Improving the Performance of Minimum Quantity Lubrication in High Speed Milling and Environmental Performance Analysis

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Word count 37,728

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List of Nomenclature

Parameters	Description	Units
A1, A2, A3	Weighting factor	-
a_e	Width of cut	mm
a_p	Depth of cut	mm
B_{chip}	Environmental burden of chip disposal	$kg\text{-}CO_2$
B_{en}	Environmental burden	$kg\text{-}CO_2$
B_E	Environmental burden of electric consumption	$kg\text{-}CO_2$
B_{CF_disp}	Environmental burden of cutting fluid disposal	$kg\text{-}CO_2$
B_{Lub_disp}	Environmental burden of lubricant disposal	$kg\text{-}CO_2$
B_{tool_disp}	Environmental burden of cutting tool disposal	$kg\text{-}CO_2$
B_{others}	Environmental burden of other related factor	$kg\text{-}CO_2$
C_1	The coefficient of the predictor	-
C_{ch}	The environmental burden factor of chips disposal	kg-GAS/kwh
C_{CO2}	Carbon dioxide emission cost per unit of product	£
CES	Carbon emission signature	$kg\text{-}CO_2/GJ$
C_{DE}	The environmental burden factor of cutting fluid disposal	kg-GAS/kwh
C_H	The environmental burden factor of tool holder disposal	kg-GAS/kwh
C_T	The environmental burden factor of cutting tool disposal	kg-GAS/kwh
C_o	The coefficient of the inverse model	-
c	Conversion factor	-
E	Energy consumption	J
E_{cut}	Energy demand for cutting	J
E_{cool}	Energy demand for coolant delivery	J
E_{DE}	Total energy consumed by spindle and feed axes along tool path, DE	J

Parameters	Description	Units
E_D	Direct electrical energy consumption	kJ
E_{ID}	Indirect electrical energy consumption	kJ
E_{part}	Energy consumption per part produced	J/unit
E_{ready}	Energy demand for ready state	J
ES^{TM}	Emission signature	kg-GAS/kWh
E_{setup}	Energy demand for setup stage	J
E_{Tot}	Total energy consumption	J
E_{tool_change}	Energy demand for tool change	J
F_c	Cutting forces	N
f_z	Feed per tooth	mm/rev
GES	Gas emission signature	kg-GAS/kwh
I	The current	ampere
i	Number of iteration	-
K_{CO2}	Carbon dioxide emission cap and trade cost per tonne	£/kJ
k	The specific energy constant	Ws/mm^3
m_W	Weighted mass flow	-
N	Rotational speed	rpm
N	Number of stages	-
n	Life of the tool holder expressed in number of insert cutting edges used before holder end life	-
P_1	Absolute final pressure	Pa
P_2	Outlet air pressure	Pa
P_{aY}	Power required to accelerate the spindle in Y-axis	W
P_c	Tool tip power	W
P_{cool}	Cooling power	W
P_{comp_o}	Basic power of compressors	W
P_{comp_ops}	Operating power of compressor	W
P_{DY}	Power to decelerate the spindle in Y-axis	W
P_f	Feed power	W
P_{hyd}	Hydraulic power of pumps	W
P_{pump_o}	Basic power of pumps	W
P_{pump_ops}	Operating power of pumps	W
P_p	Passive power	W

Parameters	Description	Units
P_{run}	The power required to run the spindle at constant speed	W
P_{ready}	Power consumed by the machine in ready to cut state	W
P_{SY}	Steady state power of spindle	W
P_o	Power consumed by the machine modules	W
P_o	Absolute initial atmospheric pressure	Pa
Q	Volumetric flow rate	ml/h
R_{ap}	Depth of cut to tool edge radius	-
R_f	Feed per tooth to tool edge radius	-
S	Productive machine utilisation ratio	-
T	Tool life	minute
T_z	Total tool life for all available cutting edges	minute
t_1	Setup time	s
t_2	Cutting time	s
t_3	Tool change time	s
t	time	s
t_{CF}	The useful life of cutting fluids	hours
t_{ready}	Ready time	s
t_{TH}	Utilisation period of tool holder	hours
V_1	Volume of air in reserve tank	m^3
V_2	Volume of air supplied through the nozzle	m^3
V	The voltage	volts
VB	Flank wear value	µm
V_c	Cutting speed	m/min
V_f	Feed rates	mm/min
$\dot{v}$	Material removal rate	mm^3/s
W_{Tool}	Weight of cutting tools	kg
W_{TH}	Weight of tool holders	kg
x	The adiabatic expansion coefficient	-
Y_E	Energy footprint per tool cutting edge	J
z	Number of available cutting edges	-
Δp	Hydraulic pressure	Pa
ζ	Nozzle position	degree
η	The mechanical efficiency	%

Parameters	Description	Units
ρ	Density of workpiece material	cm^3/kg
Φ_1, Φ_2, Φ_3	Nozzle orientation	degree

List of Abbreviations

AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
AlCrN	Aluminium Chromium Nitride
Al_2O_3	Aluminium dioxide
BHN	Brinnel Hardness Number
BP	British Petroleum
BSE	Backscatter Electron
BUE	Built-up Edge
CBN	Cubic Boron Nitride
CCL_4	Carbon tetrachloride
CECIMO	Comite Europeen de Cooperation des Industries de la Machine Outil-European Committee for Cooperation of The Machine Tool Industries
CES™	Carbon Emission Signature
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
CVD	Chemical Vapour Deposition
DC	Direct Current
DEFRA	Department of Environment, Food and Rural Affairs
DFE	Design for the Environment
DFR	Design for Recycling
DOS	Direct Oil Drop
EEA	Extended Energy Analysis
EP	Extreme Pressure
FANUC	Fuji Automatic Numerical Control
HPJ	High Pressure Jet machining
HRc	Rockwell hardness-C
HRd	Rockwell hardness-D
HSM	High Speed Machining

