Acoustic emission (AE) monitoring of the milling process with coated metal carbide inserts using TRIM C270 cutting fluid

Aditya Dhulubulu
University of Toledo

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A Thesis

entitled

Acoustic Emission (AE) monitoring of the milling process with coated metal carbide
inserts using TRIM C270 cutting fluid

by

Aditya S. Dhulubulu

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Master of Science Degree in Mechanical Engineering

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June 2015
An Abstract of

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The use of Metal working fluids for any cutting mechanism has been found to
affect the tool wear in a positive manner, but more importantly it is the way of applying
this fluid that has significantly impacted the tool wear. In this study, experiments were
conducted on AISI 4140 alloy steel to determine the performance of three different
applications of cutting fluid using an end milling process. TiAlN coated metal carbide
inserts were used for cutting under three different levels of surface speed, chip load and
depth of cut. The response variables collected were Acoustic Emission (AE), Forces,
Temperature and Tool wear based on which, cutting fluid applications were categorized
for their performances. In addition, more emphasis was given on the AE results to
observe its potential to provide necessary real time knowledge and tool wear monitoring capability during cutting process. AE Hit values were recorded as a parameter to study the tool wear results based on different ways of fluid applications. The results in this research point to the fact that different ways of applying a cutting fluid impacts the tool wear, forces, temperature and the acoustic signals in a positive manner. Furthermore, three statistical models to predict the tool wear in near future were proposed based on the response variables from this research.
Acknowledgements

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<th>Abbreviation</th>
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<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>AIS</td>
<td>American Iron and Steel Institute</td>
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<tr>
<td>BUE</td>
<td>Built Up Edge</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>DADiSP</td>
<td>Data Analysis and Display</td>
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<tr>
<td>dB</td>
<td>Decibel</td>
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<tr>
<td>HDT</td>
<td>Hit Definition Time</td>
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<tr>
<td>HLT</td>
<td>Hit Lockout Time</td>
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<tr>
<td>HPC</td>
<td>High Pressure Coolant</td>
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<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>MWF</td>
<td>Metalworking Fluid</td>
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<tr>
<td>PDT</td>
<td>Peak Definition Time</td>
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List of Symbols

U   Electrical Energy
R   Electrical resistance in ohm
V   Output potential (volt) of transducer
b   amplitude distribution slope parameter
f   resonant frequency (hertz) of transducer
N   cumulative counts
P   cumulative hits
τ   decay time (seconds) of the hit
C   Regression constant
α   Regression constant
β   Regression constant
γ   Regression constant
λ   Regression constant
V_c Surface speed
CLPT Chip Load Per Tooth
d   Depth of cut
V_b Flank wear
Chapter 1

Introduction

1.1 Overview

With the progress of industrialization, manufacturing of products with complex geometries and dimensional accuracy was possible and eventually improved the overall productivity. Engineers in this period were able to automate most of the machining process. Early days machining involved lathe centers which then gave rise to milling machines.

The milling process involves the use of rotary motion of tool with the work piece being stationary, resulting in the removal of material in the form of chips. Depending on the orientation of tool and workpiece, the task of material removal can be achieved with either a (a) Vertical milling machine, where the tool is held and rotates vertically above the workpiece or (b) Horizontal milling machine, where the tool is held in a horizontal position in line with workpiece held in a chuck.

The two basic modes of milling are (i) Face Milling and (ii) Peripheral Milling.

The process of face milling involves the use of the corner edges (nose) of the cutting tool which results in a flat surface where the depth of material removed depends
on the axial depth as well as the width of material removed is radial depth across the axis. The tool axis in this case is perpendicular to the work piece surface to be machined.

On the other hand, Peripheral milling involves cutting with the sides or the walls of a cutter and thus generates slots in the workpiece. The orientation of the tool with respect to the workpiece, in this process, is parallel to the work piece surface where the width of material being removed is the radial depth and depth of material removed is the axial depth.

The most common Peripheral milling in the cutting process is End Milling, which is the focus of this project. An end mill cutter is usually of a small diameter ranging from 5mm to 30mm which is held by the tool holder in location. The end mill and a face mill tool look similar to each other. In regards to face milling, the major difference to point out is the new surface generated is perpendicular to the cutter axis while in end milling its parallel to the cutter axis.

The tools are further categorized as single point and multipoint cutting tools based on the operation performed. Single point tools generally involve cutting inserts with the single edge of the tool; while on the other hand, multipoint has more than one cutting edge involved in cutting. Examples of which are drills, end mills, remmers, etc.
1.2 Objective:

Industries until date are struggling to control the tool wear during machining by the use of cutting fluids and figuring out the ways to apply these cutting fluids during machining. Certain operations demand abundant use of coolant while others are performed dry. Researches have been trying to implement the real time monitoring technique to understand the above relation by using – Forces, Acoustic Emission, Ultrasonic, Temperature and vibration monitoring systems. Of all the above, use of Forces and Acoustic Emission have been proven to be favorable sensing techniques to monitor the machining operation.

The Objectives of this research are summarized as below:

1. Select three different modes of cutting fluid application and study their effect on parameters like Tool wear, Cutting temperature, Forces and Acoustic Emission and accordingly rate the application.
2. Second objective of this research is to observe if there exits any relation between Forces, Temperature and Acoustic signals with Tool wear.
3. The third objective is to check the potential of the AE system in monitoring the tool wear.
4. Final objective is to establish a statistical model to predict the response variables with different input parameters for any future use.
Chapter 2

Fundamentals and Literature Review:

Metal Working Fluids:

Research has shown the use of Metalworking fluids (MWF), also known as cutting fluids, in machining has played a pivotal role and as a result has improved machinability. The major role that they play has been recognized in providing a layer of lubricant in order for it to act as a cushion to lower the friction generated between the workpiece and the tool. In addition, they are required to perform as a coolant to minimize the heat produced during machining and should be capable of flushing away all the chips generated during metal cutting operation. The studies conducted by Trent and Wright have found that the use of MWF increases tool life, improves surface finish, helps prevent overheating of the workpiece, assists in removing the swarf from the cutting area, reduce cutting forces, and prevents the occurrence of corrosion of the workpiece and machine tool (M. Stanford, P.M. Lister, 2005). Currently there are various types of MWF available in market ranging from oils, oil – water emulsion, pastes, gels, aerosols; which are made from petroleum products, animal fat, plant oil and water. The major roles they play in machining are detailed as:
Roles of Metal Working Fluids:

1.) **Transportation of chips:** Every time the tool cuts certain amounts of material from the workpiece, it is directed away from the cutting zone in the form of chips. The shape of such chips depends upon the type of material being cut. A brittle material will lead to discontinuous chips while ductile materials like steel, which is used in this project, will lead to continuous chips. In addition, the cutting parameters like depth of cut and feed also decided the shape of the chips. As the MWF help clear away the chips from the cutting zone, this ends up in generating a better surface finish. Moreover, the flushing of chips helps prevent tool breakage by preventing the tool from getting stuck in conditions such as drilling where the clogged chips tend to seize the tool in the hole drilled.

![Diagram of chip transportation](image)

Figure 2-1: Generation of Build Up Edge (BUE)
Another major issue is the formation of Build Up Edge (BUE) as shown in figure 2.1 at the contact between tool and workpiece during cutting. The chips tend to flow over the tool rake surface in normal cutting condition but in absences of cutting fluid, these chips tend to pile upon the tool and create a layer which covers the cutting edge of tool. This results in the cutting edge being inactive and thus raises the cutting forces. BUE generated thus results in a situation similar to a blunt edge. BUE can therefore be responsible for the poor surface finish of the material being cut and lead to increased temperatures.

Thus cutting fluid has been proven helpful in cutting conditions but there are certain limitations of using fluids while machining with brittle material. This includes most of the cast iron as it tends to form fine powder as opposed to chips, which when in contact with MWF, forms thick slurry causing further machining problems.

2.) **Cooling of the Tool and workpiece:** Controlling the cutting Temperature has always been a big struggle in metal cutting industries as it has been seen strongly influencing the generation of tool wear, mechanism of chip formation, workpiece surface integrity and its contribution towards thermal deformation of cutting tools (N.A. Abukhshim et al. 2006). It has also been observed that excess heat results in expansion of metals while cutting, thus affecting its dimensional accuracy. In addition, cases have been reported of tool seizures as heated metal tend to stick to tools resulting in tool failure.

A Cutting mechanism, when seen microscopically involves two major processes. The first of the major processes is the friction between cut chips and tool rake surface, and between workpiece surfaces and the tool flank surface. Secondly, the shearing action
due to interaction of the cutting edge and workpiece which is involved during cutting process.

An observation by Ernst Merchant, who was successful in measuring the temperatures at the chip-tool interface, was that heat evolves from two sources. In the first source, energy was used up in deforming the metal, known as shearing action. The second source utilized energy to overcome the friction between the chip and the tool (Byers, J. P. (Ed.), 2006). Studies indicate that friction contributes approximately 75% of the total heat generated while the rest is from the shearing action. From all of this generated heat, 70% is been carried away by chips, 15% goes into the tool and the last 15% is carried away by the fluid. In an experimental work conducted by (Wisley Falco Sales, et al., 2002), it was observed that shearing action during metal cutting tends to generate increased levels of heat even with the use of MWF that have higher cooling capability. It was attributed to the fact that, MWF which transfer larger amount of heat, reduce the softening effect of the workpiece material. This results in the utilization of more energy by the tool toward shearing and ultimately increases the temperature at the cutting zone. Figure 2.2 below shows the possible temperature values during metal cutting.
Figure 2-2: Temperature distribution in the cutting zone.
[Source: After G. Vieregge, Werkstatt and Betrieb, No. 11, 1953, p. 696]

Conditions of increased temperature indirectly result in increased cutting forces, poor surface, increased tool wear, etc. Efforts are made to control this rise in temperature with the help of using coated inserts and cutting fluids by adding certain additives which are able to absorb the excess temperature generated, keeping the tool and workpiece thermally stable. Research done by (Nambi Muthukrishnan, Paulo Davim, 2011) indicated an improvement in surface integrity due to the presence of coolant in the interface which reduced the heat generated by preventing the tool from adhesion type of wear.

Water is proven to be the best coolant until now. Its poor lubrication property and lower rust inhabiting property has resulted in discontinuing its use as a cutting fluid. Oils have been tested and proven to be exactly the opposite. By studying the above phenomena, researchers Ernst Merchant and Shaw combined high lubricity chemical with water to form a stable chemical emulsion. This resulted in a new type of cutting fluid
which has the ability of lowering the friction and the generation of high temperature
(Byers, J. P. (Ed.), 2006).

MWF are made from a mix of water and oils and categorized as oil water
emulsions, these types of MWF have been examined to lower the cutting force compared
to using neat oil during Misting application (Yanqiao Zhang, Martin B.G. Jun, 2013)
(Sunday Albert Lawal, et al., 2012).

3.) **Lubrication:** As discussed above, friction generated between tool, workpiece, and
chips generate high temperatures. Thus in order to control the temperature it is essential
to minimize the effect of friction which can be achieved with the use of certain lubricants.
The oil based cutting fluids play an important role in controlling friction to a good level.

It is observed that flank and rake are the two surfaces of a cutting tool where
much of frictional mechanism occurs. Thus efforts are made for MWF to be able to
penetrate it in these regions in order to control the overall levels of friction. A lot of
research has been involved in the past to understand the phenomena of lubrication and
ways by which MWF could penetrate into the contact zone. Of several studies, the
following ways of MWF penetration were observed: a). interfacial capillaries network,
b). voids generated during the change in contact density attributed to tool fluctuations, c).
through the cavities generated due to periodic failures of build-up on the cutting edge,
and d). diffusion through primary deformation at the point of cutting zone (V.P.
Astakhov, S. Joksch, 2012) as shown in figure 2.3.
Figure 2-3: Different ways through which a cutting fluid can enter the cutting zone [Source: Metalworking fluids (MWFs) for cutting and grinding, V.P. Astakhov, S. Joksch, 2012, pg. 11]

However studies done in recent years indicate that transportation of MWF via capillary action is considered to be an effective way compared to all other forms.

