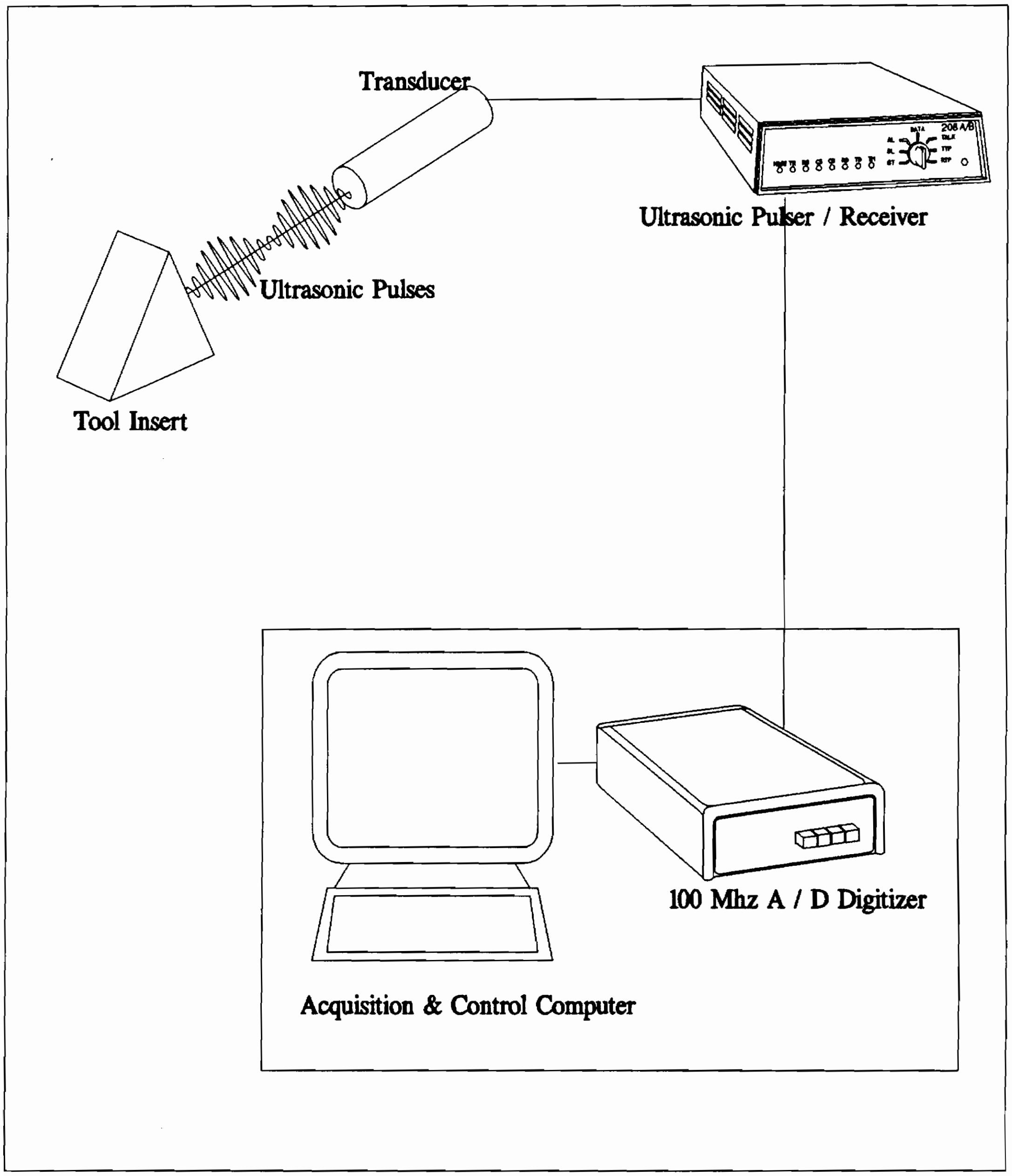

Figure 3.17. Block Diagram of the Experimental Setup

An ultrasonic delay-line (isolator) is used in conjunction with the transducer to isolate it from direct contact with the hot cutting tool. The-delay line is a proprietary Panametrics (DLHT-3) 0.125" in diameter and 0.2" in length. The transducer and delay-line combination are linked together through a threaded coupling as illustrated in Figure 3.18. This extends the range of operating temperature for the transducer to 260^{o} C for 10 second intermittent contacts.

The combination of the transducer and the delay-line are cooled by injecting air inside the tool holder in order to achieve continuos operating contact with the tool. This method of cooling is successful in maintaining the transducer's temperature below the maximum operating range. An ultrasonic pulser-receiver in burst mode, i.e., short duration spikes, activate the transducer. The pulser's maximum operating rate is 2 kHz. In addition, the pulser can be triggered by an external source on command to provide synchronization with the data acquisition system. The receiver section provides a gain of 40 dB at 10 MHz and is capable of receiving pulses of up to 20 MHz.

3.2.1.2 Tools and Tool Holder

The tool holder depicted in Figure 3.18 is specifically designed to accommodate the transducer. The tool clamp is shifted to right side of the normal position, and a hole is bored from the back of the tool to the back-end of the holder. The transducer, delay-line, and a solid handle are inserted into the tool holder, out of view and thus is protected from chips and debris. Part of the delay-line pierces the housing directly behind the cutting insert. A spring load keeps the transducer assembly in intimate contact with the back-end of the tool. Mounted on the bottom of the housing and below the transducer is an air fitting. The air is vented from the top through a hole in the housing.

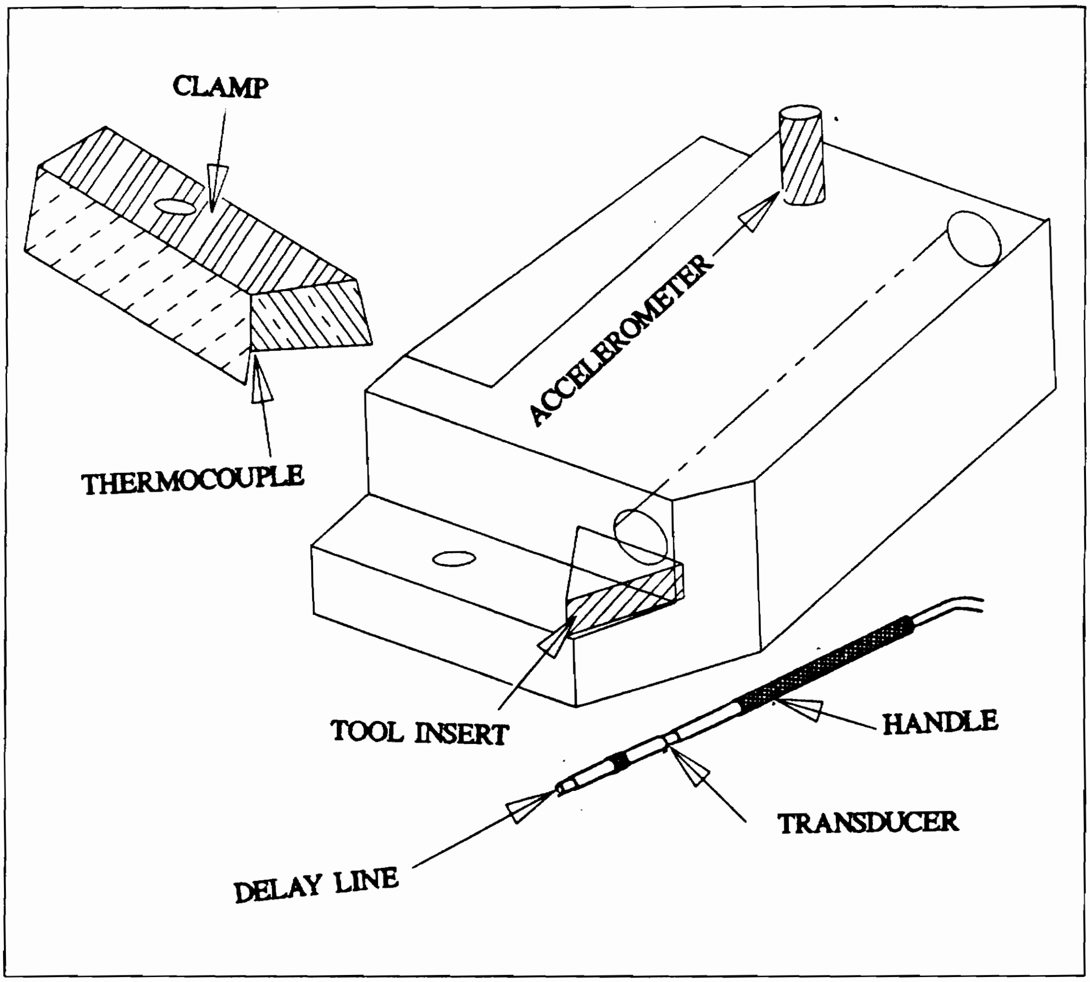

Figure 3.18. Schematic Representation of Transducer and Tool Holder

In the experiments, the tools used are (TNG333) negative triangular carbide inserts, 0.125" and 0.1875" thick with no clearance angle. The tool holder geometry provides a 6^{o} nose and main cutting edge tool clearance along with 6^{o} negative rake angle. The flat geometry of the face of the transducer and the delay-line dictated the use of negative inserts, i.e., zero clearance angle.

A study was conducted to determine the influence of the tool's nose radius on the measurements. The relative amplitude of the nose and flanks echo and the separation in time between them was shown to decrease as the nose radius decreased (see Figure 3.19). This phenomenon was shown to have no effect on the mechanics of the measurement or the methodology. As such, and due to the limitations of the current system's amplifier section, larger nose radius tools (1/8") were selected to provide adequate signal levels for the tests.

3.2.2 Data Acquisition System

3.2.2.1 Hardware

During operations, the changes in the ultrasonic echo are small and rapid. Because of the signal's high frequency (10-20 MHz), a high speed data acquisition system is needed to provide the fine resolution. Thus, the major component of the data acquisition system is an AT style bus board that operates in the computer. The board is a SONIX-AD100 high speed analog to digital converter. The board's stand alone sampling rate is 100 MHz at 8 Bit conversion resolution. The board can be operated in Equivalent Time Sampling (ETS) at rates ranging from 200 MHz to 3.2 GHz in doubling steps. This is achieved by taking repeated samples of the wave form at 100 MHz each and reconstructing the wave form to reflect the added resolution. Thus 8 repeats of the wave form are acquired and synchronized to achieve an 800 MHz ETS sampling rate.

Although the ETS mode of operation is slower than the speed in the stand alone mode, the time resolution of the signal is increased considerably. The resolution in the 100 MHz mode is 10 nano-seconds/sample and increases to 1.25 nano-seconds/sample at the 800 MHz ETS sampling rate. In the ETS mode, the overall data acquisition rate is reduced from the nominal 2 kHz for the pulser to a lower rate, depending on the ETS sampling rate. The time required for acquiring one wave form at 800 MHz is 8 times longer than the 100 MHz stand alone rate of 2 kHz, i.e., 4 micro-seconds Vs 0.5 micro-seconds.

The resolution of the current experimental setup is much more accurate in time rather than amplitude. The resolution of the signal in time is 1.25 nano-seconds at 800 MHz ETS; whereas, the amplitude resolution of the system is 8 Bit, i.e., a maximum of 256 levels. Therefore, the TOF is used, when applicable, rather than the amplitude information.

Electronic noise becomes a major factor with ETS sampling mode since the repeated acquisition of the wave form requires near perfect synchronization between the pulser and the data acquisition board. The current experimental system is capable of providing accurate synchronization up to a sampling frequency of 800 MHz. Jitters begin to appear in the signal at higher sampling rates.

3.2.2.2 Acquisition Software

The basic acquisition software uses Assembly language calls to the A/D board. The calls are integrated into a (proprietary SONIX, Inc.) C language program to provide input/output (I/O) functions to the computer and data storage.