ISO	International Standard Organization
KPV	Key Process Variable
LCA	Life Cycle Analysis
MQL	Minimum Quantity Lubrication
PH	Precipitation Hardening
PVD	Physical Vapour Deposition
RPM	Rotation per minute
SE	Secondary Electron
SEM	Scanning Electron Microscope
S/N Ratio	Signal-to-Noise Ratio
TiAlN	Titanium Aluminium Nitride
TiAlSiN	Titanium Aluminium Silicon Nitride
TiCN	Titanium Carbon Nitride
TiN	Titanium Nitride
UK	United Kingdom
VE	Vegetable oil-based Emulsion
VO	Neat Vegetable Oil

Abstract

Manufacturing by mechanical machining has historically benefited from the use of cutting fluid. Cutting fluids help to reduce temperature, friction, flush away chips, and hence prolong tool life and improve machining performance. However, uncontrolled use of cutting fluid raises concern in respect of cost and environmental burden. For these reasons, dry machining is used in conjunction with high speed machining to reduce cycle times and simultaneously deliver a greener process. However, for some workpiece materials full implementation of dry machining is not economically viable due to the absence of the essential cooling and lubricating functions delivered by cutting fluids. The most feasible bridging technology is minimum quantity lubrication (MQL) where a very small flow rate of coolant/lubricant is delivered to the cutting zones. In terms of machinability, the application of MQL is promising. However, most studies conducted on MQL focused on the feasibility of MQL application and show-casing the technical benefits. No studies had been identified in literature systematically investigating the relationship between cutting conditions and MQL with the goal of optimising the process. Moreover, the presumed environmental benefits of MQL have not been systematically assessed because Life Cycle Analysis (LCA) derived evaluation models do not explicitly model the impact of machining conditions such as feedrates, cutting velocities and depth of cut.

The motivation for this PhD work was to select the optimum machining process variables for maximising effectiveness of MQL, to explore process improvements and to assess the environmental credentials of the process in relation to other forms of cutting environments. In this work, high speed, end milling tests on tool steel were undertaken and 1) Taguchi methods were used to optimise the process, 2) the sensitivity of tool wear to nozzle position was evaluated and 3) the environmental burden of dry, MQL and flood coolants were evaluated based on direct energy needs and process outputs. A fluid soaking device was used to assess the amount of fluid collected or presumed to be delivered to the cutting zone for different nozzle orientations.

The Taguchi process optimisation suggested that in HSM the size effect, brought about by a low chip thickness, should be considered in the search for an optimum process window for HSM. A significant and novel finding of this PhD was the dominance of MQL nozzle positioning. The study clearly showed that when machining hardened steel at a high cutting speed and RPM the tool life could be significantly increased by 50% by adjusting the position of the nozzle toward the rake face in relation to the end-milled face. The work opens up new science and provides recommendations as to where to align the nozzle when end milling tool steel at high cutting speeds. The fluid trapping and the blade-wiping angle are key parameters that influenced the effective delivery of MQL when high spindle revolutions per minute are used. These results from the fluid soaking device were found to correlate strongly with observed machining performance evaluations.

In terms of modelling, the PhD developed an improved and more generic direct energy model that can be used to determine the environmental burden for direct electrical energy requirements and the energy embodied in other process material outputs. This model addresses the system boundary and activity that within the control of the manufacturing plant. The model was used to evaluate the environmental performance of dry, flood and MQL fluids. The impact of these results and models in optimising environmental performance was also illustrated.

The work in this PhD is important to industry in that it contributes to the optimisation of MQL and gives an assessment of the environmental impact. The PhD developed new and significantly important machining science in the positioning of nozzles in MQL machining at higher speeds.

List of Publications

1. Mulyadi I.H., and Mativenga P.T. Effect of key process variables on effectiveness of minimum quantity lubrication in high speed machining, in: the Proceeding of 37th International MATADOR Conference, 25-27 July. 2012, (Manchester, United Kingdom), pp 193-196
2. Mulyadi, I.H., and Mativenga P. Random or intuitive nozzle position in high speed milling (HSM) using minimum quantity lubrication (MQL), accepted for publication in Proceedings of the IMechE, Part B: Journal of Engineering Manufacture, 20 May 2013

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or another institute of learning

Copyright Statement

Dedication

To My Family

Acknowledgements

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CHAPTER 1

INTRODUCTION

1.1 Research Background

High speed machining can lead to shorter cycle time, rapid material removal rates, better surface quality ,and low cutting forces. However, machining at high cutting velocities offers challenges such as high interface temperatures and short tool life. Cutting fluids that can be utilised to reduce heat generation and temperature can be ineffective when running in high-speed milling, as it is difficult for the cutting fluids to gain access to the secondary contact zone due to highly localized stress and elevated temperatures. Elevated temperatures, as experienced in high-speed milling, can make the presence of cutting fluids detrimental to the cutting tool due to thermal cracking. Therefore, there are fundamental process drivers for HSM without the use of cutting fluids (i.e. dry cutting). Moreover, it is assumed that, machining in the absence of cutting fluid oils can be environmentally friendly. Additionally, high speed dry machining cannot always be economically feasible due to the limited capability of cutting tools to withstand and effectively perform at elevated temperatures. Thus, to partially fulfil the functions of cutting fluids without compromising the environment a bridging technology is needed.

The most credible bridging technology is minimum quantity lubrication (MQL). Intermittent processes such as milling can gain benefits from using limited cutting fluid volume. Avoiding sudden temperature reduction as in MQL reduces the chances for thermal cracks, which is predominantly caused by rapid cooling due to the use of flood coolant. However, further investigation still needs to be undertaken before full implementation on the shop floor can be achieved.

Most of research conducted focused on comparison studies of MQL with other cooling/ lubricating processes [1-4]. Meanwhile, studies of MQL in high-speed milling were limited. In HSM, coolants are constrained by the severe condition of the interfacial faces of cutting tools running at higher speeds, preventing the cutting fluids from lubricating those faces. In addition, the small quantity of cutting fluid delivered to contact zones at high cutting speeds cannot guarantee a sufficient temperature reduction. Meanwhile, the research into MQL attempted to reduce the quantity of cutting fluid delivered as low as possible [5]. Therefore, the optimisation of MQL is necessary in attempting to gain more merit for MQL. Optimum cutting conditions were rarely focused on in previous MQL studies. Thus, it is necessary to investigate ways to improve machinability.

