CHAPTER 1

1. Introduction

1.1 Preface

In the modern age millions of products are manufactured on a daily basis by a variety of processes. Many products or components of products are manufactured from metal and metal alloys. One of the most basic methods to form bulk metal into a desired final shape is through the process of metal cutting, also referred to as machining. Metal cutting is essentially the removal of excess material from a workpiece by moving a working tool over the surface of the workpiece. Through this, a certain shape is attained together with a desired surface quality of the final product. Machining is usually the final step in the manufacturing process of a metal component, following other bulk deformation processes such as casting, forging and rolling. Conventional machining operations are turning, milling and drilling. A turning operation is pictured in Figure 1.1.

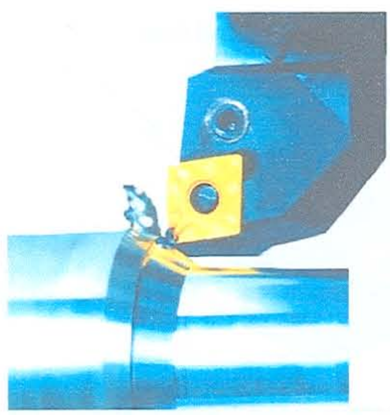

Figure 1.1: Turning operation [1]

Due to the increasing demands for faster and more accurate machining, Computer Numerically Controlled (CNC) machines are commonly used for the above-mentioned processes. These machines are often unmanned and components are moved to and from the machines with component feed devices. A modern CNC machine for turning operations (CNC lathe) is shown in Figure 1.2. Despite the high level of technology built into every aspect of machining, there is still one factor present that hampers the reliability and complete automation of the processes. This factor is the tool wear. Tool wear is the loss of material on the edges of the cutting tool. Although tool wear can be minimised by selecting proper machining conditions, it cannot be completely eliminated. Unfortunately, even a small quantity of tool wear may cause a defect in a machined component. Furthermore, secondary damage due to tool wear can be extreme and even catastrophic [2]. For this reason, many approaches to Tool Condition Monitoring (TCM) have been developed through the years. However, none of the methods developed up to date seem to fulfil the requirements for TCM in industry.

Figure 1.2: Modern CNC lathe

The aim of this thesis is to develop a system that can predict the severity of wear on the edge of turning tool inserts without a direct measurement on the tool tip. A typical turning tool holder with an insert is shown in Figure 1.3. A photo of a worn tool insert is shown in Figure 1.4.

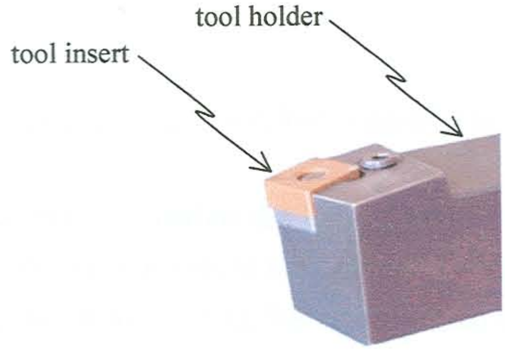

Figure 1.3: Turning tool holder with insert

In this thesis, indirect measurement methods are used in conjunction with Artificial Intelligence (AI) schemes to assist in an accurate estimation of the tool wear. Different turning operations are investigated to determine if the AI approach can be treated as a generic approach for TCM in turning. Due to the complexity of the TCM problem, many aspects of machining, signal measurement, signal analysis and AI modelling are covered in this text. The general theme of the thesis can best be described as a condition monitoring methodology with application in the field of machining.

Figure 1.4: Worn turning tool insert

1.2 Industrial need

The use of fast and accurate manufacturing equipment has gained more ground in recent years due to the high demands of the fast growing manufacturing industry. In order to justify the investment associated with the purchase of such equipment, it is necessary to achieve the maximum possible utilisation of each machine. Monitoring of the manufacturing process plays a very important role to avoid down time of the machine, or to prevent unwanted conditions such as chatter vibration, excessive tool wear or tool breakage. This is also very important in the unmanned machining environment, where the machine must be able to operate non-stop without an operator checking for errors.

Tool wear is one important factor that should be monitored if reliable machining is required. The manufacturing industry requires tool wear monitoring systems that are reliable, accurate and cost-effective. Systems that are currently available do not fulfil these requirements. Generally, wear monitoring systems is required for milling, drilling and turning operations. In the South African industry, the requirement is more focused on turning operations. Consequently it was decided to start the development of the monitoring system with turning operations. However, it is suggested that the proposed methodology can later be extended to more complex machining operations.