Figure 2-4: MWF penetration model through single capillary

[Source: Metalworking fluids (MWFs) for cutting and grinding, V.P. Astakhov, S. Joksch, 2012]
It is assumed that the possible penetration of MWF are through the number of capillaries whose axes are focused along one direction of the chip movement that emerge in the zone of a leaky contact where the chips separate from the tool as shown in figure 2.4. Thus, considering the total volume of a chip, there arises a large number of capillaries which fill the whole width of the chip during the metal cutting operation.

These capillaries, when opened up, contain a vacuum. Therefore MWF are sucked inside due to a difference in the pressure levels. As a result, the contact surface in such a restricted part of the contact area gets divided by a lubricant layer reducing the thickness of a secondary shear zone on the surface of the chip and also lessens the angle of plastic deformation.

The entire process of capillary formation to the formation of a lubricant layer, as detailed above, totally depends upon the properties of MWF, the geometrical characteristics of the capillary system, and the thermodynamic parameters of the entire process (V.P.Astakhov, S. Joksch, 2012).

Studies have also found that it is the machined surface that rubs across the flank face. Also, the chip, which is being removed by the insert, rubs against the rake surface. It is therefore important to have a larger flank face clearance angle, or relief, when machining at slow speeds, as well as a lubricating fluid to assist in minimizing the friction from the rubbing of the tool against the machined surface (Jerry P. Byers, 2006).
Application methods of Metal working Fluids (MWF):

Selection of a proper cutting fluid isn’t the only factor to increase machinability, the way it has to be applied plays an important role too. In addition to this, the time has come that industries have started to cut down investments in MWF. It was found that MWF account for up to 15-17% of a shop’s total production cost as shown in figure 2.5. Furthermore, the cost of purchase, care, and disposal of cutting fluids are found to be higher than tool costs. Also, MWF have grabbed the attention of the Environmental Protection Agency toward its use and disposal, classifying it as a hazardous waste (Viktor P. Astakhov, 2007).

Figure 2-5: Cost of coolant application compared to overall expenses

[Source : Astakhov, V. P.,2007]
Thus it is critical that the MWF are applied properly and in a right quantity. Clyde Sluhan, the founder of Master Chemical Corporation and a pioneer in the industry, used to say, “If a cutting fluid cost you $25/ gallon and it saves you money, you’re a fool not to use it!” (Jerry. Byers, 2006). There are often times when proven MWF are misapplied and their effectiveness and potential to enhance productivity is lost.

![Diagram of point of maximum heat for dry and for coolant applied on top of chip only](source)

**Figure 2-6:** Point of maximum heat for dry and for coolant applied on top of chip only

[Source: Metalworking Fluids, by Jerry Byers, 2006, p.62]

One such instance where MWF were misapplied was documented by Jerry Byers in his book “Metal Working Fluids”. The book references figure 2.6, which observe dry cutting and cutting with coolant. It was seen that during dry cutting (figure 2.6. b) the point of maximum heat moves away from the tool tip as the swarf and chips slide across the rake surface of the tool. Although there are high chances of increased temperature levels due to dry cutting, there is a large bulk of tool in to which this heat can be dissipated.
But as observed in part a. of figure 2.6, the coolant was applied improperly by delivering it to the top of the chip which resulted in quenching only the inner surface of the chip and thus making it curl tighter. This brought the point of maximum heat closer to the point of cut, where less material was present to conduct away the generated heat resulting in lowering the overall tool life.

Thus, despite the presence of MWF, the impression is given that dry cutting results in improved tool life. Yet it would have been the other way around if the MWF had applied properly to the underside of the chip and between the chip and flank face (Jerry. Byers, 2006). Hence it is necessary that the coolant reaches the cutting zone in a sufficient amount and in a right location in order to control temperature and wear.

The different delivery methods of MWF are: Flooding, High pressure- High volume (Through Tool), and Minimum Quantity Lubricant (MQL) / Misting. These different modes depend upon the type of milling process, material to be machined, tool material, quantity of coolant available, health and safety factors.

This research was focused on three different modes of application which are discussed as follows:

1.) **Flooding**: Ever since the introduction of MFW for cutting operations, traditional low pressure flood application has been in tremendous use. “It was shortly after the Industrial Revolution in America; Frederick Winslow Taylor flooded the tool-work interface with heavy stream of water and discovered that cutting speed could be increased by a factor of 2 or 3.” (Nourredine Boubekri, Vasim Shaikh and Phillip R. Foster, 2008).
The whole idea of this application is to flood the cutting zone with copious amounts of coolant all over the cutting region. The MWF are delivered through two or multiple nozzles with an even flow rate by the help of a low pressure pump thus delivering the fluid in a laminar flow. One nozzle is positioned to help cool the tool after it leaves the cutting zone and another nozzle is held behind the tool so that it can lubricate the cutting zone.

The other big advantage of this method is that it assists in flushing away the chips and keeps the workpiece and surrounding environment lubricated in order to prevent any form of corrosion. However research conducted in the field of modes of application of MWF has led to the conclusion that flooding leads to maximum tool wear while machining with coated carbide inserts.

The experiment in this research was performed with two nozzles delivering fluid at a flow rate of 2 gallons/ min., placed close to the tool in order to get better performance. In addition, measures were taken to ensure that fluid is delivered in a laminar flow. The machining performed in this project is intermittent, so the care is taken that the tool always remains in contact with cutting fluid.

2.) **MQL / Misting** : In order to control and save coolant, researchers came up with this mode of application to utilize the least amount of coolant compared to all other applications. The coolant delivered is mixed with an appropriate amount of air or gas in order to generate a mist. The reason behind generating mist is to utilize the maximum surface area created by the atomized particles of coolant.
There have been controversies about the effectiveness of Misting in lubricating the cutting zone, but this method has been shown efficient in maintaining a temperature balance which prevents thermal damage of tools.

A typical MQL / Misting device works with the help of a pneumatically operated pump that sucks up the cutting fluid by an actuator and delivers it to the point of application with the help of a capillary tube. At the same moment, a hose surrounding this capillary tube delivers high pressure air resulting in a mix of the MWF and air, eventually turning it into a mist form.

A study conducted by researcher Dhar, et al., using AISI 1040 steel, indicates that MQL reduced the cutting temperature, cutting force, flank wear, and surface roughness more than dry cutting. MQL also increased the tool life and provided greater dimensional accuracy (Nourredine Boubekri, et al., 2008).

Furthermore, it was reported by S. Kajaria that in a study conducted by Liao and Lin using high speed milling of hardened steel, MQL facilitated the formation of a protective oxide layer on the cutting edge at an optimal cutting speed (Saurabh Kajaria, 2009). This protective oxide layer was the result of MQL providing extra oxygen during the metal cutting operation. In addition, the use of less viscous oils was recommended for an improved cooling effect during metal cutting operation.

Researchers Machado and Wallbank were able to observe that there was a significant reduction in the amplitude of variation of forces with the use of MQL. This was supported by the fact that the generation of mist resulted in better penetration of MWF in the contact zone (Wiesley Falco Sales, et al., 2001).
One plausible explanation towards the performance of MQL was hypothesized to be occurring due to evaporative cooling (Anshu D. Jayal, A.K. Balaji, 2008). The continuous heat transfer from the hot contact zone led to the formation of vapor phase in the MWF droplets which were then carried away by the air stream allowing fresh new MWF droplets to reach the contact zone. This overall mechanism resulted in restricting the formation of an insulating layer of cutting fluid which used to restrict the entry for the fresh MWF.

3.) **Through Tool**: Several attempts have been performed in order to control the temperature and lubrication at the contact zone which has led to the concept of high pressure coolant application.

   Research has indicated that most of the heat generated at the contact zone between tool and workpiece is because of shearing and sliding mechanism of chips over the tool rake surface. In order to control this heat generated by friction, attempts are made to apply coolant at the very point of contact with help of high pressure laminar flow using high pressure pumps and venturis/nozzels.

   This results in the application of coolant at the tip of the insert to act as a chip breaker by lowering its shear angle and preventing it from sliding over the rake surface of the tool. Additionally, this mechanism has been observed to generate a layer of lubricant which essentially lowers the friction and thus the cutting temperature.

   In a research experiment conducted by researcher R. Kovacevic et al., it was demonstrated that high pressure through tool technique performed better than flooding in
terms of its performance based on cutting forces, tool wear, and efficiency of metal cutting operation (R. Kovacevic, et al., 1995).

These experiments revealed that High Pressure Coolant (HPC) led to an effective penetration of MWF into the chip tool interface generating a hydro-wedge which was able to provide a hydrodynamic lubrication layer resulting in minimizing the contact surface between the chips and tool surface to a large extent. As described previously, the greater area of contact results in an increased levels of friction; thus an intimate contact formed between the chips and tool surface because of low pressure of the coolant in case of flooding application resulted in higher values of friction.

In addition, it was pointed out that the generation of this hydro wedge at the chip tool interface assisted in deviating the chips away from the tool rake surface which thereby promoted a self-breaking effect. This lowered the intensity of the shearing action which was indicated by less serration on the contact surface.

Another major reason for why this application has been more effective compared to flooding is its ability to restrict the formation of film boiling. The temperatures generated during metal cutting operations, at times, can reach beyond the boiling point of coolant used. This results in the formation of a blanket of vapor which restricts further cooling effect by isolating fresh coolant from heated surface. Flooding has been seen as a poor performer; as it lacks the high levels of pressure to break the vapor blanket generated, as opposed to high pressure where the coolant pressure is effective enough in overcoming this barrier.

Studies conducted on the mechanism of High pressure coolant application concluded that (Vishal S. Sharma, et al., 2008):
• Tool life increased with increase in the supply pressure of MWF to a certain level after which this increase was observed to be negligible.

• The improved cooling and lubrication effect resulted in lowering the cutting forces and improved surface finish with workpiece surface being free from physical damages such as cracks and tears.

• Eases of access of the MWF at the chip tool interfaces resulted in lesser hardening effect and microstructure damage.

• Reduced levels of cutting and feed forces were attributed to high pressure MWF’s ability to shorten the contact length of the chip and tool rake surface.

The pressure by which the MWF in our research was delivered had been set to 200 psi with the delivery nozzle of fluid pointing to the tip of cutting insert.
Cutting Tool Inserts:

The overall performance of any milling operation is depended on the condition of a cutting tool. Factors such as the workpiece surface finish, dimensional accuracy, effect of lubrication, machining power consumption, vibration, forces and temperature are all dependent on the cutting tool. Based on the type of operation and the workpiece to be machined, the cutting tool material and its geometry are selected.

As mentioned above, cutting fluids and the type of insert play a vital role in controlling the cutting temperature at the contact zone. Thus efforts are made to lower the friction levels by designing the cutting inserts so as to provide certain level of clearance or relief angles at the flank surface so that the fresh cut metal surface can slide underneath it without any damage. In addition, modern cutting inserts are well equipped with chip breaking capabilities in the form of a geometrical shape at the rake surface of the tool tip. All these measures tend to lower the friction levels which help to reduce the generation of heat at the cutting zone and improve the tool life.

A wide variety of cutting tools that have been introduced to the metal cutting industry until date include:

1. Carbon steel
2. High speed steel
3. Cast Alloy
4. Tungsten carbide
5. Cermets
6. Titanium Carbides
7. Ceramic
8. Single crystal diamond
9. Polycrystalline diamond and CBN
In addition to the factors necessary to select a cutting tool as described above, metal cutting industries also rely on those tools which are able perform the given operation with a minimum total cost and with maximum accuracy. Total costs include:

“ i.) Initial tool cost ii.) Tool grinding cost iii.) Tool life iv.) Labor cost as influenced by cycle time, machine, operator and labor cost and v.) The proportion of tool changing cost assignable to one part” (Milton Shaw, 2005).

Thus the best tool material will not be the one that gives longest life; factors such as grindability, tool material cost, and practical levels of cutting speed and feeds for a given tool material play important roles in the selection of the best tool material for a particular operation.

Considering the above factors, the experiments in this research were carried out using Physical Vapor Deposition (PVD) coated Titanium Aluminum Nitride (TiAlN) inserts manufactured by Ingersoll Cutting Tools Co.