Furthermore, once the amount of cutting fluid delivered to the contact zone is reduced, then the effective penetration of the cutting fluid is important. This can be obtained by appropriate positioning of the nozzle. However, there is very limited information in respect of achieving this objective [6-9]. The information available in literature, in respect of fluid penetration, is aimed at identification rather than examining the most effective penetration position. Finding the effective nozzle position can help in improving machining performance in the MQL application.

Finally, many studies have been conducted in respect of exploring machinability processes using MQL applications. However, the environmental advantages still require confirmation. This can be done by evaluating the environmental burden of MQL applications. Limited references regarding environmental evaluation of MQL were found in literature [10,11].

1.2 Aim and Objectives

The aim of this PhD was to study the key process variables in end milling under MQL, optimise process performance as well as assessing environmental burden. The objectives are;

1. To review published literature on the use of MQL in machining and identify areas of agreement as well as knowledge gaps.

2. To study the key process variables aiming to clarify cutting condition ranges that are feasible for MQL application, and exploit design of experiments and statistical methods to define optimum parameters for end milling performance under MQL application.
3. To study the effect of MQL nozzle position on machinability improvements in the high-speed milling.
4. To evaluate the environmental burden of MQL in respect of energy footprint as well as waste stream and compare with dry machining and flood cooling.

1.3 Importance of Project to Industry

The die and mould industry is a significant player in the manufacturing base. This industry undertakes end milling of hardened steel dies [12]. Fabrication of the die and mould tools could be very time consuming, costly, as well as requiring high precision processes. This industry already uses high speed machining to rapidly make dies of advanced and higher quality.

Due to the high hardness of die and mould materials, the milling process is normally performed by using high-strength tool material such as Cubic Boron Nitride (CBN) [13], and ball type milling tools [14]. These materials enable extended tool life and better machining performance. However, the tool material is costly and can significantly affect the total production costs of dies or moulds. Meanwhile, if cutting fluid were utilised to reduce heat generation, cutting tools made from ceramic materials would experience severe crack propagation. Thus, if MQL can be improved and combined with high speed machining, it would be beneficial to the mould and dies industries because of following reasons:

- ✓ Enable the replacement of CBN cutting tools and, hence, reducing the costs.
- ✓ Reduction in the energy and carbon footprint of machining processes by avoiding fluid pumping which is beneficial to the environment.

1.4 Thesis Outline

This thesis contains eight chapters.

Chapter 1 Introduction

This chapter has described the project background and motivation, and importance MQL to industries, and summarises the fundamental knowledge gap that needs to be filled to improve MQL performance. Based on this, the aim and objectives of this PhD were developed.

Chapter 2 Literature Review

This chapter presents a literature review particularly focused on the use of MQL in milling a wide variety of workpiece materials. Furthermore, the environmental burden in respect of the use of MQL is reviewed in the context of manufacturing in sustainability.

Chapter 3 Experimental Method and Procedure

This chapter presents the equipment used for all research activities, workpiece material and the type of cutting tool utilised. In addition, Design of Experiments is also included in this chapter. Additionally, the methodology used to measure tool wear, surface roughness, tool edge radius and MQL flow rates is documented. Finally, the Taguchi method used to design some experiments is briefly described.

Chapter 4 Effect of Key Process Variables on Effectiveness of Minimum Quantity Lubrication in High Speed Milling

In this chapter, the effect of key process variables that contribute to the optimal condition of end milling processes under MQL was investigated. To reduce the cost and time, the Taguchi approach was used to design the experiment. Then, Signal-to-Noise Ratio (S/N analysis) and Analysis of Variance (ANOVA) were utilised to find the significant contributor for effective MQL in high-speed end milling processes. From the results, the influence of cutting parameters, as well as the effect of flow rates, was defined for machinability improvement and proposed optimal condition for end milling of H13 material using MQL applications.

Chapter 5 Random or intuitive nozzle position in high speed milling (HSM) using minimum quantity lubricant (MQL)

Nozzle positioning was identified as critical for improving the effectiveness of MQL application. The study reported in this chapter relates to seeking the best position for the nozzle. The results offer an effective strategy to improve machinability of tool steel workpiece material using MQL applications.

Chapter 6 Tool life and environmental burden analysis of milling process using minimum quantity lubricant (MQL) conditions

To access the environmental burden of dry, flood cooling and minimum quantity lubrication, an extended energy footprint model was developed. Electrical energy measurements taken in the milling tests and this information led to a characterisation and definition of numeric values for specific cutting energy coefficients for machining under dry, MQL and flood coolant conditions. In addition, the result also showed that MQL application is not only capable of energy consumption reduction (and hence lower carbon footprint) but also led to better tool life compared to dry machining.

Chapter 7 Environmental burden analysis of end milling process – An improved environmental evaluation tool

Chapter 7 reports the environmental burden of different cutting environments based on electrical energy requirements and the energy embodied in machining waste streams.

Chapter 8 Conclusions and Recommendations

This chapter summarises the scientific findings. It also includes possible future work that can be undertaken based on the key findings revealed by this study.

CHAPTER 2

LITERATURE REVIEW

2.1 High Speed Machining and Sustainability

Increasing world population and prosperity is one of the driving factors that triggers demand for products. As the number of manufacturers grows then the world faces consequences in the availability of resources to support that growing needs and the negative impact on nature.

According to the United Nation, sustainable development can be defined as an activity to *meet the needs of the present without compromising the ability of future generations to meet their own needs* [15]. More specifically, the United States Department of Commerce defines sustainability for the manufacturing sector as *the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources and are economically sound and safe for employees, communities, and consumers* [16].

Machining processes, as an important element in manufacturing, has shown rapid growth, especially in emerging countries like China. This was indicated by the growth in the machine tool market sales in China as observed by the Freedonia group, a market research institution. They predicted that China's machine tool industries had to be well prepared to manage a 14.2 % increase in demand annually through to 2014 [17].