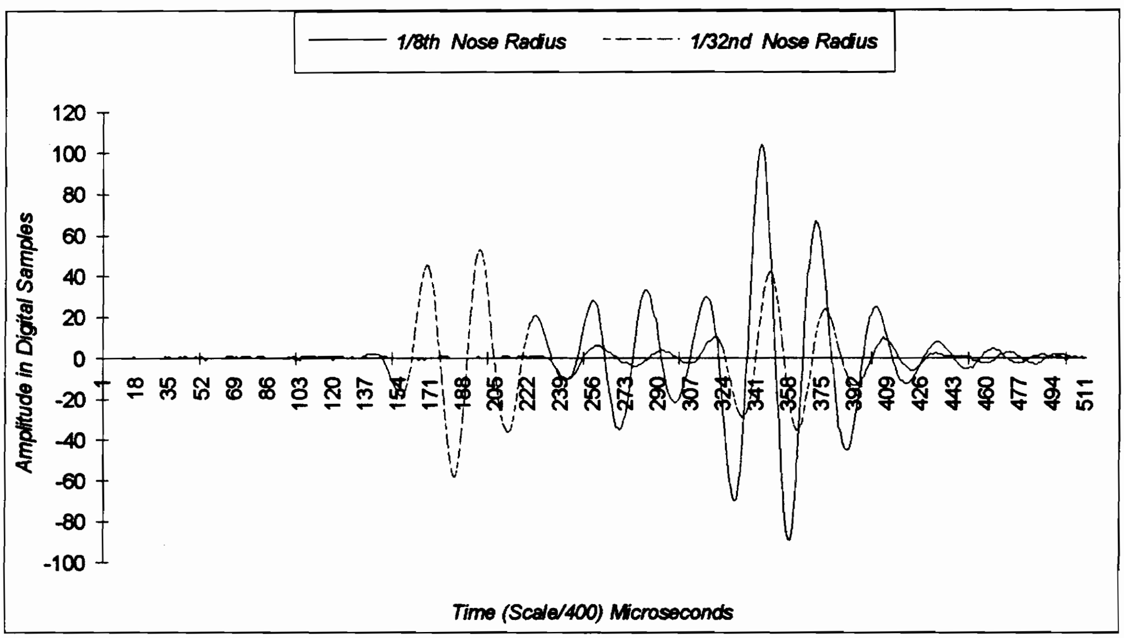

Figure 3.19. Effects of the Nose Radius on the Shape of the Echo

After each transducer firing, the wave form is fully digitized and stored in a 64K buffer. Part of the wave form can be selected and displayed on the computer screen in a digital display oscilloscope format. The system provides the capability to determine and acquire the amplitude and the time of flight for up to 8 peaks from the displayed wave form. The peaks are selected by positioning a series of gates on the screen. The gates' width and position in time along with the threshold values for amplitude detection are manually set by the user.

The over all TOF value for a particular peak is the sum of the time delay from firing the transducer to the start of the screen display in microseconds and the position of the peak within the display in digital sample. The digital sample numbers are a function of the sampling resolution of the wave form. For example the length of the screen in samples is 400, 800, 1600, and 3200 respectively for the sampling frequencies of 400, 800, 1600, and 3200 MHz. These numbers are converted to microseconds by dividing by the MHz multiplier of the sampling frequency. For example, if a signal is sampled at 800 MHz and the overall delay of the display is 8.5 microseconds, and if the position of the a peak is at 1340 in the display buffer, then the TOF for the peak is 8.5+ (1340/800) microseconds (10.175 microseconds). The position of the peak in time would remain the same regardless of the sampling frequency, except for the finer or coarser time resolution resulting from higher or lower sampling rates. In the case of sampling at 1600 MHz, the MHz multiplier is 1600, and if the display delay is the same as in the first case, i.e., 8.5 microseconds, then the position of the peak in sample numbers would double, i.e., would be 2680 instead of the 1340 in the first case. Dividing the 2680 by 1600 and adding the 8.5 microseconds screen delay would yield the same TOF as before.

The relative positions in time of the peak detector gates are maintained by the use of a follower gate. This is an additional gate, which can be positioned on a peak in the wave form and activated. The relative positions of the remaining gates, with respect to the follower gate, are calculated and stored (see Figure 3.20). Changes in the position of the peak in the follower gate trigger a correction to the position of the other gates. The positions are calculated and compensated after each firing of the transducer. Therefore, changes in the position of the wave form in time due to the increase in temperature are measured and are compensated.

The amplitude and the TOF of each peak within a gate are determined by a hardware peak detector at 100 MHz or lower sampling rates. The software performs this function in ETS sampling mode. The buffer stores the sampled wave form and the software determines the various peak amplitudes and TOFs for each gate position.

Currently, data acquisition can be performed in two modes of operation. The first is a discrete mode in which single values of the gates and the corresponding wave form can be acquired at will and written to a disk drive. The second is continuous acquisition mode in which every wave form and or the values of the gates are written to disk. In addition, the sample rate in the second mode can be varied, i.e., to sample every second or less in time. Currently, the system is capable of acquiring data at a maximum sample rate of 100 Hz and wave forms at a maximum rate of 10 Hz.

3.2.2.3 Data Acquisition and Processing

The concern of this work is the feasibility and the mechanics of the actual on-line monitoring rather than the development of a fully operational system. Therefore, although the current system's hardware is capable of operating and delivering results on-line, the interface software has not been developed to the same stage. Thus the data processing and interpretation are performed off-line.

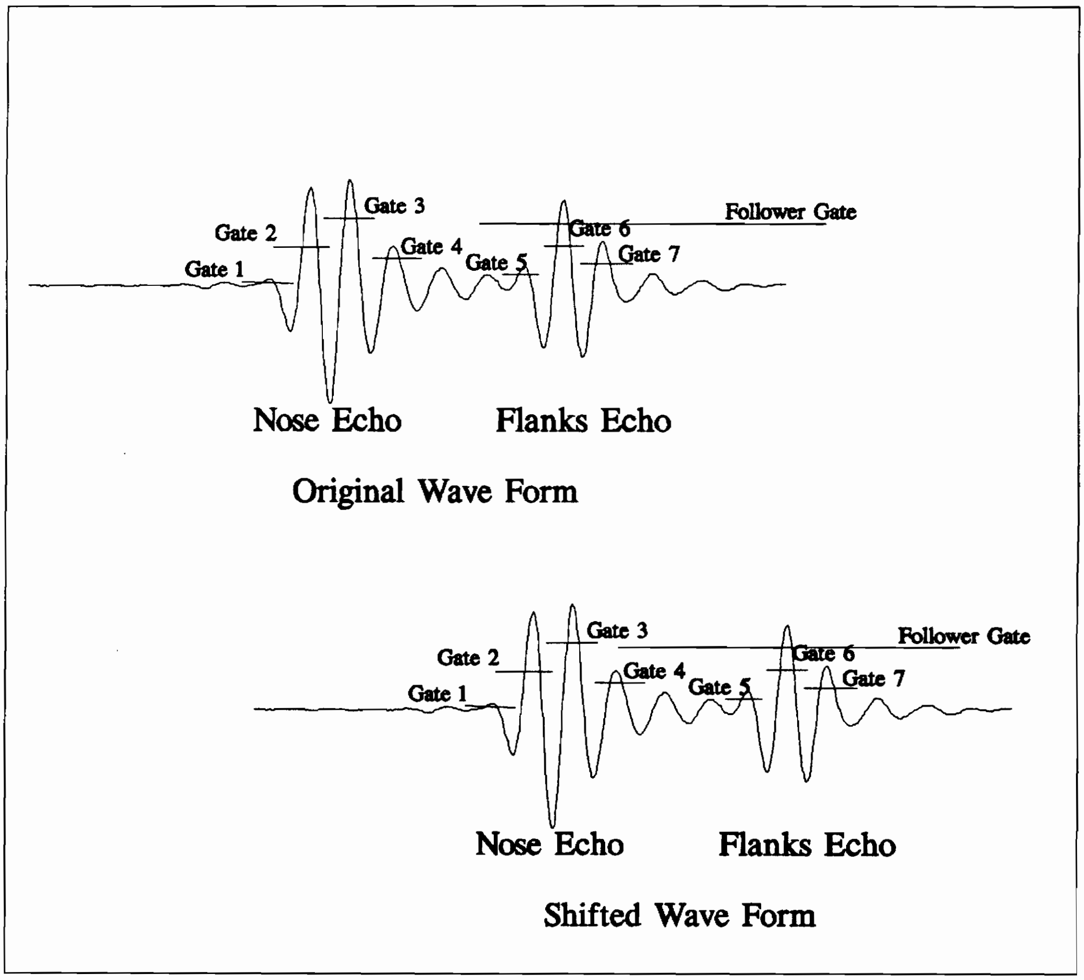

Figure 3.20. Automatic Tracking of Gate Positions

No processing is performed or required for determining the first contact or probing function. The process is accomplished by observing the change in the amplitude of the wave form on the screen as the tool contacts the work; the corresponding amplitude values and wave forms may be stored on disk for additional analysis.

Chatter, if present, is detected by analyzing the amplitude signals of the nose and flanks. The stored raw amplitude data from the nose and flanks of the tool is analyzed and searched for chatter. Spikes above the base-line of the signal larger than one digital sample are due to chatter. The maximum frequency of chatter that can be reliably measured with the current system is 50 Hz, which is one half of the system's sampling rate of 100 Hz. The tool temperature is determined from the change in the TOF of the tool nose echo. The TOF for one of the peaks in the echo is constantly tracked. The current TOF value is acquired and subtracted from the TOF base value at the nominal temperature. The Δ TOF is multiplied by the derived TOF/Temperature scaling factors for wet or dry machining to yield the value of the average tool temperature.

Gradual wear of the nose and flanks of the tool is a comparatively slow process on the order of minutes or perhaps hours in some cases. Determining gradual wear requires comparing the integral of the absolute value of the wave form to that of the new tool (base wave form). All the captured wave forms are filtered by a 1X3 median and a 1X3 moving average filters to reduce the jitters caused by the 8 bit A/D converter. In addition, the amplitude of the wave form would have to be corrected if the measurements are taken at a different tool temperature from that of the base wave form. The following procedure is used for determining gradual wear:

1. A base wave form and the TOF of a new tool's nose and flanks is captured at a reference temperature.
2. The wave form is filtered by a 1X3 median and a 1X3 moving average filters.

3. The integral of the absolute value of the nose and flanks wave form is computed.
4. A new wave form and TOF value is captured after the tool has been disengaged (1~2 milliseconds).
5. The wave form is filtered and integrated as in the case of the base wave form.
6. The Δ TOF is computed and an amplitude-temperature correction is determined by using equation (3.11). The correction is applied to the integral if warranted.
7. The difference between the integrals is computed for both the nose and the flanks.
8. The actual gradual wear is measured optically with a precision tool makers microscope.

Tool chipping and breakage are manifested by abrupt changes to the amplitude and the time of flight. These are fast variations that must be recognized as quick as possible; as such, minimal processing must be performed. The time of flight and amplitude of two or more peaks has to be continuously monitored and compared to the previous values. Sudden small changes that persist would indicate either slight tool chipping or pitting. Larger changes may indicate larger chips or tool breakage. Although the amplitude and TOF data are captured in real time, currently, the data cannot be analyzed on-line.

4.0 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 System Tests

The primary objective of this pilot study was to determine the feasibility and viability of the proposed sensing methodology of acquiring tool and process parameters in turning operations and in addition, to determine and/or outline the necessary conditions and resources required for the successful implementation of the methodology on the shop floor. As such, an experimental system has been developed with sufficient hardware and software tools to evaluate the various aspects of the proposed method's capabilities. Currently, data is acquired on-line and the processing and interpretations are performed off-line.

A sequence of tests was conducted to evaluate the validity of the proposed methodology. The tests were designed to evaluate the accuracy, repeatability, and robustness of the system in acquiring each of the individual parameters, which are:

1. Tool-work contact
2. Chatter
3. Gradual wear
4. Approximate tool temperature
5. Tool chipping and breakage

The modes of occurrence, data rates and formats associated with the parameter are different. As such, the type and number of tests were customized for the individual parameters and are discussed in detail along with the results in individual sections.

All tests were conducted with Interstate carbide inserts (TNG-333,3/8,3/16,3/64), special tool holder geometry (6^0 clearance and main cutting edge, -6^0 auxiliary cutting edge, -6^0 rake), and a variable speed control Mazak engine lathe model # MK460X15006.

4.1.1 Tool-Work Contact

In CNC turning operations, the initial locations of the tool and the workpiece are programmed into the controller. Future positions of the workpiece are calculated based on the previous operations. The tool's future positions are either assumed to be the same, determined again by probing or may be recalculated based on some type of tool wear algorithm. In the course of cutting, the tool is moved to the required position with some initial speed V, and may be slowed down just before the assumed tool-work encounter. The tool is then moved to the required full depth of cut into or ahead of the rotating workpiece. Currently, the tool-work encounter is not directly verified.