Researchers have found this type of insert to be more oxidation resistant at elevated temperatures due to the formation of protective aluminum oxide layer on the cutting surface. Additionally, it has been found that most of the carbide inserts improve lubricity, cutting edge resistance, and offer greater wear resistance at higher cutting speeds. The only drawback being that they tend to fracture when exposed to thermal shocks.

It was stated by researcher Ferraresi that in an interrupted cutting process such as milling with a carbide tool, the main type of wear observed was wear due to cyclic variation in temperature in addition to wear due to mechanically induced stresses as a result of shocks (De Melo, et al., 2006). It has been suggested that mechanical shock
loading is an important element when assessing the propagation of cracks which is assisted by the thermal effect (Bhatia, et al., 1979).

In addition, a theory reported states that it is the inelastic behavior of the tool material during the heating part of the cycle as a result of which cracks emerge during the cooling phase of an intermittent cutting cycle (M.Stanford, P.M. Lister, 2005).

This mechanism of thermal cracking was explained by De Melo, et al. as follows: cracks due to cyclic variation in temperature and due to interrupted nature of cutting process start to appear perpendicular to the cutting edge during the initial cutting period as seen in image a. of figure 2.7. As the cutting progresses, additional cracks are developed which run parallel to the cutting edge. After a certain interval of time they grow and propagate in a manner that a sizable portion of the insert material falls apart leading to formation of a comb cracking type of wear as seen in image b. of figure 2.7 (Wisley Falco Sales, et al., 2001).

Figure 2-7: Generation of thermal cracks in carbide inserts.

[Source: Wisley Falco Sales, et al., 2001]
As it has been inspected that the formation of thermal cracks are the result of thermal gradient, the use of a MWF will, excite the entire process of cracking because of the MWF cooling property that results in increasing the overall thermal variation.

The cutting insert in this research, when observed under the optical microscope, indicated more flank wear during the wet milling process compared to wear on other cutting surfaces. One plausible answer for this was the cyclic nature of stress involved in the cutting operation which resulted in destroying the coating present on the tools cutting edge and flank surface, eventually exposing the substrate layer of the insert to the cutting environment.
Acoustic Emission

Introduction to Acoustic Emission:

Acoustic Emissions are considered as the transient elastic waves that are spontaneously released by the material when deformed. The American Society of Testing and Materials (ASTM) formally defines AE as “a class of phenomena where transient elastic waves are generated by the rapid release of energy from localized sources within a material, or transient elastic wave so generated.” These Acoustic Emissions (AE) are also known as “stress wave emissions, stress waves, microseism, microseismic activity or rock noise,” (R.K. Miller, P. McIntire, 1987). The operating frequency range with which an AE system usually works is between 20 KHz to 1 MHz.

It was Josef Kaiser, the founder of modern Acoustic Emission technology, who found two major observations relating to AE. First was the near universality of AE phenomenon, where AE were observed in most of the materials viz. alloys such as steel, aluminum, glass, fibers, wood, concrete and ceramic. The second was the Kaiser effect where it was observed that, acoustic waves are emitted by the material only when the applied load exceeds the previously applied load levels (R.K. Miller, P. McIntire, 1987).

This nondestructive testing method outperforms others in various ways. Foremost being, the energy that it detects is usually released from inside of the specimen under test rather than energy which is supplied in most radiographic or ultrasonic testing methods. Secondly, this AE technique, being a dynamic testing method, is useful in determining
the growth of a crack and the plastic deformations. Table 2.1 summarizes the advantages of the AE system over other nondestructive systems.

Table 2.1: Comparison of AE with other NDT methods

<table>
<thead>
<tr>
<th>Acoustic Emission</th>
<th>Other Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects movements of defects</td>
<td>Detects geometric form of defects</td>
</tr>
<tr>
<td>Requires stress</td>
<td>Do not require stress</td>
</tr>
<tr>
<td>Each loading is unique</td>
<td>Inspection is directly repeatable</td>
</tr>
<tr>
<td>More material- sensitive</td>
<td>Less material- sensitive</td>
</tr>
<tr>
<td>Less geometry- sensitive</td>
<td>More geometry- sensitive</td>
</tr>
<tr>
<td>Less intrusive on plant/ process</td>
<td>More intrusive on plant/ process</td>
</tr>
<tr>
<td>Requires access only at sensors</td>
<td>Requires access to whole area of inspection</td>
</tr>
<tr>
<td>Tests whole structure at once</td>
<td>Scan local regions in sequence</td>
</tr>
<tr>
<td>Main problems: noise related</td>
<td>Main problems: geometry related</td>
</tr>
</tbody>
</table>

The only drawback of AE technology is the sensitivity of the transducer which is primarily limited by the ambient background noise.
Figure 2-8: Mechanism of Acoustic Emission

[Source: Acoustic Emission Inspection, Dr. Adrian A. Pollock]

Figure 2.8 explains the basic principle behind Acoustic Emission technique. It was reported that sources of AE at the molecular level include dislocation motion, directional diffusion, sliding of grain boundary, creep, and twinning, all of which result in plastic deformation. More sources of AE at the molecular level include phase transformation, decohesion of inclusions, vacancy coalescence and fracture (H.V. Ravindra, et al., 1997).

It has been observed that the signals which give rise to AE in metal cutting are mostly deformation processes such as fracture, growth of crack, and plastic deformation. These deformations give rise to stress wave which radiate out through the structure and excite a piezoelectric transducer (sensor). This transducer converts these mechanical waves into electric signals which are then sent through amplifiers to the data card for analysis and displayed on a computer screen.
Acoustic Emission Setup

a.) Transducer: A Transducer which has been commonly known as a sensor plays a major role in capturing signals. Every time a mechanical wave generated from a deformation activity hits the surface of the test piece resulting in a movement, the transducer detects this movement and converts it to an electrical signal.

![Components of an AE Sensor](image)

**Figure 2-9: Components of an AE Sensor**


An AE transducer is made up of several elements as shown in figure 2.9. The active element being the piezoelectric, this is made of a special ceramic such as Lead Zirconate Titanate, consisting of electrodes on each face. Of the two electrodes one is connected to electrical ground and the other to a signal lead.

This active element is usually protected by a backing material made up of curing epoxy containing high density tungsten particles thus enabling effective wave propagation to the element. A wear plate acts as a protective barrier for this active element; in addition to this, a case with a signal cable attached provides a mechanical
package for the sensor components along with minimizing the overall electromagnetic interference.

It has been observed that AE testing is non-directional, which means most of the AE sources appear to function as point source emitters that radiate energy in spherical wave fronts (R.K. Miller, P. McIntire, 1987). Hence, a transducer can be located anywhere in the vicinity of the AE source and it can still detect the emitted signals from the source.

Figure 2-10: AE sensor used for experimental purpose

[Image source: .physicalacoustics.com]

The type of sensor used in this research was PICO miniature High frequency sensor: 200 kHz - 750 KHz from MISTRAS Group Inc. as shown in the figure 2.10.

b.) Preamplifiers: These are signal amplifying devices used in Acoustic Emission systems. They usually provide a range of gain in the signal obtained from the transducer thus enabling increased usable voltage for further analysis. The signals from the transducer are greatly affected by electromagnetic interference; care should be taken to
place the preamplifier as close to the transducers. These preamplifiers have a wide
dynamic range and have the ability to drive the signal over longer length via cables to the
main instruments which are set away from the test piece.

![Preamplifier Image]

**Figure 2-11: A typical 20-40-60dB Preamplifier**

These preamplifiers are found ranging anywhere from 20 to 60dB and include a
high-pass, or bandpass, filter to eliminate mechanical and acoustical background noise. A
selector switch is provided to select specified gain which is located on its periphery as
seen in figure 2.11.

One of the most important factors in selecting proper gain value is to differentiate
the noise from actual signal. Thus, care should be taken not to provide excess gain
resulting in a collection of extra noise. On the other hand, care should be taken not to
lower the gain, thus losing the actual usable signal.

In this research, preliminary experiments were conducted to know the signals
generated from metal cutting, coolant impact, spindle movement, and machine vibration;
based on the experiments conducted, a decision was made to set the preamplifier to a gain
value of 20dB.
c.) Transducer coupling and Silicon rubber sealant: A microscopic observation of the transducer will indicate several infinitesimal irregularities present on the contact surface. These irregularities tend to decay the signal waves thus lowering the overall signal strength and reducing the performance of an AE system. For this purpose, it is essential to use a couplant in the form of oil, grease, or glycerin. It has been found that application of a couplant has resulted in increasing the output of the signal to thirty times that without a couplant. In addition, it serves as an adhesive bond between the test surface and the transducer contact surface providing a mechanical fix.

![Layer of grease in blue](image)

![Silicon rubber sealant](image)

Figure 2-12: AE sensor with fixture assembly used for experimental purpose

As seen in figure 2.12, the use of a couplant was applied efficiently in the contact zone between transducer and fixture and between the test piece and the contact surface of a fixture containing the sensor. This whole assemble was then attached to the test piece with the help of a C clamp to ensure a proper contact between every element.

As discussed above, the transducer is made of several electrically sensitive elements. In order to protect these elements from the surrounding wet environment, it is necessary to isolate it from moisture. Therefore, the transducer was coated with Silicon
rubber sealant as shown in figure 2.12. In addition to acting as a water proofing material, it also serves as a damper to minimize any mechanical shocks on sensors. This type of sealant is examined to retain its properties at temperatures ranging from -55°C to 300°C.

Acoustic Emission Parameters, Signal recording, and Analysis:

In order to understand the basic mechanism of signal analysis, it is important to know the parameters related to AE. The important features which are used for an AE investigation includes amplitude, duration, rise time, energy, counts, and hits. The various relations between all of these are indicated in figure 2.13.

Figure 2-13: AE signal characteristics

Amplitude: The parameter which directly helps in determining the detectability of an AE event is called amplitude and is the highest peak voltage attained by an AE waveform. These vary over an extremely wide range from microvolts to volts, and are expressed on a decibel (logarithmic) scale where 1mV at a sensor is defined as 0dBae.

It has been found through research that the intensity of a source in the material that produces an AE can be related to peak signal amplitude.

Figure 2-14: 2D Point plot of Single pass

Figure 2.14 is a screenshot of a 2-D point plot of Amplitude (dB) vs. Time (sec) of a cutting pass from the experiments performed in this research. As it can be seen, there is a rise in the levels of amplitude signals at the start and end of the cut which represent the impact of the cutting tool during its entry and exit.

Therefore, the amplitude distribution has been correlated with deformation mechanisms in specific material and can be represented in the form of the equation presented below (R.K. Miller, P. McIntire, 1987).
Table 2.2: Factors which result in the change of AE amplitude

<table>
<thead>
<tr>
<th>Increase</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Strength</td>
<td>Low Strength</td>
</tr>
<tr>
<td>High strain rate</td>
<td>Low strain rate</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>Isotropy</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>Homogeneity</td>
</tr>
<tr>
<td>Thick sections</td>
<td>Thin sections</td>
</tr>
<tr>
<td>Brittle failure</td>
<td>Ductile fracture</td>
</tr>
<tr>
<td>Crack propagation</td>
<td>Plastic deformation</td>
</tr>
<tr>
<td>Mechanically induced</td>
<td>Thermally induced</td>
</tr>
<tr>
<td>twinning</td>
<td>twinning</td>
</tr>
</tbody>
</table>

Duration: The total elapsed time from the first measured threshold crossing to the last in microseconds is known as the duration.

Rise Time: The elapsed time from the first threshold crossing to the signal peak.

Energy: It is the area under an Acoustic Emission waveform. Because AE activity is attributed to rapid release of energy in material, the energy content of the Acoustic Emission signal can be related to the release of energy.

\[ U = \frac{1}{R} \int_{0}^{\infty} V^2(t) dt \]  

............ [R.K. Miller, P. McIntyre, 1987]
The above equation describes the electrical energy $U$, present in a transient hit (R.K. Miller, P. McIntire, 1987).

Counts: These are the threshold-crossing pulses (sometimes called ringdown counts) which are considered as one of the oldest and the easiest ways of evaluating the AE signal. The magnitude of a source event, the acoustical property, the reverberant nature of the specimen, and the sensor decide the magnitude of a count. (Dr. Adrain Pollock).