Additionally, European Union producers of machine tools who are members of the CECIMO group also experienced an increase in demand for machine tools in 2011 following the economic downturn of 2009 [18]. They supplied approximately 33% of the global machine tool market share, in particular highly innovative, diversified and high-precision machine tools. Increasing demand for machine tools around the globe indicates that the demand for components produced by using machine tools is undergoing rapid increases.

This positive trend would indeed lead to economic benefits. However, it would also trigger an increase in consumption, for instance, the consumption of cutting fluids increased as well as demand for energy. Cutting fluids and energy supplies are mainly met from natural resources. Although cutting fluid, made from chemical substances has been widely used, dependence on mineral-based cutting fluids is still prominent. Meanwhile, the availability of natural resource has declined persistently.

Besides limited availability of natural resources, the impact caused by the use of cutting fluids and increasing consumption of energy would create negative effects on the environment. During machining processes, the cutting zones are traditionally enveloped with huge volumes of cutting fluid to avoid temperature elevation that can distress cutting tools and shorten service life. After fulfilling its function, cutting fluid is normally circulated back to a storage tank. However, the percentage that flows back to the fluid storage tank has reduced due to vaporisation, contaminating chips, the deposits covering machine tool components and the machined surface.

Vaporised cutting fluid creates a chemical suspension in the air; if it is inhaled by people working in enclosed machine areas it will cause health problems. In addition, the chips contaminated by the cutting fluid require purification and re-processing before they can be recycled as new raw material. Meanwhile, after use, cutting fluid has to be disposed of; which requires the correct treatment to be undertaken before it can be discarded to prevent harm being caused to the environment and living organisms. Provision of extractors, so that the machine tool ambient environment is safe, and purification processes and treatment of cutting fluid disposal need extra budgets, which affect production costs.

The energy to power up machine tools is supplied by power stations that are primarily generated by natural resources such as fossil fuel, coal, etc. The increase in demand for products manufactured by the machining process not only increases energy consumption and in turn the cost of energy; but also has implications on global warming due to the carbon released by power generators.

Thus, a stringent policy to avoid any detrimental effects on the environment is needed. In addition, the International Standard Organization (ISO) has originated an environmental management standard by releasing ISO 14000 series. Therefore, to produce highly competitive machined products, the machining industries had to address all the problems of machining processes and to seek appropriate strategy to satisfy environmental standards [19].

For decades many studies have been carried out with the intention of increasing material removal rates hence, reducing the cycle time of machining processes. This is done by shifting the conventional machining process to a high speed machining process. By implementing this technology, it not only fulfils the requirement for higher productivity and lower production costs, but also leads to a reduction in energy consumption due to lower cycle times.

To make it environmentally friendly, high speed machining operates without the use of cutting fluid. However, there are many problems associated with full implementation of this technology, and therefore, efforts for technological improvement is ongoing. Thus, a back-up technology, such as near dry machining, becomes a suitable alternative.

2.1.1 High Speed Machining

Salomon initially introduced the concept of high speed machining (HSM) [20], and cutting speed was the centre of interest in Solomon's investigation. He postulated that cutting temperature decreases significantly beyond a critical cutting speed. This trend can be seen in Figure 2.1.

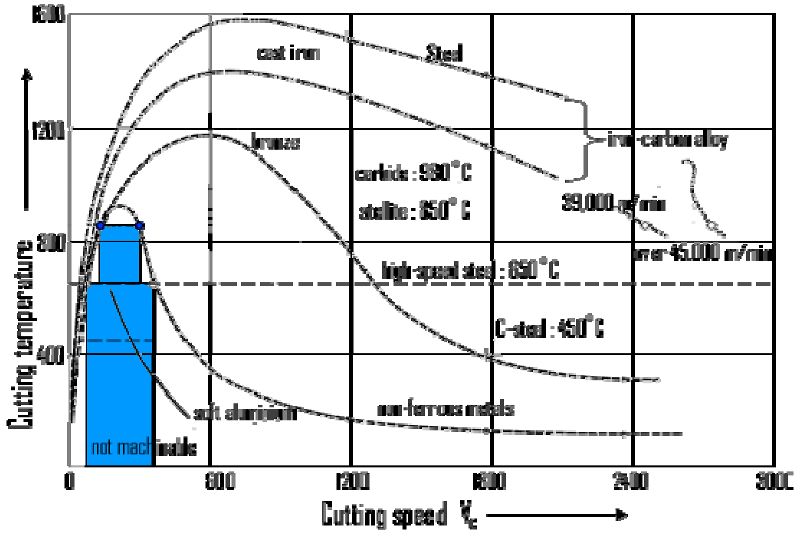

Figure 2. 1 Machining temperature trend in milling at high cutting speeds from early Solomon' now a disproved theory [21]

This concept in modern machining technology has attracted the curiosity of scientists and practitioners in the field of machining processes, particularly to gain an in-depth knowledge of the mechanism behind the concept as well as how to fully implement HSM on the shop floor. In this respect, Mc Gee [22] studied the effect of cutting speeds on cutting temperature elevation when cutting aluminium. It was found that no decline in temperature occurred after the cutting speed reached its optimum level. In fact, cutting temperatures rise gradually following a logarithmic pattern as illustrated in Figure 2.2. This finding revised the cutting temperature phenomenon in high speed machining.