Verification of the accuracy of detecting tool-work contacts with the ultrasonic system requires the use of a CNC controller. The instantaneous position of the tool has to be noted by the controller at the instant the ultrasonic sensing system detects and signals the tool-work contact. In the present experimental setup, a conventional engine lathe is used. The lathe has no position sensing capabilities. Therefore, presently, the ultrasonic tool-work contact detection capability can only be demonstrated and analyzed.

Static and dynamic tool-work encounter tests were performed to demonstrate the system's capability. The static tests were conducted in two tool-work encounter speeds, which were fast hard contact (~2"/ minute) (see Figure 4.1), and gradual soft contact (~0.5"/minute) (see Figure 4.2). The data sampling rate for the tests was 100 Hz. The two types of contacts are compared in Figure 4.3. It is apparent from Figures 4.1,4.2 & 4.3 that an initial degree of contact and intimacy occurs between the tool and the work.

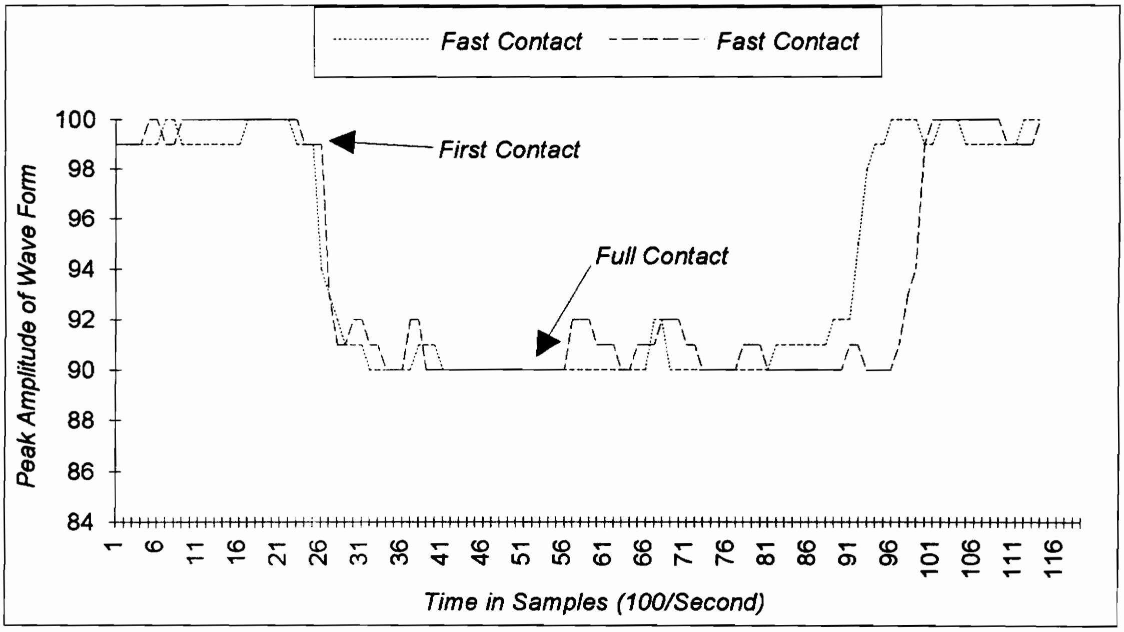

Figure 4.1. Fast Tool/Work Static Contacts

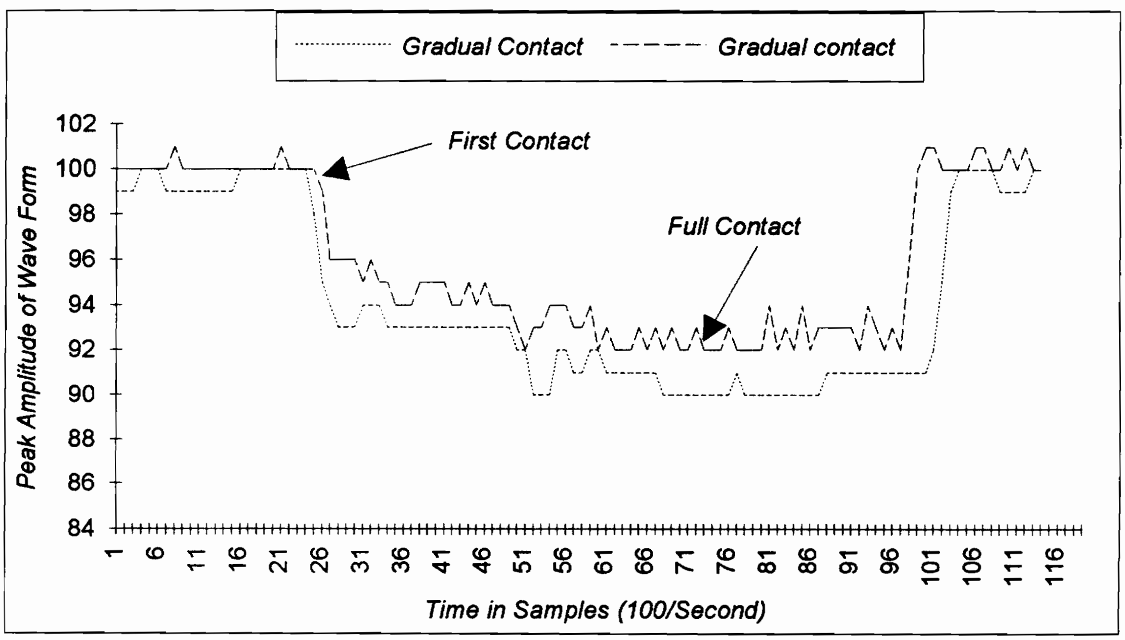

Figure 4.2. Gradual Tool/Work Static Contacts

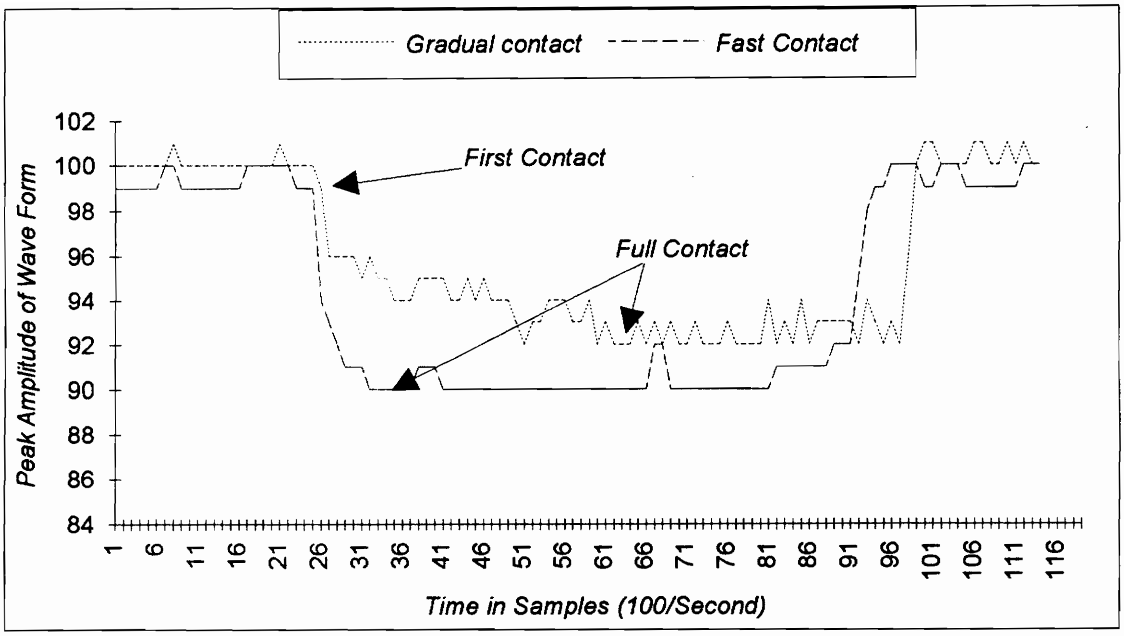

Figure 4.3. Mixed Tool/Work Static Contacts

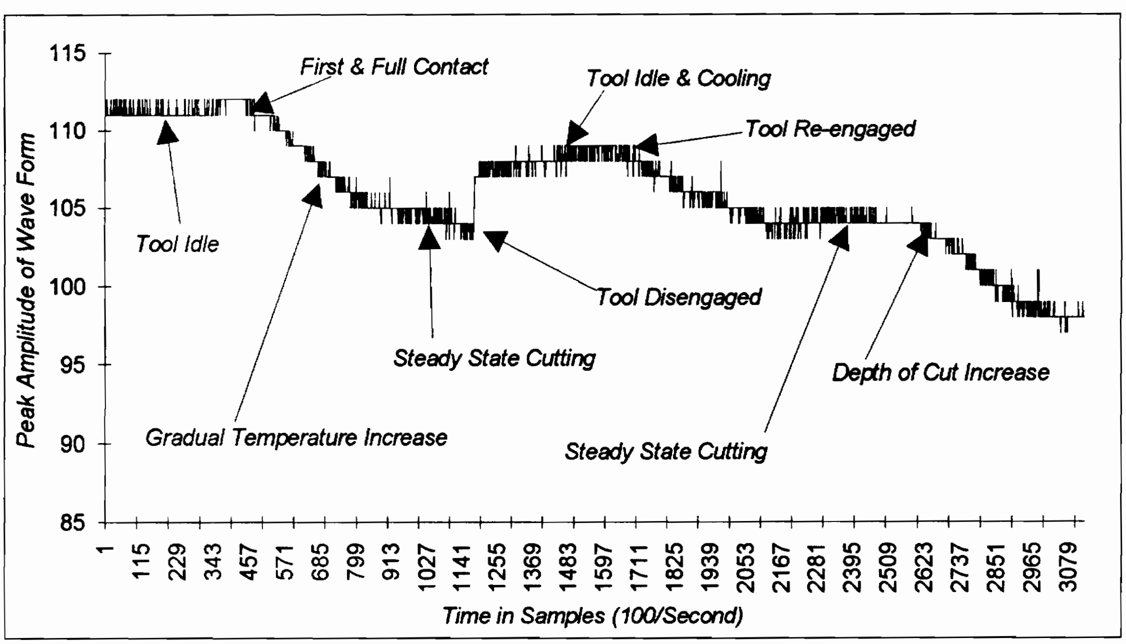

Figure 4.4. Dynamic Tool/Work Contact (Turning)

This is manifested by an initial sharp drop in the wave form amplitude in both cases. The sharp drop in the case of the fast approach reaches the maximum amplitude change as the tool first contacts the work. No further amplitude reduction is observed since the tool and the work is hard and rigid. Any further movement of the tool implies that the tool is actually plunging into the work. The amplitude of the wave form in the gradual soft contact continues to decrease as the tool is pressed harder against the workpiece until full contact is reached.

The workpiece was examined with a magnifying glass for dents resulting from the pressure of the tool on the workpiece. In all cases a microscopic dent was present. The depths of the dents were not measured but were estimated to be insignificant and on the order of a few micro-inches each. The behavior of the wave form's amplitude during dynamic contacts is considerably different from that of the static case. In the dynamic case, there is no actual intimate contact between the tool and the work since the work is moving relative to the tool. In spite of that, the contact is still visible on the amplitude curve. Figure 4.4 illustrates a first engagement, reduced depth of cut, increased depth of cut, and tool disengagement's.