Hits: The signal pulse which is generated by the AE circuit as a result of a detected event by the sensor which is represented in the form of a number. The signal received from the preamplifier is assessed for its voltage level in the circuit board, which usually checks if the signal voltage is above or below the set threshold level. The circuit board then generates its own pulse if the voltage crosses the desired threshold level. This first pulse marks the start of a hit. The signal generated then continues to oscillate above and below the threshold level until the amplitude of the signal reduces to a value less than the set threshold. After a certain interval of time, the amplitude of the signal lowers the set threshold level which marks the end of an event. During this whole period, several counts are generated, and hence, a single hit can generate only a few counts or hundreds of counts which depend on the size and shape of the signal.

The assessment of an AE signal in this research is based on the Hit value recorded during each run of every application, the values of which are then compared to analyze the performance of AE in detecting tool wear with two different applications.

The AE signals, as discussed above, are generated because of a sudden deformation in the material resulting in a pulse wave depending upon the size of
deformation. The AE signal usually occurs as one of two different types: bursts, which are high amplitude, low frequency signals commonly generated due to events such as slip-line formation, surface microcrack, and chip impacts, and continuous AE signals, which are low amplitude, high frequency signals commonly generated as a result of internal mechanism activity and plastic deformation as shown in figure 2.15 (E. Kannatey-Asibu, Jr, D.A. Dornfeld, 1981, Ichiro Inasaki, 1998). Additionally, these signals also depend upon the type of material being cut. A ductile material will result in a continuous AE while a brittle material will result in burst type signals.

![Figure 2-15: Difference between Burst and Continuous signals](image-source: Acoustic Emission Testing by Christian U. Grosse, Masayasu, Ohtsu. ISBN 978-3-540-69895-1]

It is observed that the measurement of hits, counts, and energy help in providing the intensity, or severity, of the source that assists in detecting damage and helps to make a decision over the continuity of the test (R.K. Miller, P. McIntire, 1987).
Throughout the experiment, amplitude versus time was plotted to observe the cutting mechanism.

**Literature Review:**

**Application of Acoustic Emission in Milling Process:**

Researchers in the past were successful in associating the milling process, specifically the tool wear, with the AE system. Studies conducted by Iwata and Moriwaki about the sensitivity of an AE have reported a dramatic increase in AE RMS and AE events per cut with increase in tool wear land (D. Dornfeld, 1992). One of the major reasons for successful implementation of an AE is its operating frequency range which can be set higher than the machine vibrations and external noise.

Furthermore, research was conducted using an AE to understand the fundamentals of the machining process viz. chip formation mechanism, shear and plastic deformation of the chips, and the friction between the chip and tool rake surface and the work piece and tool flank face (A.E.Diniz, J.J. Liu, D.A. Dornfeld, 1992), which led to correlate the AE with these mechanisms. Figure 2.16 helps summarize the sources of an AE in machining.
A machining process, in general, consists of a.) plastic deformation which is the result of deformation of an uncut chip by the cutting tool, b.) friction generated due to the sliding of chips on the tool rake surface and the sliding of the freshly generated workpiece surface under the tool flank surface and c.) scratching which is caused by broken, hard fragments of the tool or the workpiece that get trapped between the tool and workpiece surface and eventually get dragged over the surface. These three sources are considered to be the major contributors of an AE in addition to secondary sources like chip breaking, chip impact, and phase changes in the tool and work material.

It has been predicted that the strain energy, which is released from the dislocation zone due to deformation movements between metal atoms, gives rise to an AE (Dimla E. Dimla Snr., 1999). Studies conducted in the past also exhibit a dramatic change in AE signal levels which were positive enough to differentiate between a sharp, worn, and broken tool (S. Kakade, et al., 1994). In addition, decreased levels of Acoustic Emission signals were observed as the shape and the surface of the cutting tool were changed throughout the cutting process.
Furthermore, it was reported that AE signals were observed to be generated due to changes in certain tribological parameters such as contact pressure, efficiency of lubricants, roughness of mating surfaces in friction, and relative velocity of materials in friction (T. Jayakumar et al. 2005).

The following sections will elaborate the details of how parameters like temperature, tool wear, surface roughness, and forces relate with Acoustic Emission signals in machining.

1. Relation between AE and Tool wear:

   Tool wear has a big impact in machining owing to the fact that the role it plays in controlling cutting forces and power, contact temperature, dimensional accuracy, and surface roughness.

   The different types of tool wear and its causes include: i.) Abrasion, generated due to scratching of hard particles over softer particles during cutting, ii.) Adhesion, which is the result of welding of the chips on the tool surface occurring under extreme temperature conditions, iii.) Diffusion which occurs under the action of transfer of atoms resulting in loss of material due to the transfer effect under high temperatures and is based on the gradient of concentration of the penetrating atoms in the solvent material, iv.) Attrition is the result of the breaking of external grains which get embedded in the machined surface and are dragged over the tool surface over a period of time.

   Researchers in the past have studied a wide range of online monitoring techniques, one of which is Acoustic Emission analysis. Scientific work in the field of
acoustics has proved that AE systems are able to detect the changes in tool wear and breakage during any machining operation.

It has been found that there is a consistent rise in AE signals with tool wear which was attributed to the fact that these signals were generated due to rubbing between worn flank and rake surface with the workpiece and generated chip (A.E. Diniz, J.J. Liu, D.A. Dornfeld, 1992). So as the tool starts to wear out, the cutting insert has to spend more energy for cutting which is a result of increased Acoustic Emission energy.

Another reason for the rise in an AE signal, with increase in tool wear for a multi insert milling operation, was thought to be because of changes in the cutting condition where the chip thickness was observed to be lesser when a chipped tool was in action. This caused the next insert in action to cut extra material which resulted in the change of AE amplitude levels (Ichiro Inasaki, 1998).

Research conducted on an AE analysis of coated tools concluded that an AE was significant in determining the tool wear as tool material changed from one layer to another during the progress of tool wear (T.Moriwaki, M. Tobito, 1990).

![AE Signals from Flooding](image)

a.) AE Signals from Flooding
b.) AE Signals from Misting

Figure 2-17: 2D scatter point plot for a.) Flooding; b.) Misting application

The above images in figure 2.17 are 2-D, scatter point plots of Amplitude (dB) vs. Time (sec) of the two runs conducted under the same surface speed, chip load, and depth of cut from the experiments performed under this research. The insert flank wear for the run with image a. was observed to be 0.178mm and for image b. 0.0955mm. The graphs certainly indicate that there were changes in levels of amplitude which relate to changes in conditions of the cutting insert. The inserts in this research with a minimal wear value were due to failure of the coating, which resulted in a steady AE signal pattern. Similar results were seen during experiments performed where AE signals were seen to be low until the tool was worn out completely, after which, a sudden rise in signal level was observed which was attributed to abrupt tool failure (Krzysztof Jemielniak, et al., 1998).
2. Relation between AE and Forces:

Every metal cutting operation is performed under three major cutting parameters which are speed, feed, and depth of cut, of which the latter two have been seen to affect the volume of the chip. An increase in the area of the chip has been observed with an increase in feed and depth of cut. Thus, at a given instance, a cutting insert has to cut more material which essentially requires more force. On the other hand, tool wear has led to increased forces and AE signals.

In a research conducted by (Iulian Marinescu, Dragos A. Axinte, 2008) where they had performed operations with increased depth of cut which resulted in increased chip volume indicated a significant rise in the values of resultant cutting force and AE. Thus it was evident that there exists a relation between forces and Acoustic Emission.

Similar observations were found where the effect of feed per tooth and depth of cut on the tangential cutting force was seen to be significant as compared to cutting speed. In addition, the results were efficient enough to relate flank wear with tangential cutting force (S.K. Choudhury, Subhashree Rath, 1999).

An attempt was performed by (Pan Fu, et al., 1998) to study the condition of tool wear using ANN driven fuzzy pattern recognition algorithm with forces and an AE, where changes in amplitude and distribution patterns for both the signals were observed as tool wear progressed.

As discussed earlier, broken particles of either workpiece or tool resulted in generation of an AE during cutting. It has also been found in a research study, conducted
by (Dan, L., & Mathew, J., 1990), that changes in forces were also observed as these particles tend to squeeze between tool and workpiece.

The results obtained in this research were able to exhibit the fact that there exists a linear relationship between forces and an AE Hits value with tool wear.

3. Relation between AE and Temperature:

Researchers in the field of metal cutting have found three zones which contribute to the rise of temperature during any machining process:

- Primary deformation zone where shearing action of chips takes place
- Secondary deformation zone as a result of friction between chips and rake surface
- Tertiary heating zone developed due to friction between flank and finished surface

Temperature generated at the cutting tool and work surface acts as a catalyst for tool wear mechanisms, such as adhesion and diffusion. These contribute to dimensional inaccuracy, form accuracy, phase change transformation, and induction of tensile stress with generation of micro cracks at the surface and subsurface level. In order to withstand such extreme temperatures, it is essential to choose the right MWF, heat and wear resistant cutting tools, and the right parameters.

Research has led to the conclusion that high temperatures have resulted in reduction of cutting force to some extent because of softening or reduction in shear strength which contributes to changes in AE signals.
A microscopic view of a fresh tool and a worn tool will indicate an increase in cutting surface area because of the wear generated which then gives rise to increase in friction during metal cutting. Thus, it’s the friction which is the primary reason for the generation of heat at the secondary and tertiary zones which is demonstrated in the work done by (Byrne, G., et al., 1995).

Thus an overall increase in frictional energy which contributes to rise the in temperature has led to the conclusion that there is a noticeable change in the AE signal level during metal cutting.
Chapter 3

Experimentation

Workpiece:

The entire experiment was performed on two 152mm * 100mm * 110mm AISI 4140 alloy steel blocks with a total of fifteen passes for a single run. Table 3.1 explains the Chemical composition along with its Mechanical properties.

Table 3.1: Workpiece composition [Information source: Alro.com]

<table>
<thead>
<tr>
<th>Element</th>
<th>Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron, Fe</td>
<td>94.95 - 97.314</td>
</tr>
<tr>
<td>Chromium, Cr</td>
<td>0.75 - 1.20</td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.70 - 1.70</td>
</tr>
<tr>
<td>Carbon, C</td>
<td>0.36 - 0.46</td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>0.15 - 0.45</td>
</tr>
<tr>
<td>Molybdenum, Mo</td>
<td>0.15 - 0.35</td>
</tr>
<tr>
<td>Sulfur, S</td>
<td>0.040 (max.)</td>
</tr>
<tr>
<td>Phosphorous, P</td>
<td>0.035 (max.)</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.50 (max.)</td>
</tr>
</tbody>
</table>

Workpiece Mechanical Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>655 MPa</td>
</tr>
<tr>
<td>Yield strength</td>
<td>415 MPa</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>140 GPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>80 GPa</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>190-210 GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.27-0.30</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>260 - 321</td>
</tr>
</tbody>
</table>

This type of steel serves a wide array of purposes, from automobile, pump manufacturing, jigs, mold assembly and heavy machinery components, because of its
high fatigue strength, impact resistance, torsional strength, and toughness. For the purpose of this experiment, the hardness of this steel was not altered.

Cutting Tool and Insert:

The machining operation performed on AISI 4140 alloy steel was end milling using a VF-2 Vertical CNC Machining Center by HASS Automation Inc. This operation was performed with a single flute end mill index holder using a IN 2530 grade PVD TiAlN coated carbide inserts from Ingersoll Cutting Tool Co. which are attached to the tool holder by means of a screw. These inserts exhibit good performance against mechanical and thermal shocks. In addition, they are also able to resist most types of wear. Table 3.2 and 3.3 explain all the dimensional specifications of the tool holder and the insert.

Table 3.2: Dimensions of tool holder

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutter Number</td>
<td>12J1P-0501379R01</td>
</tr>
<tr>
<td>Nominal Diameter</td>
<td>0.5 in</td>
</tr>
<tr>
<td>Extension Length</td>
<td>1.34 in</td>
</tr>
<tr>
<td>Overall Length</td>
<td>3.25 in</td>
</tr>
<tr>
<td>Shank Size / Style</td>
<td>0.625 in / W</td>
</tr>
<tr>
<td>Inserts</td>
<td>1</td>
</tr>
<tr>
<td>Ramp Angle</td>
<td>12.5°</td>
</tr>
</tbody>
</table>
Table 3.3: Dimensions of cutting insert

| IN 2530 grade PVD TiAlN Geometry (inch) |
|--------|--------|--------|--------|
|        | l      | d      | t      |
| 0.350  | 0.250  | 0.190  | 0.031  |

The insert used had a nose radius of 0.031 inches, along with chip breaking capability in order to increase the tool life.