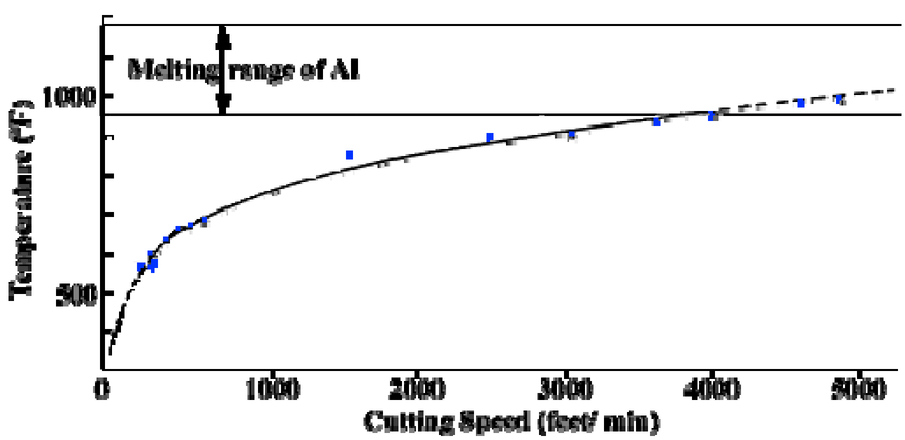

Figure 2. 2 Mc Gee's temperature and cutting speed relation graph [22]

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The concept of high speed machining can be related to many phrases such as high cutting speed, high spindle speed, high feed, and high productive machining. The most popular definition of HSM was suggested by Schulz and Moriwaki [23], who proposed that every workpiece material has its own cutting speed range for HSM (Figure 2.3). In general, it is influenced by material properties: particularly the hardness of the workpiece material.

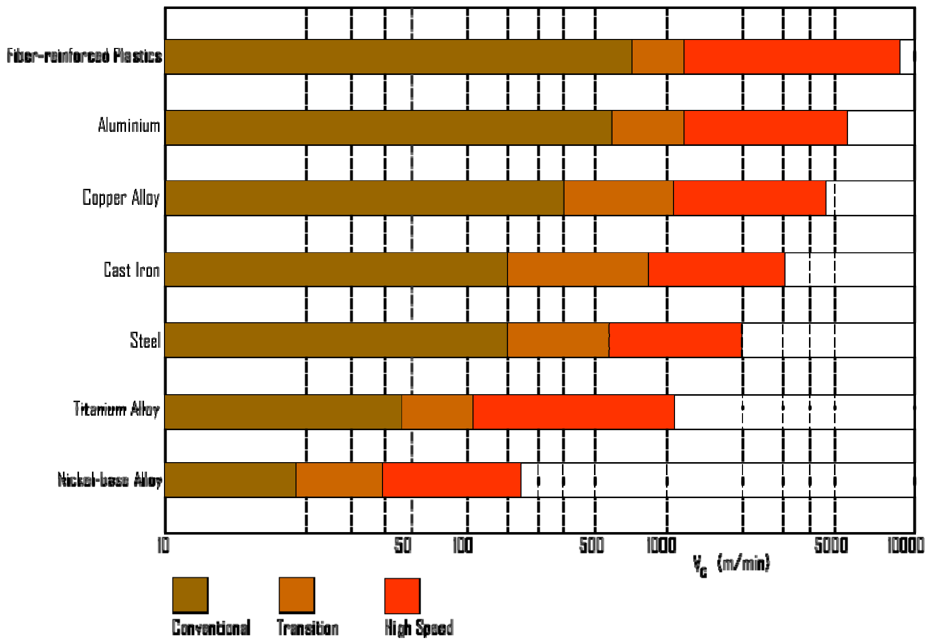


Figure 2. 3 Classification of High Speed Machining based on material type [23]

Machining aluminium parts in the aerospace industry, finishing hardened materials in the die/mould industry and producing long thin aerospace components are among the industries that benefit from using HSM [24]. In machining of aluminium components, the volumetric material removal rate could approach one thousand cubic centimetres per minute [24].

The primary motivation for using HSM is the demand for increased productivity and quality improvement in machined products. This is supported by enhanced machine tool technology such as development of new spindle speed designs and technology, machine tool construction, machine slide ways and advanced numerical control processors. Development of spindles capable of rotating at more than 10,000 rpm has promoted the use of higher feed velocity. Smart design in machine tool construction enables it to retain high-impact loads as well as external excitation forces. Accurate design of machine slide ways makes it easy to coordinate linear motion at high speed; while advanced numerical control processors offer the possibility of optimising the machining process associated with the high velocity, high accuracy and better surface finish.

In addition to lower cycle times, low chip loads normally applied in HSM technology make the process run at low cutting forces [25], and this produces minimum vibration effects on a machined surface and makes it possible to manufacture very thin wall components.

The combination of high feed velocity and low depth of cut enables extremely short engagement times, thus minimising the heat effect on workpiece materials because most of the heat generated will be removed by the chips. Therefore, cutting at higher speed could improve tolerances in machined components/parts. Better surface integrity can be guaranteed due to minimal thermal expansion encountered in workpiece materials during the machining process [26].

Thus, producing highly complex and very close tolerance parts is plausible. High geometrical accuracy of dies and moulds can be more easily achieved and it is possible, therefore, to conduct rapid assembly. In addition, using HSM makes it possible to produce better surface finish in machined parts.

Moreover, it was reported that HSM would allow a 7% to 10% reduction in manufacturing time when producing stamping dies and also a significant improvement to the surface finish [27]. This would avoid using the grinding process at the finishing stage. Figure 2.4 clearly shows the main advantages of HSM as well as its inherent technological challenges.

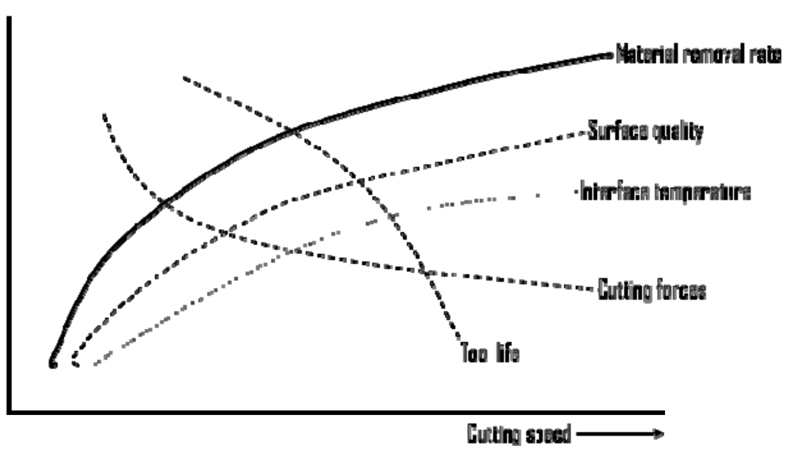


Figure 2. 4 Characteristics of High Speed Machining process [28]

In HSM, the workpiece material experiences extremely severe conditions in a very narrow band. The workpiece material suffers from severe plastic deformation and shearing rates as well as high temperatures in the primary deformation zone. Burns and Davies [29] reported that the strain rate during HSM can increase by up to 10^7/s, which is presumably higher compared to conventional material testing.