1.3 Economic aspects

Tool wear has considerable economic impacts. Therefore, intensive research are carried out in the following areas:

- development of sophisticated tool materials and tool coatings to minimise tool wear
- development of adaptive control strategies to minimise tool wear during machining
- development of Tool Condition Monitoring Systems (TCMS) to predict the tool life and optimise the use of machine tools
- optimisation strategies are used to optimise the machining parameters, mostly to maximise metal removal with minimum tool wear
- development of wear mechanism maps to optimise the use of tools and to compare different tool materials
- development of mathematical models (theoretical, numerical and empirical) to model cutting forces, tool wear, chip formation, surface finish *etc.*

The focus of this work is on TCM, which plays a significant role in the complete economic optimisation of production. The exact economic losses due to tool wear occurs due to scrapping of expensive parts, production down time and the non-optimal use of cutting inserts. Without TCM, a conservative approach is taken and the insert is recycled long before it should have been. This is done because the wear rate is very unpredictable. Sometimes the tool will wear quickly and sometimes slower, even when used with the same machining parameters. The economic impact of cutting tools on total production costs is reported in various studies, such as [3,4]. It is stated that a considerable amount of money can be saved through better use of cutting inserts themselves. Shop floor managers agree that a reliable TCMS will bring about significant cost savings and will thus justify its capital cost. Compared to the overall cost of CNC machines, installing a TCMS will only cause a slight price increase. The possibility should also exist to retrofit old machines with a TCMS at low cost. Typical savings for a manufacturing plant with effective TCM could be more than 50% less scrap, tool inserts and down time. It should be mentioned here that production facilities could also be economically optimised through research in the other areas listed above, and that savings could be more than that achieved with TCM. Nevertheless, effective TCM should be part of the production process if a manufacturer wishes to stay competitive in the global economic environment.

The automotive industry is the principal user of TCMSs. A survey of more than 1000 TCMSs installed in industry is described in [5], and shows that the emphasis is mainly on turning and drilling, as depicted in Figure 1.5.

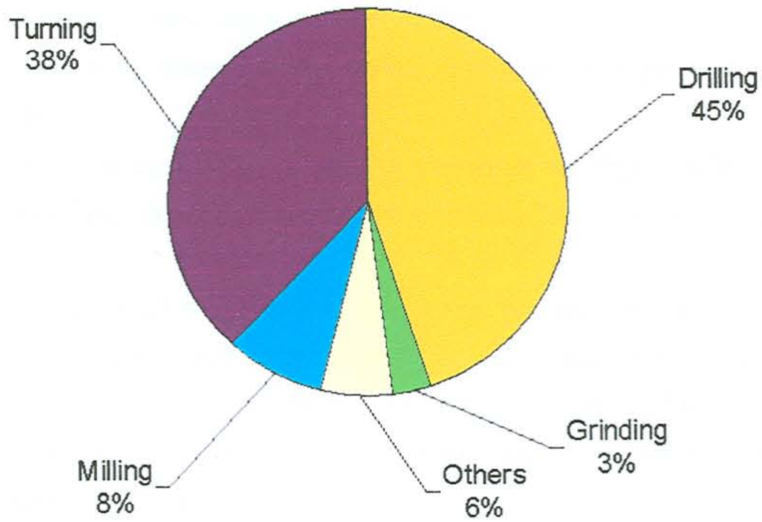

Figure 1.5: Survey of TCMSs by area of application [5]

1.4 Engineering aspects

A number of specialist engineering disciplines are combined in this work. The main focus areas are:

- Condition monitoring
- Artificial intelligence
- Signal processing
- Production / manufacturing
- Structural dynamics
- Data acquisition
- Mathematical optimisation

It will be shown that combining state-of-the-art technology from the different engineering disciplines is vital to achieve success in Tool Condition Monitoring (TCM). Many previous attempts at implementing TCM in industry failed due to a lack of knowledge in one of the key disciplines listed above.