Cutting Fluid:

The MWF used for this experiment was TRIM C270, a synthetic type of cutting fluid provided by Master Chemical Corporation and used with a 10% concentrate. Table 3.4 explains the physical properties of the fluid.

Table 3.4: Physical Properties of TRIM C270 cutting fluid

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>TRIM C270</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid Type</td>
<td>Synthetic</td>
</tr>
<tr>
<td>Color</td>
<td>Colorless to pale yellow</td>
</tr>
<tr>
<td>Color of working solution</td>
<td>Colorless to pale yellow</td>
</tr>
<tr>
<td>Odor</td>
<td>Mild, sweet</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>209°F</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.989-1.093</td>
</tr>
<tr>
<td>pH of Concentrate</td>
<td>9.0-9.3</td>
</tr>
<tr>
<td>Flash Point</td>
<td>&gt;212°F</td>
</tr>
<tr>
<td>Viscosity at 10% DI mPa S</td>
<td>1.127</td>
</tr>
<tr>
<td>Titration Factor (CGF-1 Titration Kit)</td>
<td>0.561</td>
</tr>
<tr>
<td>Coolant Refractometer Factor % Brix</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Experimental Setup:

Table 3.5 and figure 3.1 provide an outline of the experimental setup. Several trial cuts were performed before the actual test and cutting parameters recommended by the insert manufacturer were tested. Additionally, attempts were made not to exceed the standard tool wear value of 0.30mm of flank wear, after which, the tool is considered to be worn. This helped in determining range values for the parameters that were used in this experiment based on which three levels of parameter were chosen as shown in table 3.5.

Table 3.5: Experimental Cutting Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Material</td>
<td>AISI 4140 Alloy Steel</td>
</tr>
<tr>
<td>Insert</td>
<td>TiAlN Coated Carbide</td>
</tr>
<tr>
<td>Surface Speed (m/ min)</td>
<td>122 m/min, 137 m/ min, 152m/ min</td>
</tr>
<tr>
<td>Chip Load (mm/tooth )</td>
<td>0.07 mm/tooth, 0.08 mm/tooth, 0.09 mm/tooth</td>
</tr>
<tr>
<td>Depth of Cut (mm)</td>
<td>1.5 mm, 2.0 mm, 2.5 mm</td>
</tr>
<tr>
<td>Coolant Application</td>
<td>Flooding, Misting, Through Tool</td>
</tr>
<tr>
<td>Cutting Fluid</td>
<td>TRIM C270</td>
</tr>
</tbody>
</table>
The entire experimental setup was organized as shown in figure 3.1, where the AISI 4140 alloy steel workpiece to be tested was held in position by a fixture plate along with four clamps, thus ensuring correct alignment with the tool and work bed axis. Kistler 9257B Force Dynamometer was used to record the radial and feed forces and was held underneath the workpiece with the help of a fixture plate attached to the work bed of the CNC milling machine. Three computer systems were used to collect the data generated by forces, temperature, and the Acoustic Emission.
Acoustic Emission Test Setup:

A PICO miniature high frequency sensor (200 KHz – 750 KHz) from MISTRAS Group, Inc. was used to pick up the AE waves from the cutting mechanism. A special fixture was designed for this sensor in order to provide the required stability and rigidity. This fixture had an aluminum plate with a hole drilled in for holding the pico sensor in place. Additional rigidity was provided by the help of a thin plate with screws holding the sensor in location from the top. In order to protect the sensor from the outside wet environment, a layer of silicon rubber sealant was applied. The contact surface of the sensor and the fixture plate was coated with a thin layer of petroleum jell to avoid any loss of signal due to air gap. The whole AE sensor setup was held to the workpiece with a 

Figure 3-2: Experimental AE Setup

AISI 4140 Work piece
Rubber sealant
C Clamp
Fixture for holding work piece
Fixture for AE sensor
C clamp, as shown in figure 3.2, which was lowered after every three runs thus maintaining a constant distance of 1.5 inches between the top surface of the workpiece and the AE sensor.

<table>
<thead>
<tr>
<th>Threshold Type</th>
<th>Pre-Amp</th>
<th>Analog Filter</th>
<th>Waveform Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dB</td>
<td>dB Lower</td>
<td>Sample rate</td>
</tr>
<tr>
<td>Float</td>
<td>60</td>
<td>20 200 KHz</td>
<td>2 MSPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2 MHz</td>
<td>Pre-Trigger</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PDT</th>
<th>HDT</th>
<th>HLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>microseconds</td>
<td>microseconds</td>
<td>microseconds</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

Before starting the actual experimentation work, preliminary tests were conducted with an AE setup in order to achieve right signal quality and strength. The AE data was collected and analyzed using AEwin MISTRAS software for Flooding and Misting applications only, since data collection for Through Tool application was not possible for a couple of reasons: the available amplifiers had higher amplification values which were not desirable for data collection, in addition, the software was not capable of filtering the extra noise generated due to high pressure of MWF during the experiments. Hence the overall data had the signals from extra noise and the cutting mechanism making the amplitude values in the graphs look bigger than the expected results. Based on this, AE data collection for Through Tool application was avoided.
For analysis of the AE signals in this experiment, the Hit value was chosen as it was observed that it provided consistent results with the tool wear. In addition, with the available instruments and software, it was tough to collect the absolute energy and RMS voltage values.

Table 3.6 explains the configuration of the AE system for Flooding and Misting setup on which the experiments were performed.

Thermocouple Setup:

In the past, several attempts, using thermocouples embedded in either the workpiece or on the cutting tool to record the temperature at the cutting zone, were performed. One attempt of measuring the temperatures was conducted by Abrao et al., where they used a remote implanted thermocouple in an AISI E52100 bearing steel workpiece which was machined using ceramic and PCBN tools. It was observed through this investigation that this method was not capable of providing the actual temperature at the cutting zone, but can be effectively used for comparative purposes (H.A. Kishawy 2002).

Throughout the experiments in this research, temperatures were collected only for the 15th pass and recorded as a rise in temperature from the readings collected from initial and final temperature values. A J type thermocouple in a shape of thin wire was used to record the temperature held in the holes drilled in the workpiece with the help of the fixture. The setup was designed in a way to record the temperatures generated at a
0.25mm distance from the cutting zone. This fixture, with thermocouple, was lowered to a new hole after every run, thus enabling the recording of accurate data.

Tool wear Measurement:

Tool wear measurements were performed after every run in order to assess the tool condition. Throughout the experiments, the cutting insert was taken out of the tool holder and cleaned for any traces of coolant or chip particles present on the surface. Since it was found that the insert indicated consistent wear on the flank surface of the tool, the wear measurements were performed on it. Figure 3.3 indicates the insert geometry.

![Geometry of the cutting insert](image)

**Figure 3-3: Geometry of the cutting insert**

The insert, as seen in Figure 3.3, had one flat surface present on the back and a curved surface on the front which made flank surface measurements difficult. In order to overcome this, a fixture was designed so that the insert was supported on its back, thus maintaining a flat consistent surface for every measurement performed. An optical
microscope with a magnification of 128X was used for this measurement. Sufficient lighting was maintained throughout the measurement period in order to avoid any inconsistency in measurement due to shadows generated because of the inserts curved edges.

Force Measurement

In addition to the collection of AE signals and temperatures, forces were also collected using the force dynamometer placed under the fixture holding the workpiece. The signals collected by the force dynamometer were then processed using Lab view software. In this experiment, only the feed (X) force and radial (Y) force were collected. Further, DADiSP software was used to separate the forces generated only for the last pass, so as to study the wear generation mechanism between different runs of three applications. The force values represented in the observation tables 4.2 to 4.4 for each application are in the form of resultant RMS values of feed and radial forces of the last pass.
Chapter 4

Results and Analysis

As discussed earlier, the three different methods of MWF application were used in this experiment. The input parameters viz. Surface speed, Chip load, and Depth of cut were selected by conducting a preliminary test in order to get desired tool wear. Thus, all these parameters were categorized into minimum, medium, and maximum levels. These three levels of parameters were then randomly organized by keeping two parameters constant for every run, resulting in a 3 * 3 * 3 factorial design contributing to a total of 27 runs for every application.

The response variables collected for every run were Temperature, Forces, AE data, and Tool wear. Table 4.1 provides the summary of all three levels of input parameters, the corresponding response values, and units for each.

The values of AE Hits, forces, and temperature have been seen to vary with tool wear of the insert and also with change of application between Flooding, Misting, and Through Tool. Tables 4.2, 4.3 and 4.3 represent the values of response variables collected during the experiments from force, acoustic, thermocouple sensors, along with tool wear.
Table 4.1: Design of Experiment

<table>
<thead>
<tr>
<th>Coolant Application</th>
<th>Process Variables</th>
<th>Min.</th>
<th>Med.</th>
<th>Max.</th>
<th>Response Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>Surface speed (m/min)</td>
<td>122</td>
<td>137</td>
<td>152</td>
<td>Rise in Temp. (°C)</td>
</tr>
<tr>
<td></td>
<td>Depth of cut (mm)</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>Forces (N)</td>
</tr>
<tr>
<td>Through Tool</td>
<td>Chip load (mm/tooth)</td>
<td>0.07</td>
<td>0.08</td>
<td>0.09</td>
<td>Acoustic Emission (Hits)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tool wear (mm)</td>
</tr>
</tbody>
</table>
Table 4.2: Recorded values for Flooding application

<table>
<thead>
<tr>
<th>Application</th>
<th>Surface Speed (m/min)</th>
<th>Chip Load (mm/tooth)</th>
<th>Depth of cut (mm)</th>
<th>Tool wear (mm)</th>
<th>Rise in Temp. (°C)</th>
<th>Resultant Force (N)</th>
<th>AE Hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>122</td>
<td>0.07</td>
<td>1.5</td>
<td>0.097</td>
<td>8</td>
<td>142.61</td>
<td>58339</td>
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<tr>
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<td>2</td>
<td>0.074</td>
<td>16.06</td>
<td>240.86</td>
<td>110187</td>
</tr>
<tr>
<td>Flooding</td>
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<td>0.07</td>
<td>2.5</td>
<td>0.177</td>
<td>11.56</td>
<td>286.94</td>
<td>132001</td>
</tr>
<tr>
<td>Flooding</td>
<td>122</td>
<td>0.08</td>
<td>1.5</td>
<td>0.085</td>
<td>10</td>
<td>159.55</td>
<td>48505</td>
</tr>
<tr>
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<td>0.08</td>
<td>2</td>
<td>0.093</td>
<td>10.89</td>
<td>211.03</td>
<td>78253</td>
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<td>122</td>
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<td>2.5</td>
<td>0.136</td>
<td>12.56</td>
<td>302.78</td>
<td>103970</td>
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<tr>
<td>Flooding</td>
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<td>0.07</td>
<td>2</td>
<td>0.123</td>
<td>14.06</td>
<td>271.57</td>
<td>113265</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.07</td>
<td>2.5</td>
<td>0.13</td>
<td>15.5</td>
<td>312.13</td>
<td>91564</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.07</td>
<td>2</td>
<td>0.14</td>
<td>11</td>
<td>271.57</td>
<td>113265</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.07</td>
<td>2.5</td>
<td>0.152</td>
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<td>327.23</td>
<td>103753</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.08</td>
<td>1.5</td>
<td>0.076</td>
<td>9.17</td>
<td>148.04</td>
<td>93505</td>
</tr>
<tr>
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<td>137</td>
<td>0.08</td>
<td>2</td>
<td>0.105</td>
<td>8.83</td>
<td>227.01</td>
<td>79856</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.08</td>
<td>2.5</td>
<td>0.178</td>
<td>9.89</td>
<td>344.12</td>
<td>135087</td>
</tr>
<tr>
<td>Flooding</td>
<td>137</td>
<td>0.09</td>
<td>1.5</td>
<td>0.079</td>
<td>4.94</td>
<td>178.13</td>
<td>46427</td>
</tr>
<tr>
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<td>2</td>
<td>0.116</td>
<td>11.83</td>
<td>213.71</td>
<td>76806</td>
</tr>
<tr>
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<td>0.09</td>
<td>2.5</td>
<td>0.145</td>
<td>10.94</td>
<td>326.38</td>
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</tr>
<tr>
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<td>152</td>
<td>0.07</td>
<td>1.5</td>
<td>0.084</td>
<td>5.78</td>
<td>148.52</td>
<td>98538</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.07</td>
<td>2</td>
<td>0.14</td>
<td>9.39</td>
<td>245.48</td>
<td>114553</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.07</td>
<td>2.5</td>
<td>0.138</td>
<td>15.78</td>
<td>274.87</td>
<td>101547</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.08</td>
<td>1.5</td>
<td>0.085</td>
<td>7.39</td>
<td>174.38</td>
<td>84998</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.08</td>
<td>2</td>
<td>0.094</td>
<td>10.11</td>
<td>219.67</td>
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</tr>
<tr>
<td>Flooding</td>
<td>152</td>
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<td>2.5</td>
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<td>300.89</td>
<td>86487</td>
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<tr>
<td>Flooding</td>
<td>152</td>
<td>0.09</td>
<td>1.5</td>
<td>0.075</td>
<td>6.89</td>
<td>167.84</td>
<td>60297</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.09</td>
<td>2</td>
<td>0.087</td>
<td>6.78</td>
<td>229.06</td>
<td>75859</td>
</tr>
<tr>
<td>Flooding</td>
<td>152</td>
<td>0.09</td>
<td>2.5</td>
<td>0.111</td>
<td>18.5</td>
<td>399.53</td>
<td>65578</td>
</tr>
</tbody>
</table>
## Table 4.3: Recorded values for Misting application