In addition, in HSM, the chips flowing over the rake face will remove most of the heat generated from the primary zone [30]. This creates a bulk-elevated temperature on the rake face. Consequently, the rake face of the tools will undergo very severe contact conditions and establish regions of sticking and sliding.

The sticking region is where the loads do not allow cutting fluid to penetrate sufficiently. Therefore, most HSM is performed without cutting fluid [31], which is known as dry machining. However, dry machining is not yet feasible for all processes due to difficulty in providing a trade-off function for cutting fluids [32, 33]. The need for cooling and lubrication needs to be balanced with the need to avoid thermal shock, which can be caused by sudden temperature drop owing to exposure to cutting fluid.

2.1.2 *Environmental friendly machining processes*

For decades, machining processes have relied on the use of cutting fluids to extract the heat generated during the process. The heat generated at the primary and secondary cutting zones has a negative effect on the cutting tools, promoting wear. Increasing wear degrades the cutting tool’s performance, consequently affecting the quality of machined parts/components, which is essential in machining processes. Therefore, the use of cutting fluids is an important part of a machining process system.

Without cutting fluid, tools have only a short life, which makes the machining process costly. Solid tools need regrinding so that they can be reused and insert-type cutting tools require the cutting edges to be rotated so that a new cutting edge is ready to cut. These processes add extra costs. Frequent tool changing due to tool wear and/or breakage can increase the cycle time of machine tool operation. Because of these reasons, cutting fluid usage becomes crucial in cutting operations and this sometimes leads to uncontrolled use of cutting fluid which in turn increases direct fluid usage costs along with other costs such as, recycling, maintenance and fluid disposal as shown in Figure 2.5 [34].

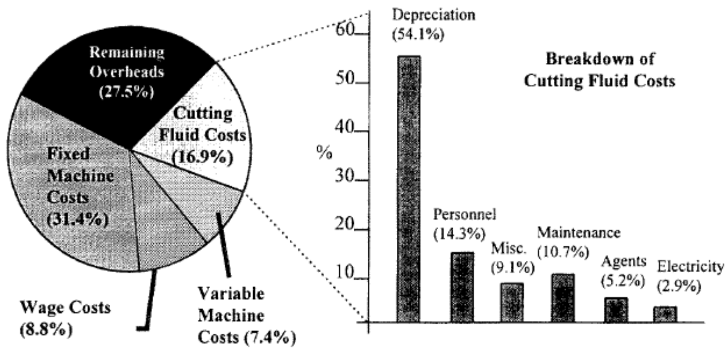


Figure 2. 5 Breakdown of machining cost [34]

For example, in Germany, in 1998, there was an increasing trend for cutting fluid utilisation from 7 - 17% [35]. Since cutting technology is a universal science, it means every country would try to adopt new improved technology invented by others. Thus, the value of cutting fluid consumption in Germany can be used as a good estimate for other countries, particularly industrial countries such as the United Kingdom.

By comparison, Blasser Inc., a worldwide producer of cutting fluid, conducted a survey of typical end-use of coolant. They discovered that utilisation of coolant in machining processes could reach 16% of total manufacturing cost (Figure 2.5). This magnitude was higher than the cost of cutting tools. It is interesting that the 16% reported by Blasser is close to the 16.9% for the data given in Figures 2.5 by Young et al [34].

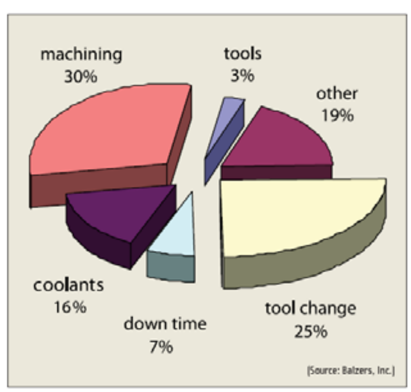


Figure 2. 6 Typical end-user machining cost

Increasing cutting fluid consumption increases associated costs and it creates problems in the environment. Improper use of cutting fluid will subject individuals, working on the shop floor, to health problems and daily exposure to air borne contaminants gradually increases the health risk for workers, causing severe health problems such as respiratory disorder, skin disease and increasing the risk of cancer [35]. In addition, besides causing detrimental health problems, improper treatment of cutting fluid residue could also increase the environmental impact in categories such as acidification, eco-toxicity etc.

Increasing cutting fluid consumption and related costs and the detrimental impact on the environment are the drivers for machining scientists and practitioners around the globe to address sustainable development strategies. In order to do this a proposal was initiated to eliminate the use of cutting fluid use on the shop floor. This method is recognised as dry machining. Studies have shown that dry machining can be employed for certain processes; while investigations are still underway in other areas to break down the obstacles to full implementation of dry machining, a bridging method known as near dry machining has been introduced.

2.1.3 Cutting fluid in machining

2.1.3.1 The role of cutting fluid in machining

The process of machining involves a shearing mechanism to transform a workpiece to an end shape. This fundamental mechanism creates a high friction load between the cutting tool and the workpiece, which significantly increases the cutting temperature. In addition, friction dissipates energy thus generating heat, which if it is not properly controlled might have a detrimental effect on the cutting tool and machined component. The main sources of heat are normally generated in two areas known as the primary or shear zone (1) and tool-workpiece interface (2). Moreover, a third zone (3) of heat is generated where friction between the tool and the chip occurs (Figure 2.7).