In addition to the wave form amplitude change, the time of flight is also effected upon dynamic contact of the tool and the work. The rubbing action of the tool against the work and the microscopic cutting both generates localized heat. This is manifested by the increase in the temperature as indicated by the increase in the TOF in Figure 4.5. The temperature effect lags the change in the amplitude as can be seen in Figure 4.6. The time difference is on the order of 1/20th ~ 1/10th of a second. In an actual operating system, it is possible to detect the tool-work contact and stop the tool motion or note the contact position without damaging the workpiece or losing positional accuracy. For example, an ultrasonic system has a pulse and sample rate

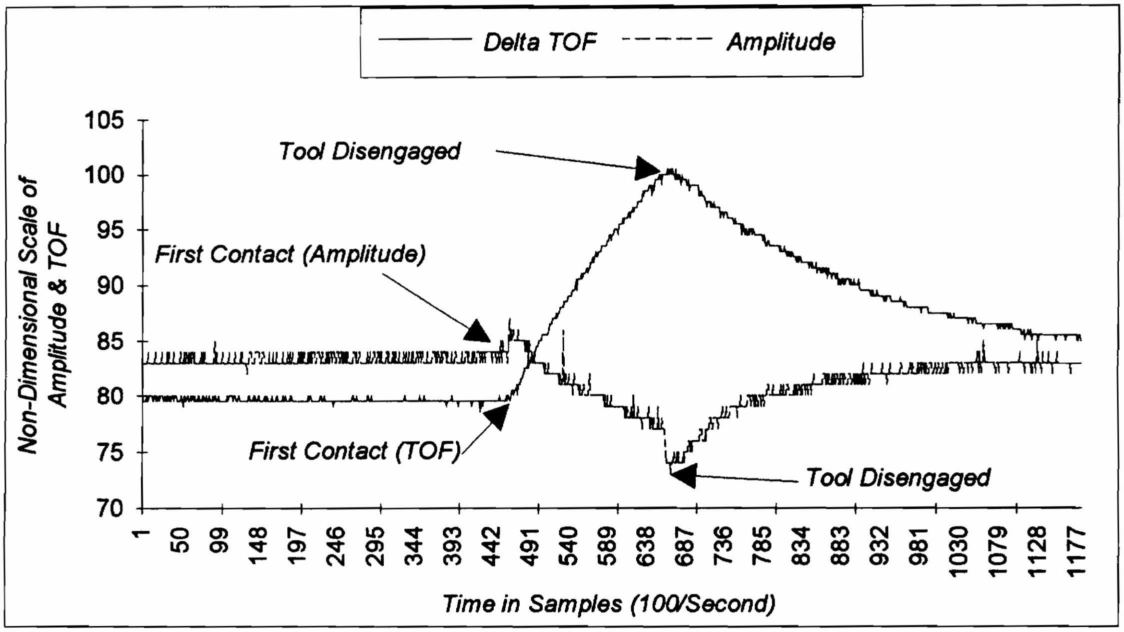

Figure 4.5. Time of Flight Vs Amplitude for Dynamic Tool/Work Contacts

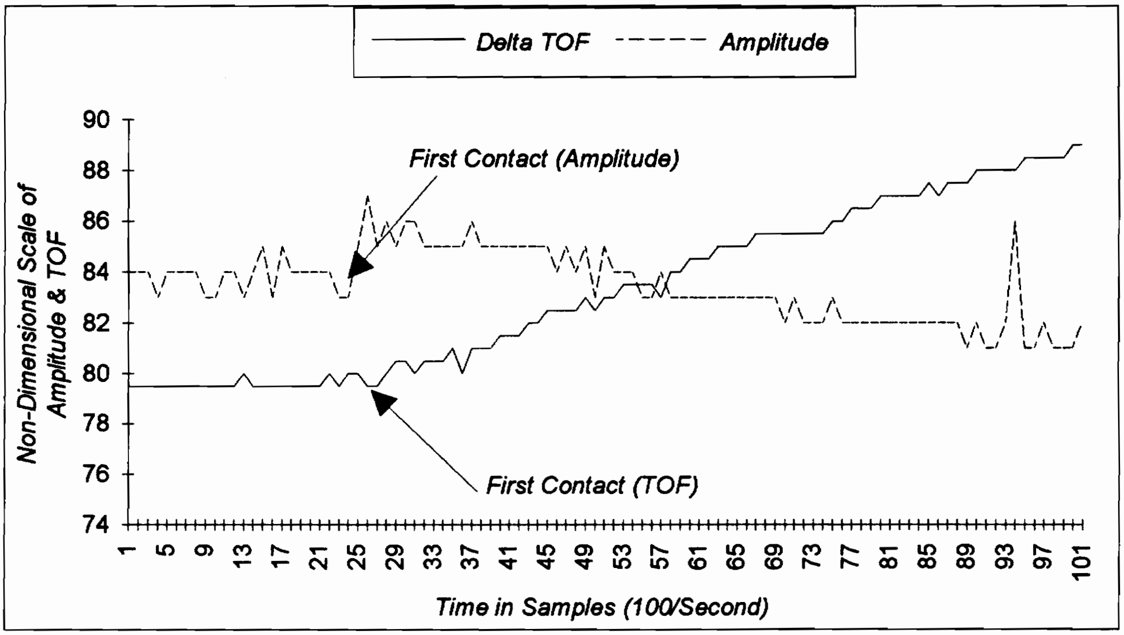

Figure 4.6. Close Up of TOF & Amplitude During Dynamic Tool/Work Contact

of 10 kHz (available commercially) and a tool is moving toward the work at 2"/minute (0.0333 inches/second). Assuming that it takes a minimum of five samples (.5 milli second) to verify the tool-work contact. An additional .5 millisecond is needed for the signal processing and for stopping the tool's motion. The total time from the initial contact would be one millisecond. The tool would have traveled an additional 33 micro-inches (0.0000333"). For slower moving tools, i.e., ~ .5"/second, the tool will move less than nine micro-inches after detection. In either case, the system will be able to achieve a very high degree of positional accuracy and will be able to automatically compensate for tool wear.

4.1.2 Chatter

Low level chatter is inherent in all machining operations. During cutting, high levels of chatter can be developed. The frequency of chatter can span a few Hz to upwards of 8 kHz. The energy level or chatter severity is defined in units of Gravitational acceleration G and is measured by an accelerometer. The level can range from very low ,i.e., < 0.1G to upwards of several Gs. As was previously noted, the maximum sampling rate, of the experimental system is 100 Hz; therefore, the maximum frequency of chatter that can be detected is 50 Hz. This frequency band contains substantial energy and can be easily observed.

Three tests were conducted to determine the minimum level of chatter that can be detected by the current setup. The results were compared to the values obtained with an accelerometer, which was mounted at the tool post as depicted in Figure 4.7. The output of the accelerometer was displayed on and processed by a Techtronix 7854 digital storage oscilloscope. The RMS value of the acceleration signal was calculated by the

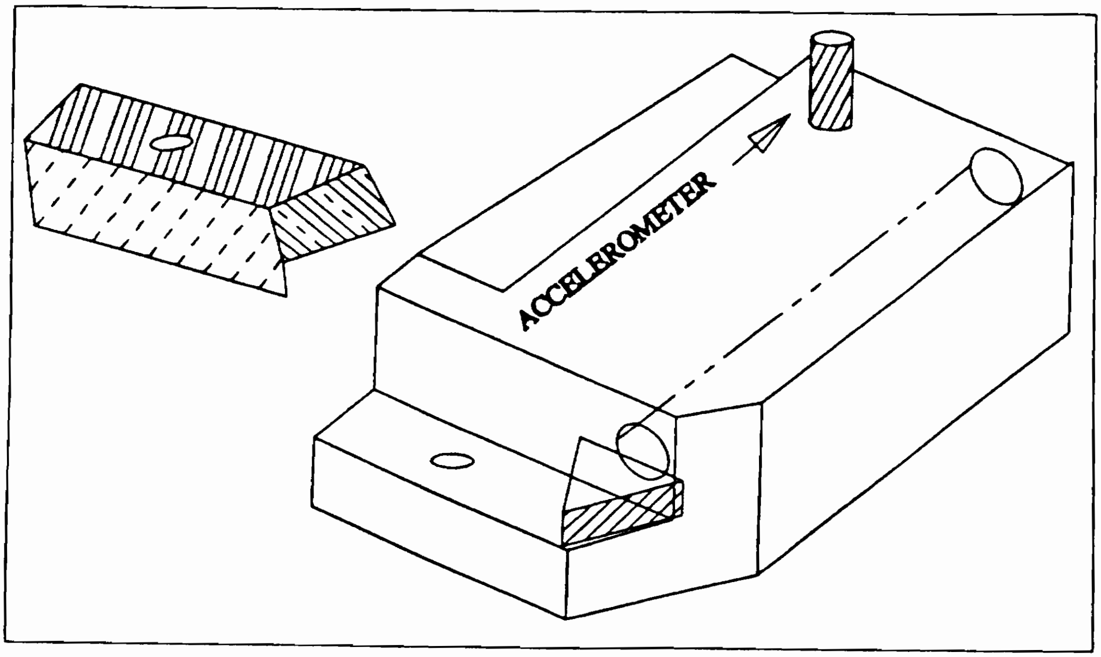

Figure 4.7. Location of the Accelerometer

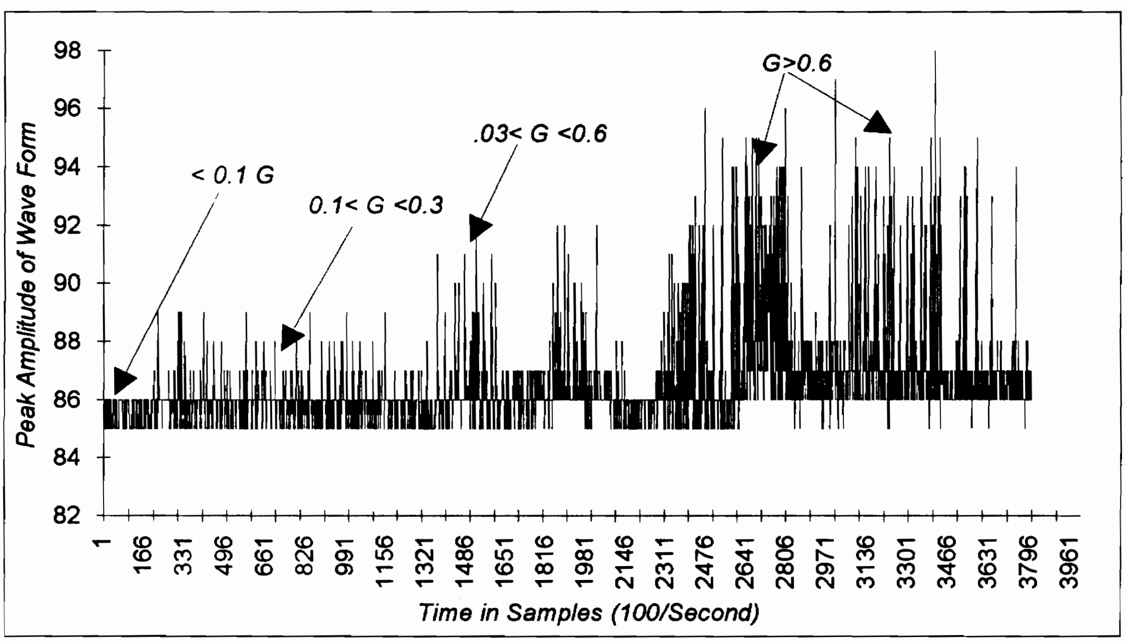

Figure 4.8. Ultrasonic Detection of Chatter

oscilloscope's wave form calculator. The conversion factor of the accelerometer signal is 1V-RMS = 1.0G.

Chatter was induced by setting the cutting speed to 60 SFPM (surface feet/minute), a feed of .084"/revolution, and a 0.03" depth of cut. The tool was positioned slightly above center to make it more favorable for generating chatter. The level of chatter was varied by gradually loosing the dead center on the tail stock of the lathe. Four bands of chatter (denoted Chat. x) levels were generated, which were:

Chat.x <0.1G

0.1G < Chat.x < 0.3G

0.3G < Chat.x < 0.6G

0.6G < Chat.x < 1.0G

The peak amplitude of the base ultrasonic echo was ~ 336 millivolts on a 1 volt digital wave form display scale. The peak amplitude in digital samples was represented by the numbers 85-86, i.e., ~ 4mv/sample. The height of the chatter spikes (see Figure 4.8) detected by the ultrasonic system in the below 50 Hz range for the four chatter bands were:

Chatter Level	System Response
Chat.x <0.1G	--------------------
0.1G < Chat.x < 0.3G	2~3 samples (8~12mv)
0.3G < Chat.x < 0.6G	4~5 samples (16~20mv)
0.6G < Chat.x < 1G	8~9 samples (32~36 mv)

Chatter levels below 0.1G were not detected by the 8 bit digital acquisition system, however, they were clearly visible with an analog display oscilloscope. In addition, very small chatter levels, which were not detected by the accelerometer, were observed on the analog display oscilloscope.

4.1.3 Tool Temperature

A series of tests was conducted to verify the accuracy of the ultrasonic system in measuring the cutting tool's temperature. A type K thermocouple was used along with the ultrasonic system for all the temperature test. The thermocouple readings after correction as per section 3.2.1.3, were used for the temperature reference in all tests.