<table>
<thead>
<tr>
<th>Application</th>
<th>Surface Speed (m/min)</th>
<th>Chip Load (mm/tooth)</th>
<th>Depth of cut (mm)</th>
<th>Tool wear (mm)</th>
<th>Rise in Temp. (°C)</th>
<th>Resultant Force (N)</th>
<th>AE Hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misting</td>
<td>122</td>
<td>0.07</td>
<td>1.5</td>
<td>0.091</td>
<td>24</td>
<td>117.11</td>
<td>126052</td>
</tr>
<tr>
<td>Misting</td>
<td>122</td>
<td>0.07</td>
<td>2</td>
<td>0.0895</td>
<td>44.5</td>
<td>161.05</td>
<td>107793</td>
</tr>
<tr>
<td>Misting</td>
<td>122</td>
<td>0.07</td>
<td>2.5</td>
<td>0.155</td>
<td>50.28</td>
<td>235.01</td>
<td>110891</td>
</tr>
<tr>
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<td>122</td>
<td>0.08</td>
<td>1.5</td>
<td>0.0755</td>
<td>26.56</td>
<td>136.99</td>
<td>93338</td>
</tr>
<tr>
<td>Misting</td>
<td>122</td>
<td>0.08</td>
<td>2</td>
<td>0.1634</td>
<td>38.28</td>
<td>181.37</td>
<td>115705</td>
</tr>
<tr>
<td>Misting</td>
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<td>2.5</td>
<td>0.105</td>
<td>43.61</td>
<td>222.27</td>
<td>90112</td>
</tr>
<tr>
<td>Misting</td>
<td>122</td>
<td>0.09</td>
<td>1.5</td>
<td>0.0875</td>
<td>26.17</td>
<td>201.72</td>
<td>72952</td>
</tr>
<tr>
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<td>122</td>
<td>0.09</td>
<td>2</td>
<td>0.0635</td>
<td>20.78</td>
<td>243.74</td>
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<td>122</td>
<td>0.09</td>
<td>2.5</td>
<td>0.102</td>
<td>19.39</td>
<td>245.66</td>
<td>62402</td>
</tr>
<tr>
<td>Misting</td>
<td>137</td>
<td>0.07</td>
<td>1.5</td>
<td>0.0635</td>
<td>26.45</td>
<td>176.15</td>
<td>78404</td>
</tr>
<tr>
<td>Misting</td>
<td>137</td>
<td>0.07</td>
<td>2</td>
<td>0.085</td>
<td>28.95</td>
<td>174.42</td>
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<tr>
<td>Misting</td>
<td>137</td>
<td>0.07</td>
<td>2.5</td>
<td>0.187</td>
<td>58.62</td>
<td>205.16</td>
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</tr>
<tr>
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<td>0.08</td>
<td>1.5</td>
<td>0.079</td>
<td>24</td>
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</tr>
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<td>0.094</td>
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<td>231.11</td>
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</tr>
<tr>
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<td>137</td>
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<td>1.5</td>
<td>0.065</td>
<td>20.95</td>
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<td>61977</td>
</tr>
<tr>
<td>Misting</td>
<td>137</td>
<td>0.09</td>
<td>2</td>
<td>0.0775</td>
<td>33.39</td>
<td>248.26</td>
<td>53312</td>
</tr>
<tr>
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<td>0.09</td>
<td>2.5</td>
<td>0.08</td>
<td>31.06</td>
<td>308.2</td>
<td>52233</td>
</tr>
<tr>
<td>Misting</td>
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<td>0.07</td>
<td>1.5</td>
<td>0.06</td>
<td>27.89</td>
<td>160.33</td>
<td>78334</td>
</tr>
<tr>
<td>Misting</td>
<td>152</td>
<td>0.07</td>
<td>2</td>
<td>0.119</td>
<td>28.17</td>
<td>203.31</td>
<td>97306</td>
</tr>
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<td>274.79</td>
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</tr>
<tr>
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<td>0.08</td>
<td>1.5</td>
<td>0.054</td>
<td>10.33</td>
<td>178.37</td>
<td>19480</td>
</tr>
<tr>
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Table 4.4: Recorded values for Through Tool application

<table>
<thead>
<tr>
<th>Application</th>
<th>Surface Speed (m/ min)</th>
<th>Chip Load (mm/tooth)</th>
<th>Depth of cut (mm)</th>
<th>Tool wear (mm)</th>
<th>Rise in Temp. (⁰C)</th>
<th>Resultant Force (N)</th>
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<tbody>
<tr>
<td>Through Tool</td>
<td>122</td>
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<tr>
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<td>2.5</td>
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</tbody>
</table>
Selection of Significant Process variables:

As discussed above, a cutting process is primarily dependent on three major variables viz. Surface speed, Chip load, and Depth of cut. One of the major goals of this research was to find out what parameter affected the response variable in a significant way. In order to study this, a general ANOVA regression analysis was conducted using Minitab software based on the experimental data where the response variable selected was Tool wear. The ANOVA analysis results represented in the tables below for Flooding, Misting and Through Tool application indicate a strong conformation with the experimental values where it can be seen that Depth of cut is significantly affecting all of the response variables compared to surface speed and chip load. This is represented in the regression equations shown below with a positive value coefficient for depth of cut and also in the Analysis of Variance Table with a P value of less than 0.05. These results were calculated based on a 95% confidence interval.

In addition to this, one look at table 4.1 will indicated that the three levels of values selected for Depth of cut show a considerable difference in range values compared to levels of values for other two factors.
Regression Equation for Flooding application

Tool wear = 0.074842 - 0.000173273 Surface Speed - 0.788889 Chip Load + 0.0617777 Depth of cut

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.074842</td>
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<tr>
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<td>Chip Load</td>
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Analysis of Variance

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<th>Adj SS</th>
<th>Adj MS</th>
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</table>

Regression Equation for Misting application

Tool wear = 0.0701841 - 5.21021e-005 Surface Speed - 0.675 Chip Load + 0.0448889 Depth of cut

Coefficients

<table>
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<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
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Analysis of Variance

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<th>Adj MS</th>
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<td>0.0008201</td>
<td>0.0008201</td>
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</table>
Regression Equation for Through Tool application

Tool wear = \(-0.0449952 + 0.000390991 \times \text{Surface Speed} - 0.272222 \times \text{Chip Load} + 0.0592222 \times \text{Depth of cut}\)

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
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Analysis of Variance

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Hence based on these results, all further analysis was performed by focusing only on Depth of cut as the process variable.
Figure 4-1: Results of a.) Tool wear, b.) Rise in temp., c.) Resultant force and d.) AE Hits with increase in Depth of cut for Flooding
Figure 4-2: 3D Plot representing changes of AE Hits in correspondence with Tool wear, Temp. and Resultant forces for Flooding
Effect of Flooding Technique on Tool wear, Temperature, Forces and AE with Depth of cut:

Tool wear with Depth of cut:

Graphs in figure 4.1 and 4.2 indicate that there is a strong linear relationship between tool wear and depth of cut. This is attributed to the fact that the insert surface has been exposed to more cutting action as the DOC is increased. As discussed earlier, if the DOC is increased, the insert has to input an extra amount of energy to generate necessary force required to shear the increased volume of the chip. This certainly will result in an increased tool wear.

Furthermore, since the insert’s cutting surface tends to increase with DOC, this results in an increased chance of thermal damage. When the tool leaves the cutting zone, due to the Flooding application, the hot insert suddenly comes in contact with an enormous amount of MWF. This tends to generate thermal stress and eventually tool failure. Thus as the DOC goes on increasing, we see an increase in tool wear on the flank surface.

This explanation conforms to the graphs where we see a rise in tool wear in table 4.1 a. and rise in tool wear and the AE values with DOC in table 4.2
Temperature vs. Depth of Cut:

It can be observed from the graphs in figure 4.1 and 4.2 that there is a rise in cutting temperatures with depth of cut. This directs to the fact that as the tool cuts more volume of material throughout the entire span of cutting process, it starts to heat up and then the MWF is ineffective in carrying away this heat efficiently. In an experiment conducted by (Shaw, et al. 1951), where they studied the effect of cutting fluid on chip tool interface temperature, they were able to conclude that the efficiency of MWF in reducing the cutting temperature decreased with an increase in depth of cut and cutting speed.

One reason that was studied through past research is the generation of film boiling during which the MWF in contact with a hot surface tend to enter a vapor phase where formed bubbles restrict entry of fresh MWF. This eventually results in the building up of heat which could damage the tool in the long run. In addition, it was also observed that the Flood application technique is not effective in supplying MWF in the cutting zone. The reason for this was the operating fluid pressure and the surface tension. Since most of the flooding techniques operate under low pressure, it’s close to impossible for MWF to reach the tool workpiece contact zone. Also, a fluid, when applied in the form of a laminar flow, generates surface tension which restricts it from entering any crevices or microscopic cracks if present in the contact zone. All of this leads to lowering the
performance of MWF via Flooding technique by conducting away the generated heat during metal cutting operation.

Forces vs. Depth of cut:

The increase in volume of the uncut chip and tool wear resulted in the rise of cutting forces which is seen in the graphs of figure 4.1 and 4.2. Whenever the depth of cut is increased, the total area under the contact of the tool increases, which results in increased cutting power and cutting forces. Also, in a similar fashion, the tool wear results in a loss of cutting edge making it round, thus increasing the cutting area. These two reasons explain why the cutting forces increased with DOC.

Also the viscosity of MWF plays a vital role in controlling the cutting forces. It has been studied in past research that MWF with high viscosity tend to lower the cutting forces. This is due to fact that it provides an extra damping effect. Table 3.4 indicates the value of viscosity of TRIM C270 as 1.127 mPa S which certainly reflects a low value.

Acoustic Emission vs. Depth of cut:

The Hit based analysis for an AE performed in this experiment shows consistent results with forces; graphs in figure 4.1 and 4.2 indicate this pattern. Previous discussions about tool wear vs. DOC come under consideration while discussing the occurrence of an AE. As discussed earlier, whenever there is any occurrence of an event inside the workpiece or in the cutting insert, a Hit value is generated. In addition, research in the
field of AE in machining has shown an increase in the levels of AE signals with tool wear. The results obtained through experiments do indicate the fact that AE was successful in detecting any activity generated in either the workpiece or the tool. The tool wear values obtained from tool measurements in table 4.2 indicate that there was certainly some amount of loss of material from the insert during the cutting operation.