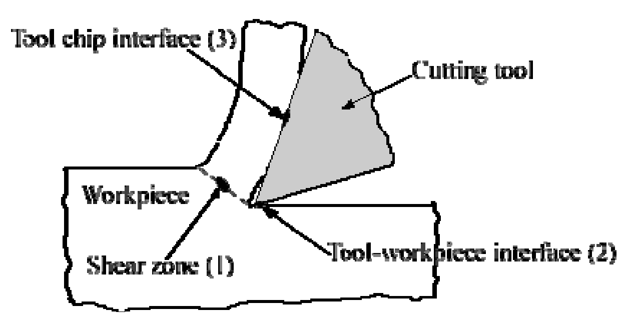


Figure 2. 7 The Sources of heat in machining

Control of the heat generated can be achieved by reducing cutting temperature and friction. Cutting temperature has a positive and negative impact. A higher cutting temperature would be necessary, to some extent, to make the deformation process occur easily; as in hot machining processes. On the other hand, it generates excessive heat, which will affect tool life and in some cases the surface integrity of components.

Heat induced by temperature rise is cutting speed dependent i.e. increasing the cutting speed increases the cutting temperature. Shaw [37] found that at a cutting speed of 1.5 m/min, the Built-up Edge (BUE) was formed, but this can be retarded by employing cutting fluid. BUE is a small portion of the workpiece material that becomes the cutting edge during the cut. However, Shaw’s cutting speed is too low for conventional machining (i.e. industrial setting).

Korkut and Donertas [38] provided a more defined theory about the tendency for BUE formation in face milling processes. They underlined that the BUE formation occurred at cutting speeds ranging from low to moderate. In this range, the BUE tends to remain stable. Subsequently, if the cutting speed increases above the moderate magnitude then the BUE becomes less stable. The main function of cutting fluid is to provide a cooling action to the cutting zone during the cutting process.

In addition to its cooling action, the lubricating effect of cutting fluid makes a significant contribution in friction reduction. In machining, where the heat generated is foremost at the interfacial face of the tool and chip, the presence of cutting fluid particles will enhance the lubricating action over the face.

In addition, the use of cutting fluid in cutting operations is also beneficial in order to;

1. Flush the chips off the machined surface to prevent the chips from scratching the machined surface.
2. Reduce friction so that the cutting force is lower and chatter can be minimised.
3. Create a thick film to provide a layer of protection for the machined surface to prevent chemical reaction that could promote corrosion. The lubricant film also prevents the chips from being welded to the machined surface.
4. Avoid a welding effect on the rake face, which could promote tool failure.

However, most cutting fluid applications are performed by flooding. There are several mechanisms identified in which cutting fluid works [39]. These mechanisms are briefly described below;

1. Capillary action: the asperity of two vicinity solid bodies moving relatively would tend to create tiny channels that are recognised as minute capillaries. This capillary action helps the spread of fluids between two vicinity surfaces.
2. Diffusion mechanism: this refers to penetration through the metal lattice caused by different fluid concentrations. With this mechanism, the fluid particles infiltrate to form bonds with the workpiece's metallurgical structure.
3. Volatilisation: vaporisation of fluid that changes the viscosity as well as the state, increasing the penetration capability.
4. Rehbinder effect: interaction of surface-active species (usually chlorine) with the workpiece material tends to reduce the shear strength in the primary deformation zone.

Additionally, all these mechanisms can work well if cutting fluid possesses good cooling and lubricating capabilities. Cooling capability is a predominant necessity at high cutting speeds; yet cutting fluid fails to provide proper lubricating actions at high cutting speeds. However, because of the elevated temperatures during the high speed cutting operation, the right combination between the type of cutting fluid used and the cutting tool material has to be taken into consideration to prevent tool failure. Cutting tools based on ceramics used in intermittent processes are at risk if exposed to the high cooling capability of cutting fluid.

On the other hand, lubrication would be effective at low cutting speeds due to the possibility of cutting fluid penetration at the tool-chip interface. In addition, preventing the formation of built-up edges occurring at low cutting speeds can be addressed by improving the lubricating action.

However, effective cutting fluid application cannot be achieved if it fails to meet some prerequisites such as easy access to the source of heat and having sufficient thermal capability for heat dissipation [40]. So, by fulfilling these conditions the main advantages of cutting fluid application can be achieved.

2.1.3.2 Types of cutting fluid and their performance

A perfect cooling action can be gained if cutting fluids have high thermal conductivity and high specific heat. Water has these special characteristics besides being economically inexpensive. However, water is a poor lubricant and in addition promotes corrosion on ferrous material more easily. Therefore, the use of pure water as a coolant tends to be avoided but is still used to some extent by adding an emulsion that can overcome the poor lubricating action and corrosive tendency of pure water. This type of coolant is known as soluble oil. Alternatively, to gain good lubrication on interfacial contacts in machining operations mineral lubricating oil can be used. However, in comparison to water, mineral oil has poor thermal conductivity and specific heat therefore; additives are normally incorporated to enhance the performance of mineral oil. Accordingly, extreme pressure agents, known as EPs, are sometimes employed in severe cutting operations. Based on the brief description above, cutting fluids can be classified into three main groups as shown in Figure 2.8.

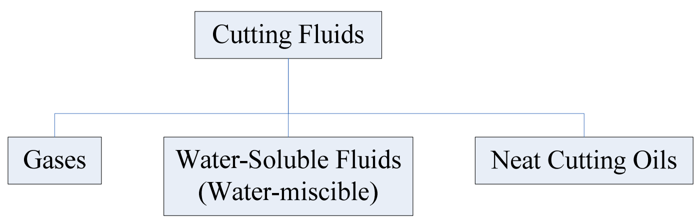


Figure 2. 8 Classification of cutting fluids (adapted from El Bardie [40])

2.1.3.2.1 Water-soluble fluids

Water soluble fluids are a type of cutting fluid comprised of an emulsifier to blend oil and water. However, due to adverse characteristics they do not dissolve. Nonetheless, created from two substances that possess good cooling and lubricating capabilities makes this type of cooling media preferable for metal removal processes running at high speed and low pressure [41]. Furthermore, water-soluble fluids can be classified, as shown in Figure 2.9, and can be utilised for light, medium and heavy-duty tasks.