Tests were conducted for wet and dry machining. The cutting speeds, feeds, and depth of cuts were varied randomly to generate varied and transient tool temperatures. The response of the ultrasonic system was compared to the thermocouple response for several test conditions, which are rise and fall times, maximum temperature, steady state, and transient conditions. The responses of both sensors in all of the test conditions are presented together in five illustrations Figures 4.9-4.13. Each of the illustrations exhibit the various testing conditions. As such, they will not be referred to individually during the discussion. The results of the tests are as follows:

The rise or response time of both sensors was close but different in all cutting situations. The maximum rise lag time of the ultrasonic sensor from that of the thermocouple occurred during dry machining, which was ~ 5 seconds. The maximum fall lag time (cooling off time) also occurred during dry machining and was on the order of 2 minutes. The maximum lag of rise and fall times during wet machining were on the order of 2 and 30 seconds respectively.

The lag in the rise and fall response time of the ultrasonic sensor is mainly due to it measuring the overall temperature of the tool rather than the temperature of the cutting point. As such, the measurement is more weighted by the temperature of the

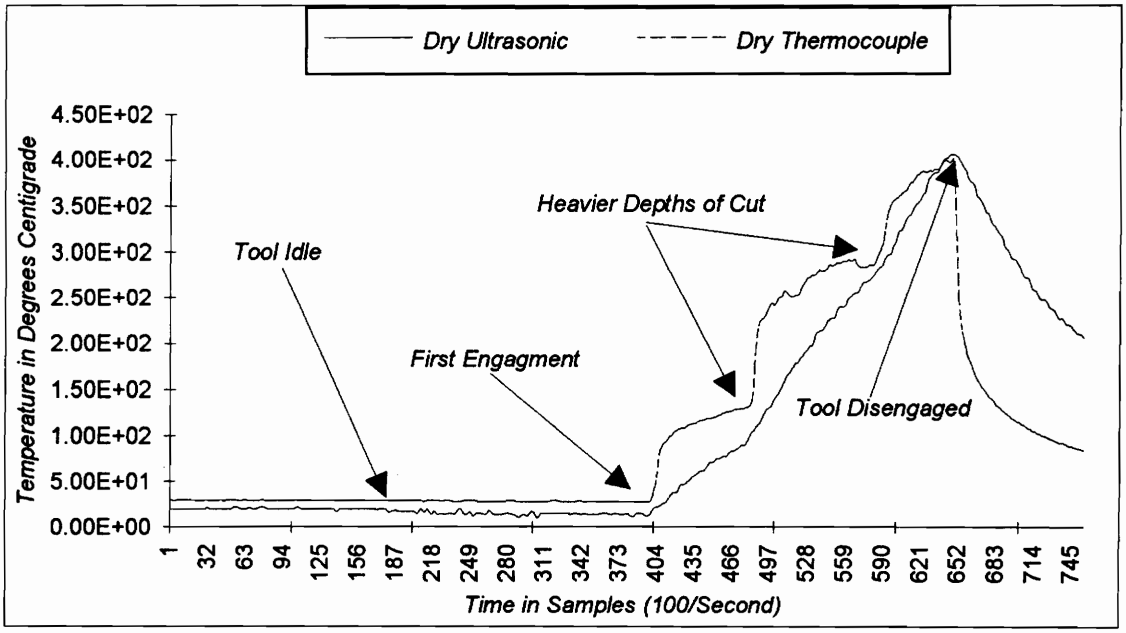

Figure 4.9. Ultrasonic and Thermocouple Temperature Response to Gradual Increase in the Depth of Cut (Dry Turning)

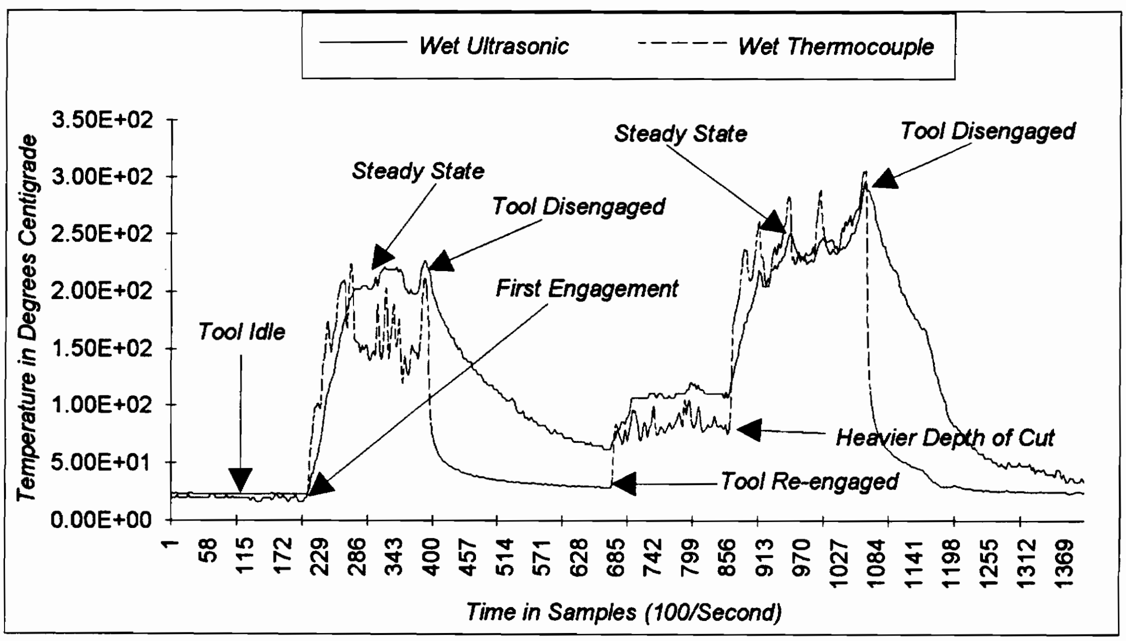

Figure 4.10. Ultrasonic and Thermocouple Temperature Response (Wet Machining)

body since the ultrasonic path in the body is much longer than in the cutting point. In the case of the reference thermocouple, its measurement is much more weighted by the cutting point's temperature since it is located very close to it. Therefore, the expected response time for the thermocouple should be faster than the ultrasonic sensor. As such, the experimental results are consistent with the expectations.

In the case of wet machining, the cutting fluid directly cools the body of the tool, and indirectly cools the obscured cutting point. Therefore, the rate of cooling is faster for the body than the cutting point. Thus the temperature of the tool body in this case has less influence on the ultrasonic sensor's response. Although the overall change in the TOF is smaller for wet machining than dry machining, the rise and fall times of the ultrasonic sensor are sharper and closer to those of the thermocouple.

In most of the cases, the maximum temperatures recorded by the ultrasonic sensor were within ± 5% of thermocouple's readings, and in few of the cases were within ± 10% (see Figures 4.9-4.13). The ±10% readings occurred during repeated engagements and disengagement's of the tool during dry machining. The maximum ultrasonic temperature, in general, lagged the thermocouple by a maximum of ~ 5 seconds. The largest differences between the two sensors occurred after the disengagement of the tool and especially during multiple engagements-disengagement's (see Figure 4.13).

During steady state cutting, there was an overall agreement between the two sensors. The differences were on the order of ± 5%. However, there were small fluctuations measured by the thermocouple, which were not as noticeable on the ultrasonic curves. The fluctuations were on the order of $\pm 20^0$ C. The ultrasonic sensor's response was similar to that of averaged thermocouple responses. This is consistent with the overall slower and integrated response of the ultrasonic sensor.