This loss resulted in increased tool contact area because of dullness of the insert, thus as wear progressed, more area of the insert came into action resulting in a rise of AE Hits. The major sources of AE in machining include friction and plastic deformation as discussed previously; it has been observed that tool wear severely affects both of these resulting in an increased value of AE Hits. Graphs 4.2 shows that the results obtained from an AE were the same as the results from Forces, Temperature and Tool wear which are indicated by a linear relationship. In a similar research study, it was observed that the AE amplitude and the AE energy increased with increase of depth of cut (XiaoQi, C., et al., 2001).

This certainly indicates that AE was successful in monitoring the tool wear with Flooding application.
Figure 4-3: Results of a.) Tool wear, b.) Rise in temp., c.) Resultant force and d.) AE Hits with increase in Depth of cut for Misting.
Figure 4-4: 3D Plot representing changes of AE Hits in correspondence with Tool wear, Temp. and Resultant forces for Misting
Effect of Misting Technique on Tool wear, Temperature, forces and AE with Depth of cut:

Tool wear vs. Depth of Cut:

Throughout the experiments it was observed that misting resulted in less tool wear compared to the other two techniques which was attributed to the fact that the levels of thermal damage observed was less. Yet it is still seen in the graphs of figure 4.3 and 4.4 that there is a consistent rise in tool wear with DOC.

As stated above, the sole reason behind rise in tool wear with DOC is the increase in volume of uncut chip resulting in exposing the cutting insert to maximum cutting area under cutting action. The result of mist on tool wear was not seen to be detrimental because of the fact that misting utilized a very small quantity of MWF thus preventing the tool from thermal damage.

Therefore, the use of coated carbide inserts with MWF under Misting applications has been observed to control the tool wear to a greater extent.
Temperature vs. Depth of cut:

From the graphs in figure 4.3 and 4.4 it indicates that there was a considerable rise in cutting temperature with an increase in depth of cut. This has been for obvious reasons because the MWF applied through misting did not provide sufficient quantity of fluid in order to transfer the heat generated. The only possible way to carry the heat away was through either convection or radiation both caused by turbulent air present in the near vicinity of the cutting zone due to a rotating tool and the air delivered to it from the mister. Thus, it was observed that these two heat transfer methods were not efficient in the cooling process. Also, as the misting application did a poor job in flushing away the chips, it was thought that these hot chips which were caught in the cutting zone caused an increase in friction between the tool and the chips resulting in the rise of temperature.

Additionally, the increase in uncut chip volume with an increase in depth of cut forced the insert to perform an extra amount of work which resulted in the rise of temperature. Thus, with an increase in cutting time, it can be predicted that this rise in temperature will eventually reach to a level that could damage the tool and results in diffusion or deformation wear pattern.

Force vs Depth of cut:

The increase in forces with depth of cut using the misting application was attributed to tool wear and an increase in volume of uncut chip. It can be observed from
the table 4.3, that the values of tool wear are trivial. This leads to an indication that the rise in volume of the uncut chip affected the forces most.

**Acoustic Emission vs. Depth of cut:**

The increase in tool wear always resulted in a rise of AE signals which can be seen in the graphs of figure 4.3 and 4.4. As it was observed throughout the experiment, there was a rise in tool wear with increase in depth of cut. This certainly resulted in an increased number of AE Hits. Furthermore, as discussed above, there were instances where chips were not cleared from the cutting zone. This resulted in the friction between chips and tool rake surface. This friction, as mentioned above, is one of the three primary sources of AE, thus it resulted in a rise of an AE signal with increase in depth of cut. Graphs in figure 4.4 indicate a linear relationship between AE, Tool wear, Forces and Temperature with increase in depth of cut.
Figure 4-5: Results of a.) Tool wear, b.) Rise in temp., c.) Resultant force and d.) AE Hits with increase in Depth of cut for Through Tool

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Effect of Through Tool Technique on Tool wear, Temperature, Forces and AE with Depth of cut:

Tool wear vs. Depth of cut:

As similar to the other two applications, the tool wear in Through Tool was also observed to increase with depth of cut, which is seen in graph of figure 4.5. As the depth of cut increased, it increased the total volume of uncut chip, thus generating higher friction creating an increased temperature. This rise in temperature then resulted in a temperature gradient which was the major cause of thermal damage.

It was observed that this method of fluid application assisted the insert in metal cutting as the high pressure of the coolant jet was able to curl the chips, thus enabling decreased levels of friction generation between tool rake surface and the sliding chips. This resulted in lowering the temperature generated at the cutting zone to a certain limit which eventually lowered the tool wear and is also the reason why the tool wear was seen to be lower than the flooding application.

Temperature vs. Depth of cut:

The graph of figure 4.5 represents the relationship between the rise in temperature and the increase in depth of cut. It can be observed that the increase in the volume of the chip resulted in a generation of higher temperature. Since there was a rise in depth of cut,
there was an increase in friction and tool wear. These two elements were the main causes of increased temperature.

Also, it has been studied that the Through Tool application, due to its high pressure delivery rate, restricts the formation of film boiling. Due to high temperatures, there is a phase change in the MWF where it transforms into bubbles. These bubbles then obstruct the entry of fresh MWF in the cutting zone. Through tool using, a high pressure of coolant jet was seen to be effective in breaking this layer of vapor, thus enabling the entry of fresh MWF in the cutting zone and lowering the overall heat generated at the cutting zone.

**Forces vs. Depth of cut:**

From the graphs of figure 4.5, it can be seen that as the depth of cut increases, there is a rise in forces. This rise of force was attributed to the fact that the cutting insert had to exert extra force to cut the increased volume of chip for every time there was a rise in depth of cut.

It was also studied in past research that high pressure jets of MWF were effective in diverting the chips away from the rake surface to a certain limit; this resulted in the reduction in the angle of plastic deformation which lowered the amount of efforts for a cutting insert to cut the material.
Figure 4-6: Graphs representing performance of three application with a.) Tool wear, b.) Cutting Temperature, c.) Resultant force and d.) AE Hits for flooding and misting
One of the major goals of this research was to study the effects of all three MWF applications and compare it based on its performance to control the tool wear, cutting temperature, resultant forces, and to examine the generated changes in an AE signal. Thus in order to summarize the overall results of the performance of the three applications based on tool wear, temperature, forces and AE, interval plots were plotted with a 95% confidence interval level as shown in the graph of figure 4.6 by using Minitab software.

The graph of figure 4.6. a. indicates the comparison made between the three applications based on its ability to control the tool wear. As observed, misting did a better job followed by through tool. The ability of flooding in controlling the tool wear was seen to be the least.

As discussed previously, thermal damage was observed as the major cause of tool wear throughout the experiments. It was clear that flooding application resulted in a higher temperature gradient. Whenever the hot cutting insert left the cutting zone, it was impacted by copious amounts of MWF which resulted in thermal cracks and eventually lead to the fracture of tool material. Yet in the case of through tool application, because of such a high pressure coolant jet, there was a possibility that the MWF were able to be in contact with the cutting insert during the cutting operation and not only for the very moment when it left the cutting zone as in flooding. This lowered the chances of generating higher heat and resulted in decreased levels of thermal gradient.

Since the amount of MWF used for misting application is very minuet, it is not an effective application method if controlling the cutting temperature is the primary reason. We can see from the graph of figure 4.6 b. that its efficiency in controlling the cutting
temperature compared to the other two applications is low. As the use of MWF employed in flooding and through tool is abundant, it certainly has an upper hand in controlling the temperature than misting.

In addition, it is observed that through tool application performed better compared to flooding, though by a small level. The reason is, it was able to lower the temperature as it reduced the friction generated between chips and tool rake surface because of its ability to deviate the chips using a high pressure jet.

As the tool starts to lose its sharpness during the span of a cutting process, the tool has to exert more force to cut the material in the same way as we need to during the use of a blunt knife. As observed in the graph of figure 4.6 a., tool wear results were higher for flooding, hence, there was a rise in forces compared to misting where tool wear was seen to be least. It was observed that the levels of cutting force for through tool were slightly lower than flooding but higher than misting application. As discussed previously, the high pressure jet’s ability to deform the chips lowers the efforts on the cutting insert during metal cutting, thus resulting in reduced amounts of forces.

The increased surface area of a blunt tool resulted in a generation of higher AE Hits, thus it is seen in the graph of figure 4.6 d., that the AE Hits values for flooding recorded were higher than misting application.
4.5 Regression Modelling

The last objective of this research, as stated earlier, was to establish a mathematical relationship (model) between the measured and cutting parameters. The cutting process employed in this research depended upon three major parameters viz. Surface speed, Chip load and Depth of cut which are seen to affect the response variables. In addition, it was also found that the change in tool wear impacted the response variable to a certain limit. Thus it was necessary to consider the effect of tool wear with modeling the response variables.

For the purpose of this research, Resultant forces were modeled for all three applications with Surface speed ($V_c$), Chip load (CLPT), Depth of cut (d) and tool wear ($V_b$) being the dependent parameters. In order to observe the impact of these parameters the following polytropic equation was proposed:

Resultant Force model:

$$F_{xy} = C \times (V_c)^\alpha \times (\text{CLPT})^\beta \times (d)^\gamma \times (V_b)^\lambda$$

Where $F_{xy}$ is the resultant force to be determined in Newton (N), $V_c$ is the surface speed (m/min.), CLPT is the chip load per tooth (mm/tooth), d is the depth of cut (mm), $V_b$ is the flank wear in (mm), and $\alpha$, $\beta$, $\gamma$, $\lambda$ and $C$ are the respective regression constants.

Now in order to determine the values of all five regression constants the above equation was transformed into Log form as below;

$$\log(F_{xy}) = \log(C) + \alpha \log(V_c) + \beta \log(\text{CLPT}) + \gamma \log(d) + \lambda \log(V_b)$$

The values for the constants are then calculated as shown in below tables with the help of MINITAB using a general regression analysis.
4.5.1 Resultant Force Model for Flooding application:

Regression Equation (Minitab output)

\[
\log(F_{xy}) = 2.44011 + 0.0748984 \log(V_c) + 0.426407 \log(\text{CLPT}) + 1.19507 \log(d) + 0.121579 \log(V_b)
\]

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>2.44011</td>
<td>0.517571</td>
<td>4.71453</td>
<td>0.000</td>
</tr>
<tr>
<td>Log( Vc)</td>
<td>0.07490</td>
<td>0.204301</td>
<td>0.36661</td>
<td>0.717</td>
</tr>
<tr>
<td>Log(CLPT)</td>
<td>0.42641</td>
<td>0.188667</td>
<td>2.26010</td>
<td>0.034</td>
</tr>
<tr>
<td>Log(d)</td>
<td>1.19507</td>
<td>0.159424</td>
<td>7.49620</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(Vb)</td>
<td>0.12158</td>
<td>0.123608</td>
<td>0.98358</td>
<td>0.336</td>
</tr>
</tbody>
</table>

Summary of Model

\[ S = 0.0412957 \quad R^2 = 91.44\% \quad R^2\text{(adj)} = 89.88\% \]

\[ \text{PRESS} = 0.0653400 \quad R^2\text{(pred)} = 85.08\% \]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
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<td>0.400517</td>
<td>0.400517</td>
<td>0.100129</td>
<td>58.7153</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(Vc)</td>
<td>1</td>
<td>0.000157</td>
<td>0.000229</td>
<td>0.000229</td>
<td>0.1344</td>
<td>0.717</td>
</tr>
<tr>
<td>Log(CLPT)</td>
<td>1</td>
<td>0.007174</td>
<td>0.008711</td>
<td>0.008711</td>
<td>5.1080</td>
<td>0.034</td>
</tr>
<tr>
<td>Log(d)</td>
<td>1</td>
<td>0.391536</td>
<td>0.095828</td>
<td>0.095828</td>
<td>56.1930</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(Vb)</td>
<td>1</td>
<td>0.001650</td>
<td>0.001650</td>
<td>0.001650</td>
<td>0.9674</td>
<td>0.336</td>
</tr>
<tr>
<td>Error</td>
<td>22</td>
<td>0.037517</td>
<td>0.037517</td>
<td>0.001705</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.438034</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fits and Diagnostics for Unusual Observations

<table>
<thead>
<tr>
<th>Obs</th>
<th>Log(Fxy)</th>
<th>Fit</th>
<th>SE Fit</th>
<th>Residual</th>
<th>St Resid</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>2.60155</td>
<td>2.51710</td>
<td>0.0200146</td>
<td>0.0844510</td>
<td>2.33798</td>
</tr>
</tbody>
</table>

R denotes an observation with a large standardized residual.