1.5 Scope of research

1.5.1 Contribution

Despite the industrial need and many research papers a TCMS using AI has never successfully been implemented in a real production environment. The following list of quotes from recent literature suffice as proof that this has not yet been achieved [6]:

- "Although many unique characteristics of neural networks appeal to the researchers…, the physical realisation of a neural network monitoring system has not been seen in industries yet. The gap between academic enthusiasm for the neural network approach and industrial needs for a practical and reliable monitoring system tends to be caused by the simple adoption of existing neural network methodology without consideration of some critical issues in implementation of the tool-wear monitoring systems" – [7]
- "A reliable on-line wear measurement system does not exist yet and research in this area is continuing." – [8]
- "The process of metal cutting is a complex phenomenon that has been researched for many years but the aim of practical tool condition monitoring has yet to be achieved." – [9]

This list could easily be continued with remarks from other researchers active in the area of TCM. The proposed contribution of this research is to achieve practical tool wear monitoring using AI. This should be achieved with an AI methodology that is unique in terms of formulation and application. This research aims to make a significant contribution towards more reliable, accurate and cost-effective tool wear monitoring for turning.

1.5.2 Summary of scope

The scope of the research can be summarised as:

- To investigate the use of sensor signals to develop a wear monitoring system for turning tools.
- The wear monitoring system should utilise the advantages given by AI modelling.
- Sophisticated signal processing and AI methods must be investigated to improve the accuracy and reliability of the system.
- The proposed methods must be shown to apply to two different types of turning operations, and also be able to monitor more than one wear mode.
- An industrial implementation of the complete AI monitoring system must be achieved, and must be unique in terms of its formulation and application. It should be the first implementation of AI for TCM in a production environment.
- The research will provide significant new knowledge to the research community of how to approach the problem of TCM.
- The system must be a robust and cost-effective solution to TCM on a shop floor, providing a useful product to industry.

These are the main aspects of the research. There are also a number of detail factors that must be investigated, and these are divided into three subsections, listed below:

1.5.3 Signal measurement

- Investigate force, acoustic emission and acceleration measurements for TCM.
- Interpret the signals with respect to the particular machining operation.
- Identify the best signal collection approach for robust and cost-effective TCM.
- Install the selected sensor approach on a shop floor for TCM.
- Characterise the new sensor approach appropriately.
- Collect data under normal shop floor conditions with an automated data logger.
- Show that the proposed technique can be used for continuous wear estimation under shop floor conditions.

1.5.4 Signal processing

- Investigate various signal processing techniques with respect to the machining operation.
- Time, frequency, time-frequency as well as statistical analyses must be investigated for feasibility towards TCM.
- Conclude towards signal feature sensitivity and machining conditions.
- Compare wavelet analysis with digital filtering.
- Attempt to identify and filter the effect of disturbances from signals.
- Investigate and conclude towards the best feature selection and reduction methods for TCM.
- Suggest appropriate rules for feature selection for practical TCM.

1.5.5 Modelling and monitoring

- Investigate the feasibility of analytical, empirical and numerical modelling with respect to TCM.
- Show that an AI approach for TCM is the most advantageous for practical TCM.
- Conclude towards the feasibility of sensorless approaches (tool life equations).
- Suggest an AI approach for TCM that can estimate tool wear on-line using dynamic NNs.
- The AI method should be applicable to more than one turning operation, insensitive to noise, must be able to handle the effects of machining parameters, monitoring more than one wear mode and must be able to follow any geometrical development of tool wear.
- Compare the proposed method with other conventional NN paradigms.
- Attempt to improve the method and investigate the repeatability of the method.
- Investigate proper training algorithms for on-line NN training and implement the best algorithm.

1.5.6 Research steps

To achieve these objectives, the following studies / steps were undertaken:

- Review of machining (kinematics, processes *etc.*)
- Exhaustive review of commercially available TCMSs and related patents

- Exhaustive review of literature in the area of machining and TCM
- Various industrial visits to identify industrial and economic requirements
- Various academic visits to identify the state-of-the-art in relevant technology and identify limitations of previous work
- Review of methods for modelling machining kinematics and tool wear
- Review, design and development of custom hardware
- Planning and conduction of experiments and processing results
- Design, analysis and proposal of monitoring strategy
- Comparison with other approaches
- Proving and improving monitoring strategy
- Documentation

1.6 Structure

Taking the research objectives into account, two turning operations were investigated:

- Hard turning (in a research laboratory)
- Aluminium turning (on a real shop floor)

The reasons for these particular choices are discussed in Chapters 4 and 5 respectively. The hard turning experiments were conducted at the Laboratory of Machine Tools and Manufacture (WZL) at the Aachen University of Technology, Germany. The Aluminium turning experiments were conducted at Kolbenco Pty (Ltd) in Alrode, South Africa. In Chapter 6, there is a discussion with respect to the results of both sets of experiments. A review of relevant literature, and a short review of the mechanics of metal cutting and tool wear are documented in Chapters 2 and 3. The Conclusion and Future Outlook are included in Chapter 7. Many of the technical details are described in Appendices A – I.