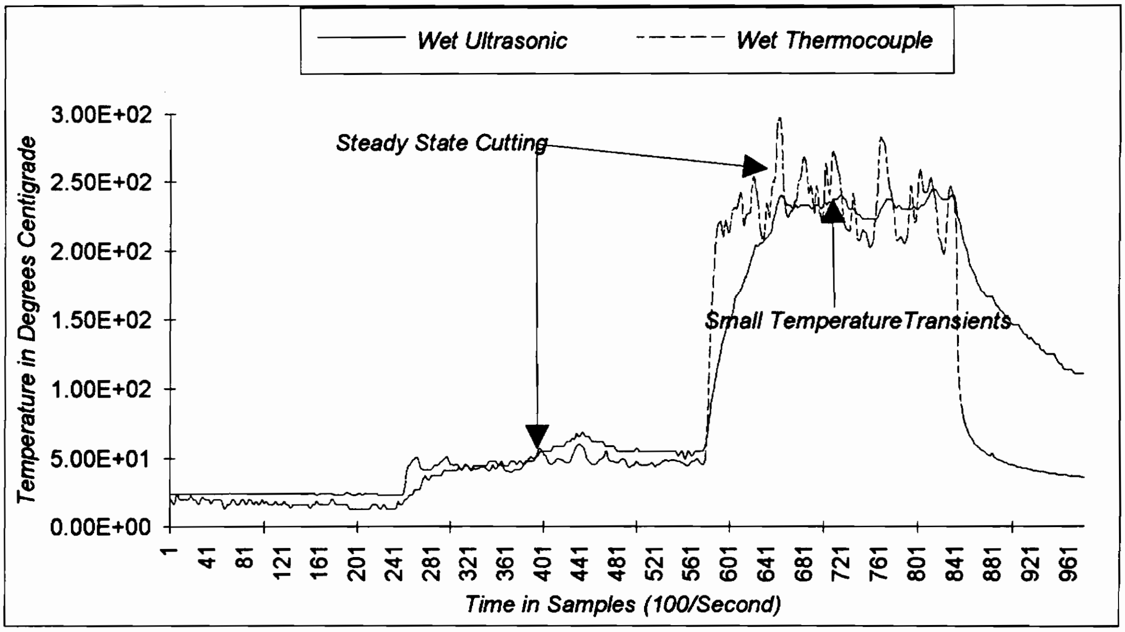

Figure 4.11 Ultrasonic and Thermocouple Response to Small Transients

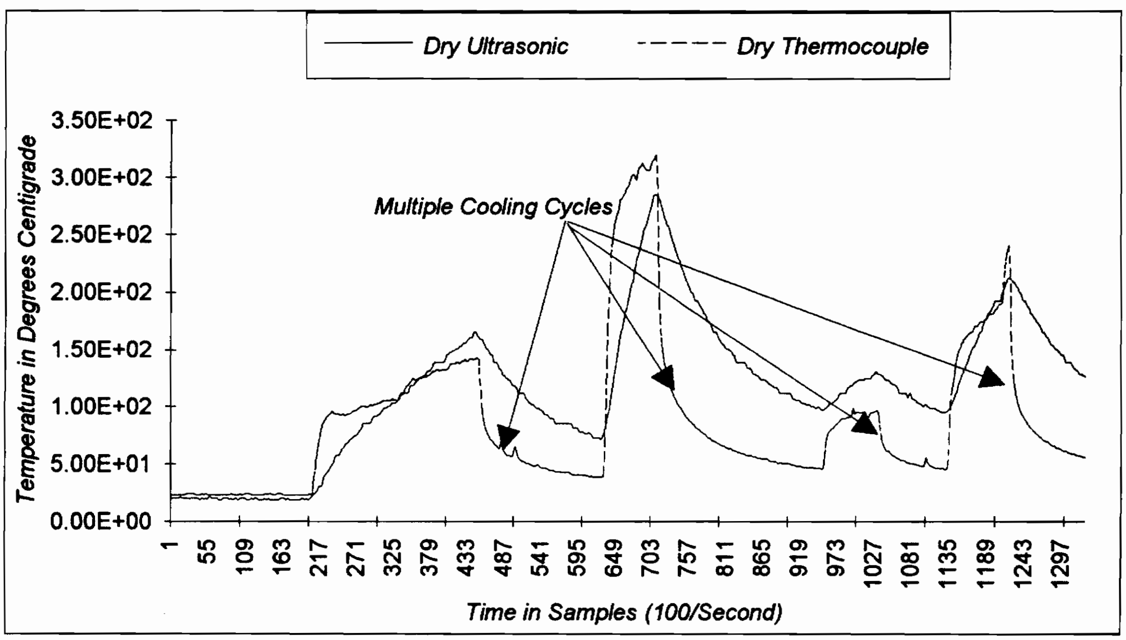

Figure 4.12. Ultrasonic and Thermocouple Response to Multiple Cooling Cycles

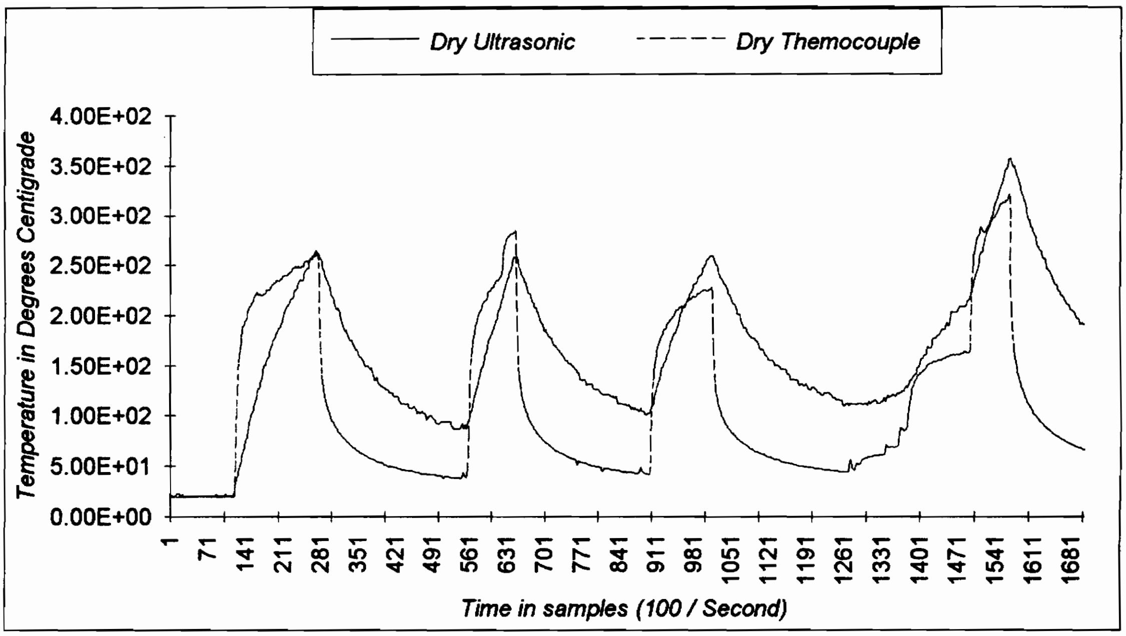

Figure 4.13. Temperature Over Estimation by Ultrasonics During Repeated Engagements

Large transients resulting from quick repeated tool engagements and tool disengagments and/or larger depths of cut caused the ultrasonic sensor to overestimate the maximum temperature during dry machining. The maximum error recorded was within the ± 10% of the thermocouples' readings. This is due to the longer fall time of the ultrasonic sensor and the use of a single conversion factor for both the rise and the fall response.

4.1.4 Gradual Wear

Six tool wear tests were conducted to evaluate gradual wear measurement of the nose and the flanks. Wear was developed by cutting 4130 HR 52 steel at various speeds, feeds, and depths of cut. Cutting fluid was applied during all machining operations. In all cases, the wear varied randomly at different measurement points from uniform to somewhat irregular. Maximum wear land height VB in the range of 0.015"~ 0.017" was used as the criteria for tool life end. The ISO standards (refer to section 2.2.2) for uniform and irregular tool wear are, VB = 0.3 mm (0.0118") for uniform wear or VBmax = 0.6 mm (0.0236") for irregularly worn tools.

The measurement procedures were as follows:

1. A wave form and the TOF were recorded for the new tool (base wave form).
2. The tool was then used to cut for 10~15 minutes.
3. After disengaging the tool, at random time intervals (20~100 seconds), a new wave form and the TOF were recorded.
4. The tool holder was then removed and the wear land height and width was measured with a tool maker's microscope while the tool remained in the holder.
5. The cycle was repeated until the wear land height reached ~ 0.016".

Since the measurements were taken at random intervals, the total number of measurement points per tool varied from 8~10 points. All wave forms were recorded at 800 MHz sampling rate and 500mv full scale display. The wave forms were later processed off-line following the procedure outlined in section 3.2.2.4. The Amplitude-temperature correction, in most cases, was small or negligible since the tools were cooled rapidly by the cutting fluid.

The objective of these tests was to determine if a correlation exists between the ultrasonic measurement and the gradual tool wear of the nose and the flanks. Several comparisons were made between the two types of data, which were:

1. The change in the nose and flanks integrals Vs wear land width
2. The change in the nose and flanks integrals Vs wear land height
3. The sum of the changes in the nose and flanks integrals Vs wear land width and height
4. The absolute value of the change in the nose and flanks integrals Vs wear land height
5. The sum of the absolute value of the changes in the nose and flanks integrals Vs wear land height

The change in the wave form integrals of the nose or the flanks, and their sum Vs the wear land width followed a somewhat erratic behavior, in that the difference in the integrals between two samples could increase or decrease. Although the overall trend increased with wear, the correlation with the width of the wear land was poor as illustrated in Figure 4.14.

Comparing the change in the integrals of the nose or the flanks, and their sum to the wear land height resulted in similar erratic behavior as in the previous comparison.

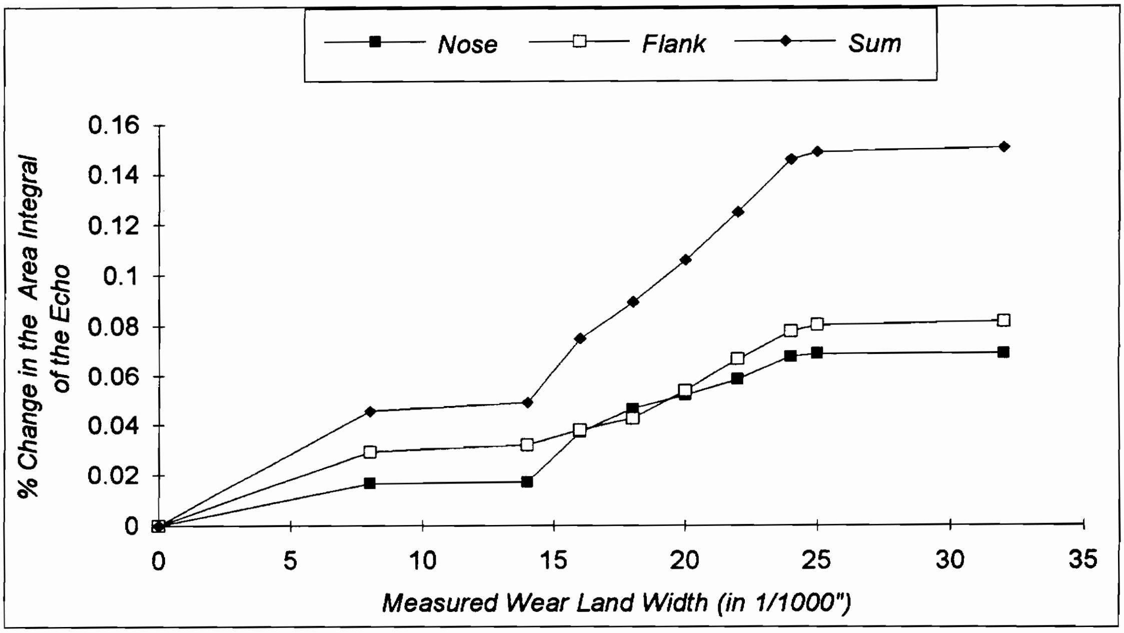

Figure 4.14. Differences in the Wave Form Integrals Vs Wear Land Width

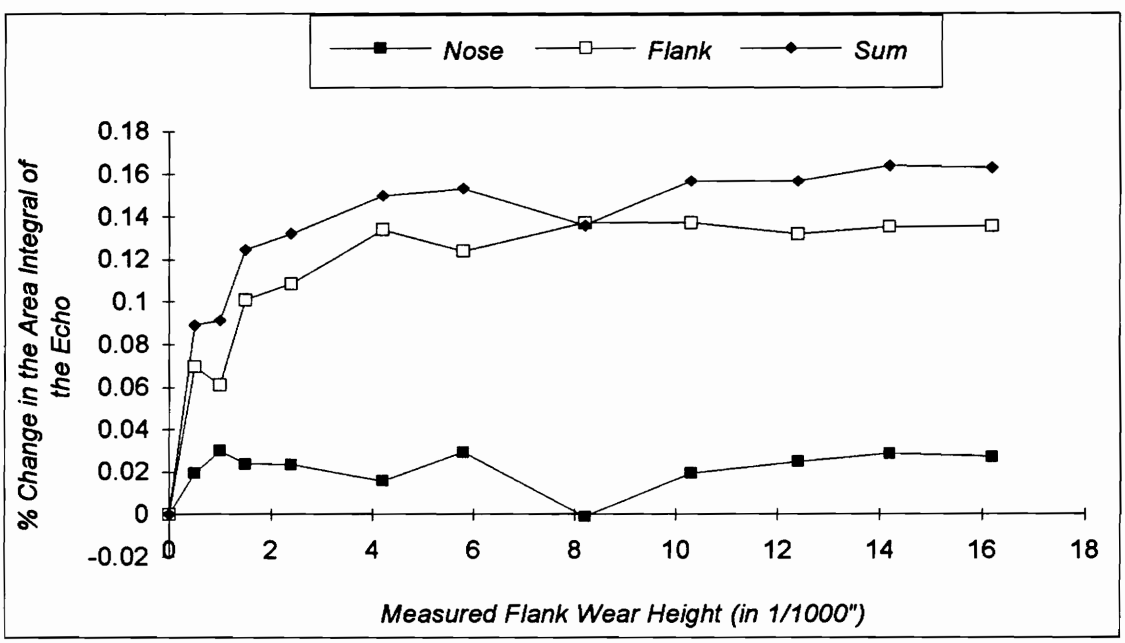

Figure 4.15. Differences in Wave Form Integrals Vs Wear Land Height for Tool One

In essence, the ultrasonic data has not changed. In addition to the erratic behavior, the trend is considerably different for each tool as illustrated in Figures 4.15 and 4.16.

The absolute value of the change in the integrals of the nose or the flanks yielded a much better correlation with the wear land height. The trends for both the nose and flanks were much more stable and followed the gradual wear trends. However, the sum of the nose and flanks measurements were much smoother and followed a much more stable trend as illustrated by Figure 4.17.

All the tools exhibited excellent correlation between the combined nose and flanks measurements of the absolute change in the wave form integrals of the nose and flanks with the wear land height. However, the individual tool's trends were different from each other as can be seen in Figures 4.17 and 4.18.

The sum of the absolute values of the changes in the integrals of the nose and the flanks of six tools Vs the wear land height is presented in Figure 4.19. Although each tool exhibited its own individual trend, however, two main clusters appear in the Figure 4.19. The two clusters could not be attributed to the selection of the tools since all came from the same box, and only one cutting side of each tool was used in each of the experiments.

4.1.5 Tool Chipping and Breakage

Tool chipping is rare, sudden and an unpredictable phenomena. As such, and with the present experimental system, massive amounts of wave forms would have to be acquired and analyzed off-line to retrace the occurrence of chipping. The phenomena can be equally and easily demonstrated off-line by comparing the wave forms of chipped tools to new ones.