Resultant Cutting Force Model: using the regression analysis we get:

\[ \log(C) = 2.44011, \text{ therefore } C = 10^{(2.44011)} = 275.4926 \]

\[ \alpha = 0.074898 \quad \beta = 0.426407 \quad \gamma = 1.19507 \quad \lambda = 0.121579 \]

\[ F_{xy} = 275.4926 \times (V_c)^{0.074898} \times (\text{CLPT})^{0.426407} \times (d)^{1.19507} \times (V_b)^{0.121579} \]
Figure 4-7: Residual Plots generated by Regression Force model for Flooding application
4.5.2 Resultant Force Model for Misting application:

Regression Equation (Minitab output)

\[
\log(F_{xy}) = 0.878106 + 1.02064 \log(V_c) + 0.995596 \log(\text{CLPT}) + 1.0615 \log(d) - 0.0494266 \log(V_b)
\]

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.87811</td>
<td>0.543442</td>
<td>1.61582</td>
<td>0.120</td>
</tr>
<tr>
<td>Log(V_c)</td>
<td>1.02064</td>
<td>0.229113</td>
<td>4.45475</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(\text{CLPT})</td>
<td>0.99560</td>
<td>0.201664</td>
<td>4.93690</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(d)</td>
<td>1.06150</td>
<td>0.119839</td>
<td>8.85769</td>
<td>0.000</td>
</tr>
<tr>
<td>Log(V_b)</td>
<td>-0.04943</td>
<td>0.077821</td>
<td>-0.63513</td>
<td>0.532</td>
</tr>
</tbody>
</table>

Summary of Model

\( S = 0.0462623 \)  \( R^2 = 87.52\% \) \( R^2(\text{adj}) = 85.26\% \)

\( \text{PRESS} = 0.0722985 \) \( R^2(\text{pred}) = 80.84\% \)

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>4</td>
<td>0.330313</td>
<td>0.330313</td>
<td>0.082578</td>
<td>38.5843</td>
<td>0.000000</td>
</tr>
<tr>
<td>Log(V_c)</td>
<td>1</td>
<td>0.043718</td>
<td>0.044272</td>
<td>0.044272</td>
<td>19.8448</td>
<td>0.000199</td>
</tr>
<tr>
<td>Log(\text{CLPT})</td>
<td>1</td>
<td>0.055130</td>
<td>0.052163</td>
<td>0.052163</td>
<td>24.3730</td>
<td>0.000061</td>
</tr>
<tr>
<td>Log(d)</td>
<td>1</td>
<td>0.230602</td>
<td>0.167918</td>
<td>0.167918</td>
<td>78.4587</td>
<td>0.000000</td>
</tr>
<tr>
<td>Log(V_b)</td>
<td>1</td>
<td>0.000863</td>
<td>0.000863</td>
<td>0.000863</td>
<td>0.4034</td>
<td>0.531894</td>
</tr>
<tr>
<td>Error</td>
<td>22</td>
<td>0.047084</td>
<td>0.047084</td>
<td>0.002140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.377398</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fits and Diagnostics for Unusual Observations

<table>
<thead>
<tr>
<th>Obs</th>
<th>Log(F_{xy})</th>
<th>Fit</th>
<th>SE Fit</th>
<th>Residual</th>
<th>St Resid</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2.30475</td>
<td>2.20560</td>
<td>0.0220250</td>
<td>0.0991511</td>
<td>2.43716 R</td>
</tr>
<tr>
<td>10</td>
<td>2.24587</td>
<td>2.15522</td>
<td>0.0193827</td>
<td>0.0906523</td>
<td>2.15807 R</td>
</tr>
</tbody>
</table>

\( R \) denotes an observation with a large standardized residual.

Resultant Cutting Force Model: using the regression analysis we get:

\[
\log C = 0.878106, \text{ therefore } C = 10^{0.878106} = 7.552765
\]

\( \alpha = 1.02064; \beta = 0.995596; \gamma = 1.0615; \lambda = -0.0494266 \)

\[
F_{xy} = \frac{7.552765 \times (V_c)^{1.02064} \times (\text{CLPT})^{0.995596} \times (d)^{1.0615}}{(V_b)^{0.0494266}}
\]
Figure 4-8: Residual Plots generated by Regression Force model for Misting application
4.5.3 Resultant Force Model for Through Tool application:

Regression Equation (Minitab output)

\[
\log(F_{xy}) = 0.474174 + 0.79876 \log(V_c) - 0.165455 \log(CLPT) + 0.884234 \log(d) + 0.273343 \log(V_b)
\]

Coefficients

\[
\begin{align*}
\text{Term} & \quad \text{Coef} & \quad \text{SE Coef} & \quad T & \quad P \\
\text{Constant} & 0.474174 & 0.656339 & 0.72245 & 0.478 \\
\log(V_c) & 0.798760 & 0.265401 & 3.00964 & 0.006 \\
\log(CLPT) & -0.165455 & 0.222928 & -0.74219 & 0.466 \\
\log(d) & 0.884234 & 0.142503 & 6.20504 & 0.000 \\
\log(V_b) & 0.273343 & 0.086334 & 3.16612 & 0.004 \\
\end{align*}
\]

Summary of Model

\[
S = 0.0516464 \quad R^2 = 86.57\% \quad R^2(adj) = 84.13\% \\
PRESS = 0.0876821 \quad R^2(pred) = 79.94\%
\]

Analysis of Variance

\[
\begin{align*}
\text{Source} & \quad \text{DF} & \quad \text{Seq SS} & \quad \text{Adj SS} & \quad \text{Adj MS} & \quad F & \quad P \\
\text{Regression} & 4 & 0.378336 & 0.378336 & 0.094584 & 35.4599 & 0.000000 \\
\log(V_c) & 1 & 0.043705 & 0.024161 & 0.024161 & 9.0579 & 0.006449 \\
\log(CLPT) & 1 & 0.001490 & 0.001469 & 0.001469 & 0.5508 & 0.465824 \\
\log(d) & 1 & 0.306403 & 0.102700 & 0.102700 & 38.5025 & 0.000003 \\
\log(V_b) & 1 & 0.026738 & 0.026738 & 0.026738 & 10.0243 & 0.004475 \\
\text{Error} & 22 & 0.058682 & 0.058682 & 0.002667 & \\
\text{Total} & 26 & 0.437018 & \\
\end{align*}
\]

Fits and Diagnostics for Unusual Observations

\[
\begin{align*}
\text{Obs} & \quad \log(F_{xy}) & \quad \text{Fit} & \quad \text{SE Fit} & \quad \text{Residual} & \quad \text{St Resid} \\
2 & 2.19293 & 2.29357 & 0.0213746 & -0.100639 & -2.14053 \quad R \\
10 & 2.32692 & 2.22786 & 0.0204391 & 0.099060 & 2.08855 \quad R \\
\end{align*}
\]

R denotes an observation with a large standardized residual.

Resultant Cutting Force Model: using the regression analysis we get:

\[
\log C = 0.474174, \text{ therefore } C = 10^{0.474174} = 2.97971 \\
\alpha = 0.79876; \beta = -0.165455; \gamma = 0.884234; \lambda = 0.273343
\]

\[
F_{xy} = \frac{2.97971 \times (V_c)^{0.79876} \times (d)^{0.884234} \times (V_b)^{0.273343}}{(CLPT)^{0.165455}}
\]
Figure 4-9: Residual Plots generated by Regression Force model for Through Tool application
From the regression analysis performed using MINITAB as shown above, it can be seen that the S value is low and the R sq. is high for all three models. This indicates that the model generated fits well with the actual experimental data. In addition, the P values for ANVOA of the output parameters, which are lower than 0.05, represent that those parameters are significant to the model. The predictors with higher P values than 0.05 imply less significance and thus have a low or a negative regression constant.

The Normal Probability Plots for all three models show that all the residuals appear along the straight line with incredibly less outliers. In addition, the graph of Residuals vs. Fitted values plot for all three models indicates no obvious pattern of the spread for residuals. All of this point to the fact that the models generated are adequate.
4.5.4 Validation of Models:

The statistical models established above for three different cutting fluid applications to predict the resultant cutting force were evaluated to check their credibility. In here, the experimental values were compared with the predicted values which were calculated using the models generated by using MINITAB. The resultant force values generated by models gave results almost similar to the experimental values of the resultant force with an error of 4 – 10%. This indicates that the model fits well to predict the values of resultant forces based on parameters (surface speed, chip load, depth of cut and tool wear) inputted by the user.

Table 4.5 below indicates the exact percentage of error between the results obtained from experimental and predicted values for three different fluid applications. This shows that the three resultant force models obtained can be used in future for the purpose of monitoring cutting processes under Flooding, Misting and Through Tool fluid application.

<table>
<thead>
<tr>
<th>Fluid Application</th>
<th>R square values</th>
<th>Experimental Value (N)</th>
<th>Model value (N)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooding</td>
<td>91.44 %</td>
<td>183.66</td>
<td>183.47</td>
<td>0.1</td>
</tr>
<tr>
<td>Flooding</td>
<td>91.44 %</td>
<td>289.52</td>
<td>264.02</td>
<td>8.8</td>
</tr>
<tr>
<td>Misting</td>
<td>87.52 %</td>
<td>160.84</td>
<td>174.89</td>
<td>8.73</td>
</tr>
<tr>
<td>Misting</td>
<td>87.52 %</td>
<td>278.30</td>
<td>288.65</td>
<td>3.71</td>
</tr>
<tr>
<td>Through Tool</td>
<td>86.57 %</td>
<td>138.53</td>
<td>146.48</td>
<td>5.74</td>
</tr>
<tr>
<td>Through Tool</td>
<td>86.57 %</td>
<td>284.33</td>
<td>263.97</td>
<td>7.16</td>
</tr>
</tbody>
</table>
Chapter 5

Conclusions

The focus of this thesis research was to study the effects of three different MWF applications methods on various response variables. It was found out that variables like tool wear, cutting temperature, forces and acoustic emission were significantly affected by the method of fluid application. In addition, experimental results along with statistical analysis indicated that, of the three process variables viz. surface speed, chip load and depth of cut, it was the depth of cut which had a major impact on tool wear.

It was also observed that thermal wear was the type of tool wear that resulted in lowering tool life throughout the experiments.

The following points detail the various conclusions derived from the experimental results:

1.) Tool wear was seen to be poor when the milling operation was performed under flooding application which was followed by through tool and there was an increase in tool life with the use of misting application.

2.) The tool wear was attributed to thermal damage because of the thermal gradient as a result of constant impact of MWF on the hot insert.

3.) The results of tool wear were monitored using forces and acoustic signals which indicated a rise in signal level with increase in tool wear.
4.) It was observed that cutting temperatures increased dramatically with the use of misting applications where as through tool was seen performing a better job in controlling the cutting temperature to a significant level. This indicated that, the amount of MWF being used played a major role in controlling this variable.

5.) Lower values of forces and acoustic emission for through tool application were attributed to the fact that the high pressure jet assisted in lowering the friction and the cutting force by curling the chips away from the rake surface of the cutting tool.

6.) The experimental observations and the statistical analysis indicated that, of the three process variables viz. surface speed, chip load and depth of cut; the depth of cut was seen to a significant factor which contributed to an increase in tool wear, cutting temperature, forces and acoustic emission signals.

7.) The increase in total volume of uncut chip due to an increase in depth of cut resulted in higher forces, temperature, tool wear, and acoustic emission signals.

8.) Based on the results obtained from this experiment, it is recommended to use the coated metal carbide insert under misting application if tool wear and the quantity of MWF being used is of major concern, where on the other hand the use of high pressure coolant is recommended if controlling the cutting temperature is the sole point of interest.
References


Astakhov, V. P. (2007). Cutting Fluids (Coolants) and Their Application in Deep-Hole Machining.