In most cases, small chunks are chipped off the nose of the tool. At a minimum, this would appear as a step in the gradual wear curve. Since the geometry of a tool chip is

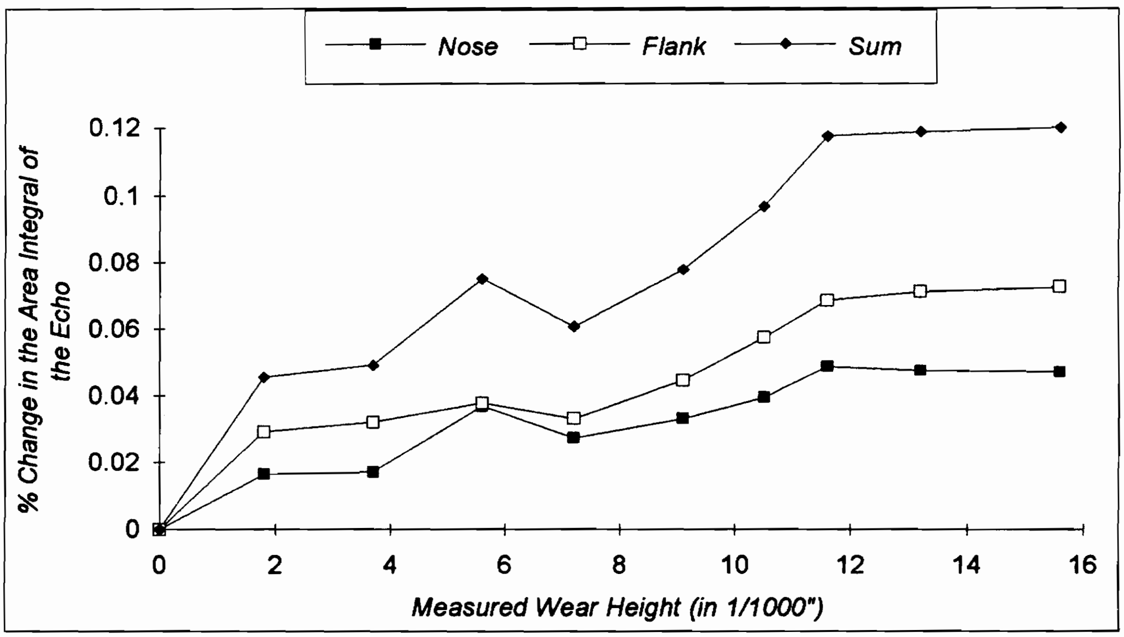

Figure 4.16. Differences in the Wave Form Integrals Vs Wear Land Height for Tool Two

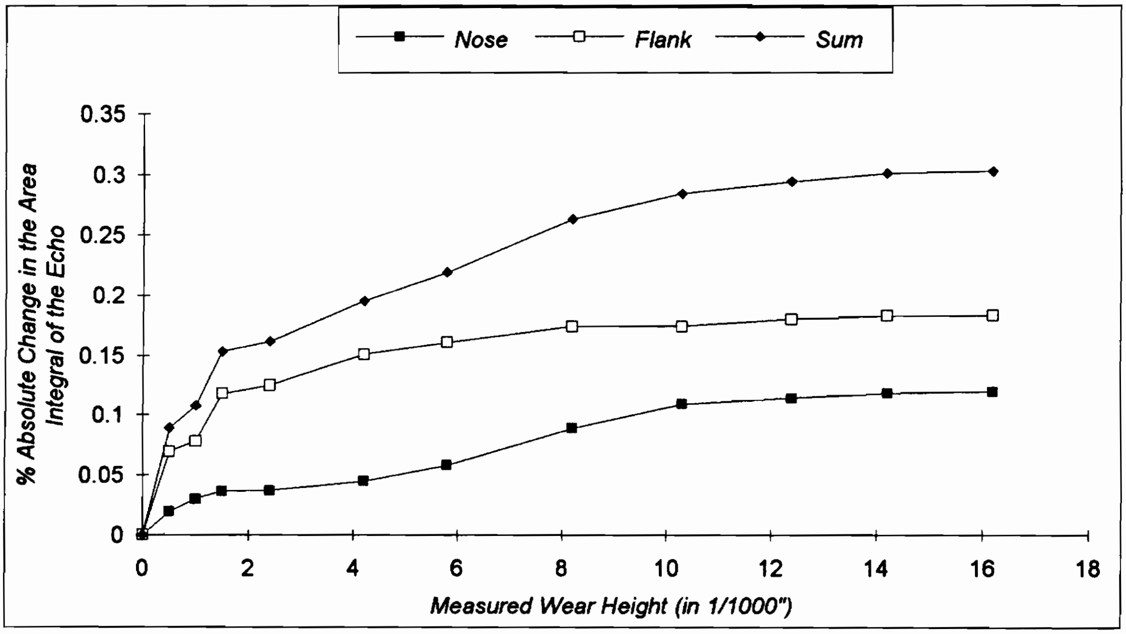

Figure 4.17. Absolute Value of the Differences in The Wave Form Integrals Vs Wear Land Height for Tool One

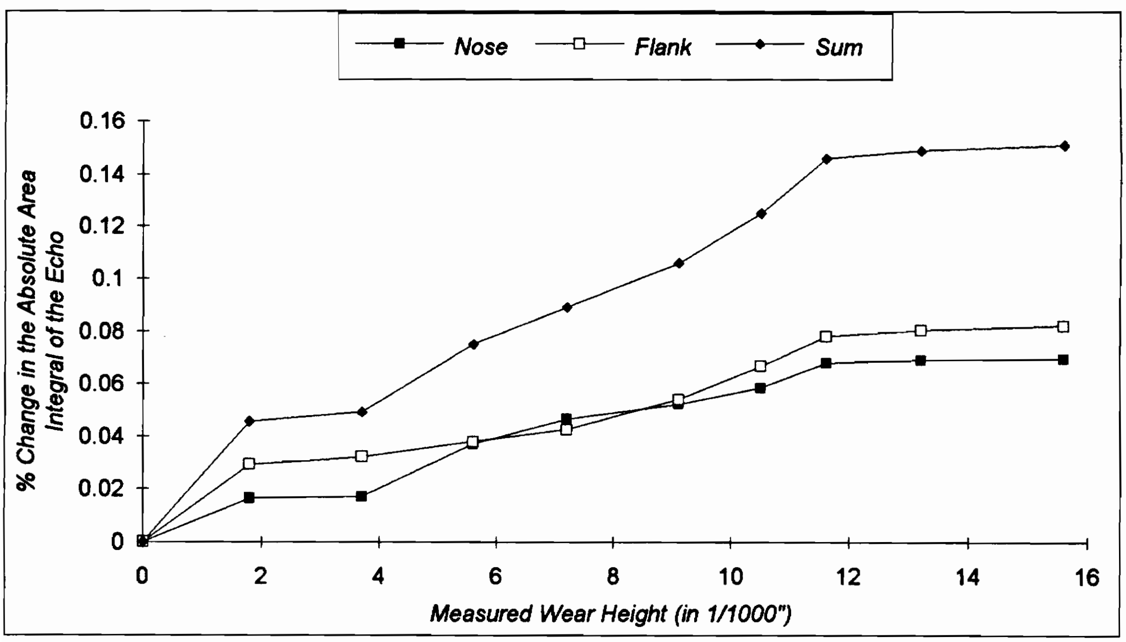

Figure 4.18. Absolute Value of the Differences in The Wave Form Integrals Vs Wear Land Height for Tool Two

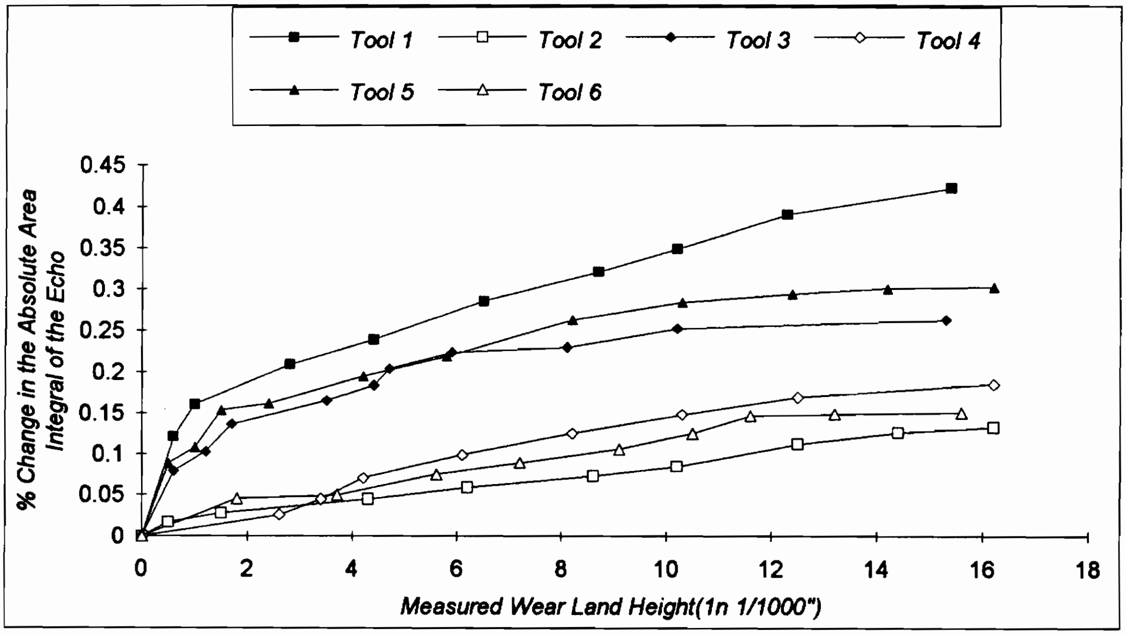

Figure 4.19. Ultrasonic Gradual Wear Measurement Vs Wear Land Height

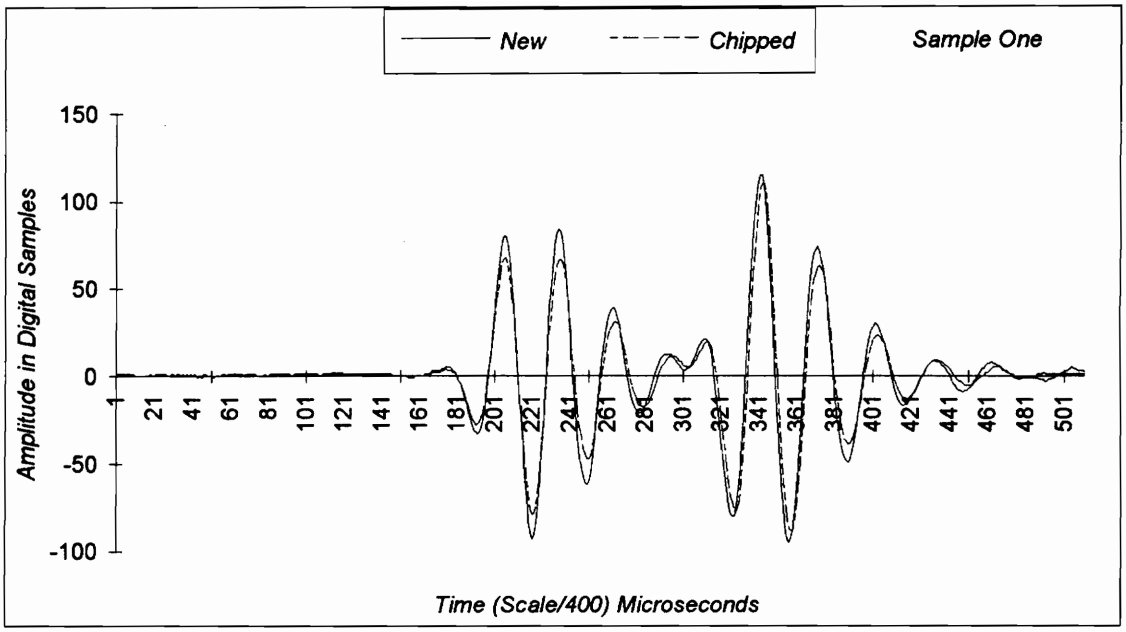

Figure 4.20. Ultrasonic Tool Chipping Detection (Sample One)

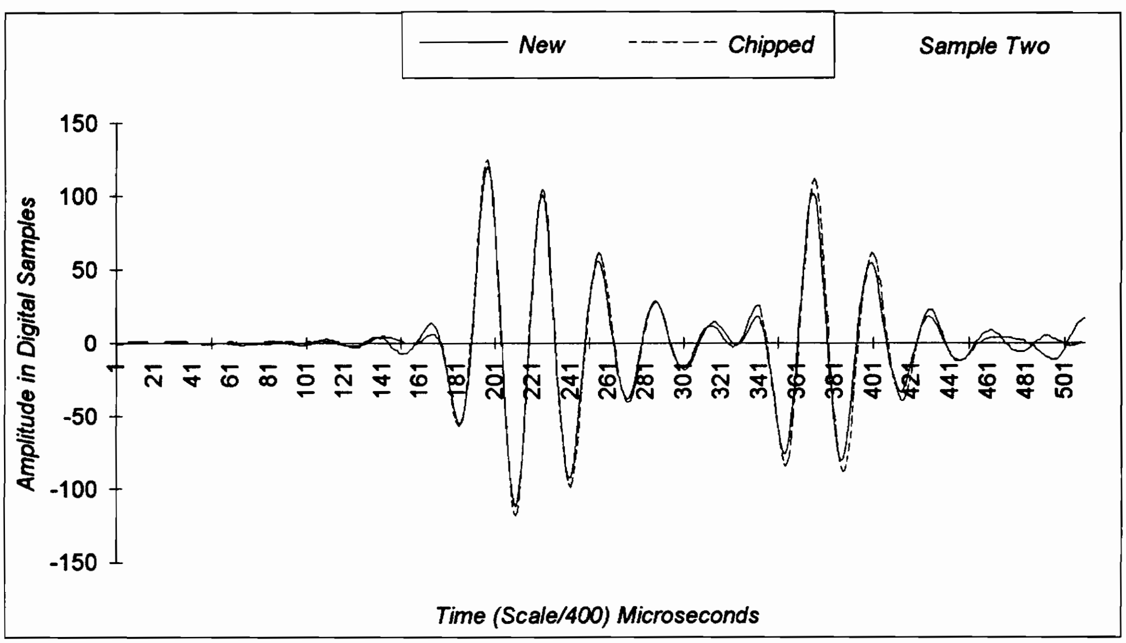

Figure 4.21. Ultrasonic Tool Chipping Detection (Sample Two)

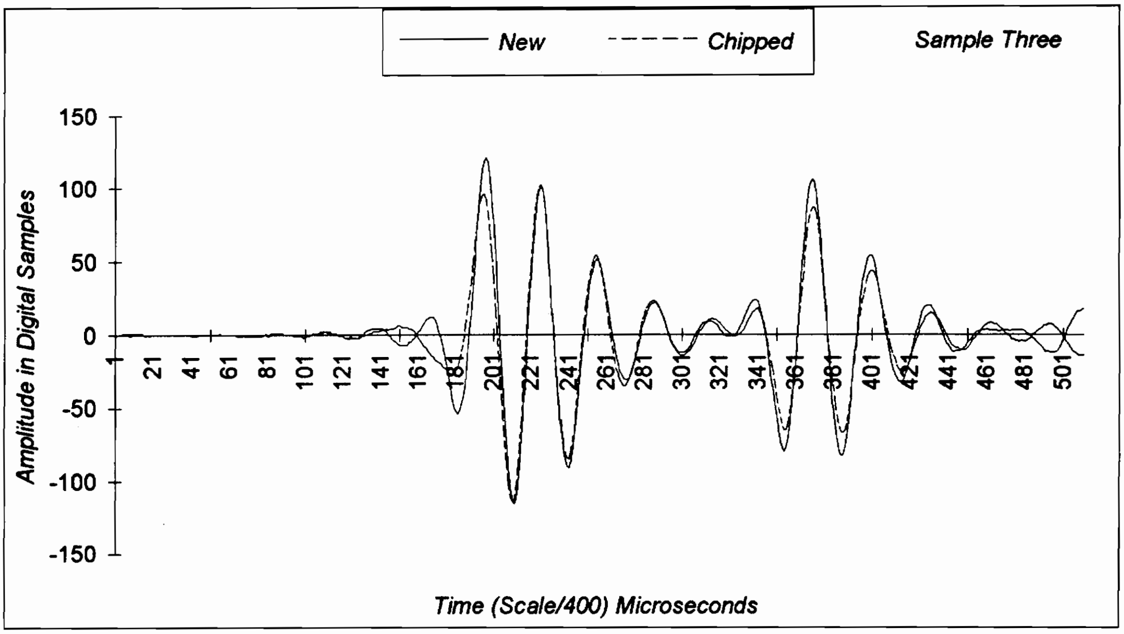

Figure 4.22. Ultrasonic Tool Chipping Detection (Sample Three)

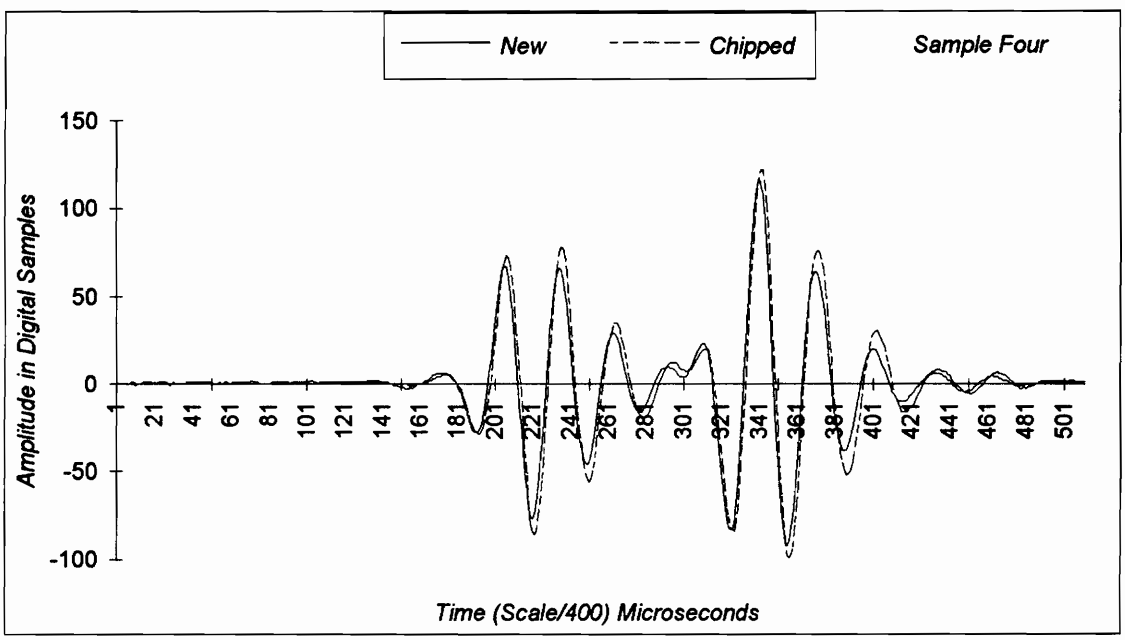

Figure 4.23. Ultrasonic Tool Chipping Detection (sample Four)

unlike gradual wear, in that its orientation is random, direct and an exact correlation between the chip size and the magnitude of the step in the area integral of the wave form is impossible. However, there will always be a recognizable change or a step in the wave form. In addition, if the chip is large enough or if the tool breaks, both of these conditions would cause large changes in the wave form's amplitude and/or may alter the wave form completely.

Examples of both scenarios are presented in five illustrations. The wave forms for four relatively small size chips are presented in Figures 4.20-4.23. The magnitudes of change in each of the area integrals of the nose and the flanks for each tool are: +14.6%, -10.6%, +9.2%, and -11.8% respectively. In the case of the large chip, the change was 48.7%.

In principle, stress cracks appear in the tool before a chip actually separates from the body of the tool. The speed of crack propagation and the actual separation of the chips is fast and is currently not known. Ultrasonic waves, among other nondestructive evaluation methods, have been used extensively to detect stress cracks in solids. Therefore, in theory, stress cracks leading to tool breakage and chipping can be detected if the sampling rate and the processing of the signal are faster than the actual propagation of the stress cracks.

4.2 Summary of Results

The test results were successful in all areas of concern, and were conclusive in two of the tested areas, which are tool temperature and chatter. The capabilities of the system in reacting to the physical phenomena's of tool chipping and tool/work contacts were demonstrated. The system's response to gradual wear differed for individual tools;

however, there was an excellent correlation between the ultrasonic measurements and gradual wear for each tool.

Both forms of tool-work contacts can be clearly identified from the wave form amplitude changes. The repeatability of the positional accuracy of contact detection cannot be verified with the current experimental system. However, the potential is clearly demonstrated by the results. The positional accuracy can be greatly enhanced by higher sampling rates and higher A/D converter resolution.

Chatter levels below 0.1G were not detected by the 8 bit digital acquisition system, however, they were clearly visible with an analog display oscilloscope. In addition, very small chatter levels, which were not detected by the accelerometer were observed on the analog display oscilloscope. The change in the signal in the observable range was gradual and consistent with the levels indicated by the accelerometer.

There was good agreement between the two sensors in measuring the tool temperature under most conditions. In addition, there was excellent agreement in the critical area of maximum temperature. The response of the ultrasonic sensor improved considerably during wet machining, which is the prevailing mode of operations. The largest discrepancies were encountered during tool disengagments, which is not a critical area.

Gradual wear requires additional work to resolve the differences in the trends between the different tools before the measurement can be utilized. Apparently the ultrasonic signal is effected by an intensive property of the various tools. Currently, and based on the previous results, one cannot determine which trend line the tool will follow without optically measuring the tool at two or three initial wear points. The measurement in this case could be used as an overall wear indicator.

Several tool chipping examples were presented and discussed. In all cases the changes in the wave form integrals were significant and observable. The methods employed in detecting gradual wear were used to measure the impact of chipping on the wave form. Although the tests conducted were static, none-the-less, the physics of tool chipping detection was demonstrated.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results of the feasibility study indicated that it is possible to measure several relevant tool and process cutting parameters directly and on-line in turning operations. This study further showed that these parameters can be measured efficiently by a single active ultrasonic sensor. Most of the required acquisition hardware is available commercially. However some engineering and wave mechanics issues remain to be resolved in future work.

Overall, the ultrasonic system's ability to measure or detect the proposed parameters and/or conditions were excellent. There is no need for further study of the physical phenomena of four of the five parameters tested; they are tool-work contact, tool temperature, chatter detection, and tool chipping. Currently, and with the present tool-transducer assembly, it is possible to measure all of the parameters on-line, given a CNC lathe, a higher resolution A/D board, a 10 kHz pulser-receiver pulse rate, and the completion of the acquisition software. Any limitations in the system's ability to fully measure or detect these parameters and/or conditions are solely due to the inadequacy of the current experimental system.

5.2 Future Work

Application of the current system is limited to turning with the present tools, tool holder, and transducer combination. In addition, the current system's A/D conversion accuracy, data acquisition speeds, and the acquisition software restrict its operation to laboratory settings. In order to fully utilize the system on the shop floor, the following improvements and /or studies are needed:

1. Data Acquisition. A minimum of 12 bit, 100 MHz independent, and 800 MHz ETS A/D converter is needed to improve the resolution of the system and reduce the jitters in the measurements. The software acquisition and throughput rate must be increased to 1 kHz in order to measure the full spectrum of chatter and to reduce the reaction and decision making time.

2. Transducers and Tools. A transducer capable of coupling to the various shapes and styles of turning tools must be developed. A generic tool holder is also needed in order to accommodate the transducer/tool assembly.

3. Ultrasonic Studies. A study of the mechanics of wave propagation in cutting tools is needed in order to determine the optimal transducer geometry, type, and frequency. In addition, a study is needed to resolve the differences in the gradual wear trends and/or to develop a robust calibration methodology.

5.3 Applications

The maximum benefits of the proposed sensing methodology can be realized by its application in full in CNC and unattended machining as part of an adaptive control strategy. The ultrasonically measured parameters of the tool condition and the cutting process state form the feed back inputs, solely or coupled with other inputs, as needed. In such an application, the machining process performance can be improved by 20-80%, depending on the part's geometry and complexity of the operations. Furthermore, the down time resulting from chipped and or damaged tools can be reduced by up to 6-8%. Inaccuracies due to tool wear can be reduced considerably by the tool/work contact detection and the potential capabilities of measuring gradual wear on-line.

Parts of the system can be utilized in conventional machining for tool condition monitoring and tool/work contact detection. The system's outputs can be displayed in a format, which would help the operator maximize the operations performance and improve the dimensional accuracy. Damage caused by catastrophic tool failures can be reduced as in the case of CNC and unattended machining by automatically disengaging the tool and stopping the machine.

The system can be used as a research tool for the study of turning operations. Temperature behavior, wear characteristics, and the degree of intimacy between the tool and the work can be studied without removing or moving the tool. Very low levels of chatter were observed with an analog oscilloscope. With a fully operational system, fine resolution chatter studies can be conducted.

Other applications include, tool/work contact detection may be used in other machining operations, such as milling to determine the multi-axis zero positions of the tool with respect to the work. Tool chipping and breakage in drilling, tapping, boring and milling operations may also be determined, subject to further studies.

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Taysir Nayfeh was born on October 6, 1951 in Jordan, immigrated to the US in 1969, and became a US citizen in 1980. He worked in various industrial capacities after completing high school education in 1970. Started his college education in 1974 at Virginia Polytechnic Institute and State University (Virginia-Tech) and returned to industry in 1980 before completing his degree. Taysir completed his B.S. in Physics in 1987. In 1989, Taysir returned to Virginia-Tech and received an M.S. and a Ph.D. in Industrial and Systems Engineering in 1991 and 1993 respectively.

He was employed by Schlumberger Well Services from 1980-1989 at various locations and in several positions in field service, marketing, engineering, and manufacturing. Taysir has developed several products and solved many engineering problems, which earned him the General Managers Award in 1986.

Taysir has been appointed to the rank of an Assistant Professor of Industrial Engineering at Cleveland State University. He will be teaching and conducting research at the University and at Cleveland's Advanced Manufacturing Center starting in the fall of 1993.