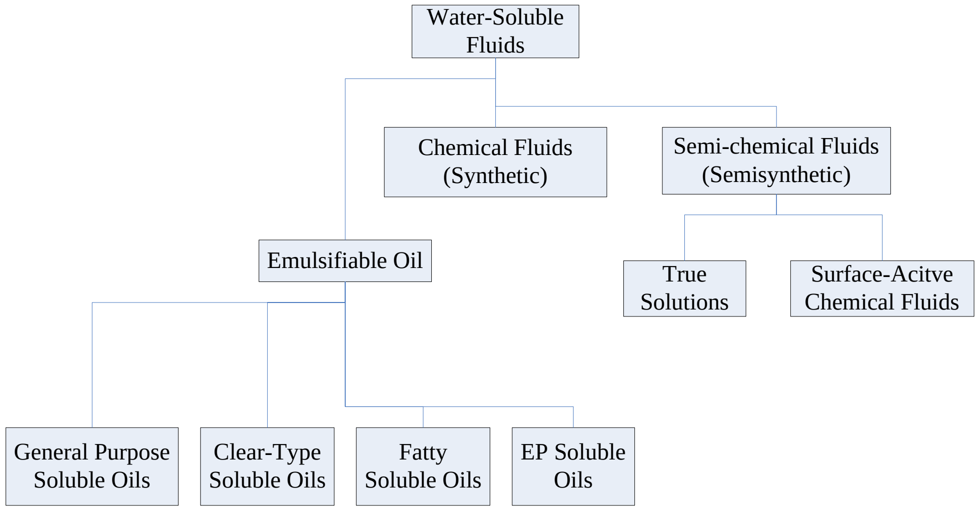


Figure 2. 9 Classification of water-soluble fluids (adapted from El Bardie [40])

2.1.3.2.1.1 Soluble oils

Soluble oils, as the emulsions are popularly known, are bi-phase composites of mineral oils added to water in proportions that vary from 1:10 to 1:100. It contains additives (emulsifiers) to allow the fusion of oil particles and water. These additives decrease the surface tension and form a stable monomolecular layer in the oil/water interface thus generating the formation of small particles of oil, which results in transparent emulsions. The stability of the emulsions is related to the development of an electrical layer in the oil-water interface. Repulsing forces among particles of the same charge avoid their coalescence. To prevent the poor effects of the water in these emulsions, anticorrosive additives, like sodium nitrite, are used. Biocides are also in the formulation to avoid the growth of bacteria. They fluid must not be toxic to human skin. The EP and anti-wear additives that increase the lubrication properties are the same as used in neat oils. However, the use of chlorine in cutting fluids is being restricted all over the world owing to its detrimental impact on the environment and to human health, thus it has been replaced by sulphur and calcium based additives. Both, animal and vegetable grease can also be used to enhance lubrication properties.

2.1.3.2.1.2 Semi synthetic fluids (Micro-emulsions)

Semi synthetic fluids have 5% to 50% mineral oil plus additives and chemical composites, which dissolve in water forming individual molecules of micro-emulsions.

The presence of a large amount of emulsifiers, compared to soluble oil, provides a more transparent appearance to the fluid. The low volume of mineral oil and the presence of biocides increase the life of the fluid and reduce health risks, compared to emulsions. EP and anticorrosion additives are employed as in the soluble oils. Additionally, additives, which can guarantee a more acceptable colour for the fluids are also used.

2.1.3.2.1.3 Solutions

Solutions are mono-phase composites of oils that are completely dissolved in water, so they do not require emulsifiers, because the composites react chemically forming a mono-phase. Synthetic fluids (without mineral oils) can be classified within this subgroup.

2.1.3.2.1.4 Synthetic fluids

This type of cutting fluid does not have mineral oil in its composition. It is based on chemical substances, which form a solution with water. They are made of organic and inorganic salts, lubricant additives, biocides, etc. They have a longer life than other fluids due to bacteria resistance, thus reducing the number of replacements required. They enable the formation of transparent solutions which offer good views of the machining process and have additives which can improve wet ability and, therefore, high cooling ability. The most common synthetic oils also possess good corrosion protection. The most complex ones are in general use and have good cooling capabilities as well as good lubricating qualities. When the synthetic fluids have only anticorrosion additives without having extreme pressure (EP) properties then they are classified as either chemical fluids or true solutions and possess good cooling properties.

2.1.3.2.2 Neat cutting fluids

Vegetable and animal oils were the first lubricants used as pure oil in metal cutting. However, their use became impractical due to high costs, unstable oxidation and quick deterioration; but they are still used as additives in mineral fluids, aimed at increasing the lubrication properties. Neat oils are basically mixed either with pure mineral oils or with additives, generally of the extreme pressure type. The use of this type of cutting fluid has been reduced due to inherent problems of high purchase costs, disposal processing costs, fire risk, inefficiency at high cutting speeds, poor cooling ability, smoke formation and high risk to the human health when compared to water based cutting fluids.

The cutting fluid is mixed with additives, such as chlorine or sulphur or a mixture of both of these substances, resulting in increased EP properties in the fluid; this aids the distribution of the fluid to inaccessible areas during the machining process. Phosphorous and fatty additives are also used to act as anti-wear elements. Mineral oils are hydrocarbons obtained from the petrol refining of crude oil and their properties will depend on the chain length, structure and refining levels. Briefly, the types of additives frequently used to improve the performance of cutting fluids are listed below [41];

a. oxidation inhibitors,
b. rust-preventing agents,
c. foam inhibitors,
d. wetting agents,
e. odour-controlling agents
f. antiseptic.

2.1.4 *Tool wear mechanisms*

Tool wear mechanism can be classified according to the cause of tool damage [42] as shown in Figure 2.

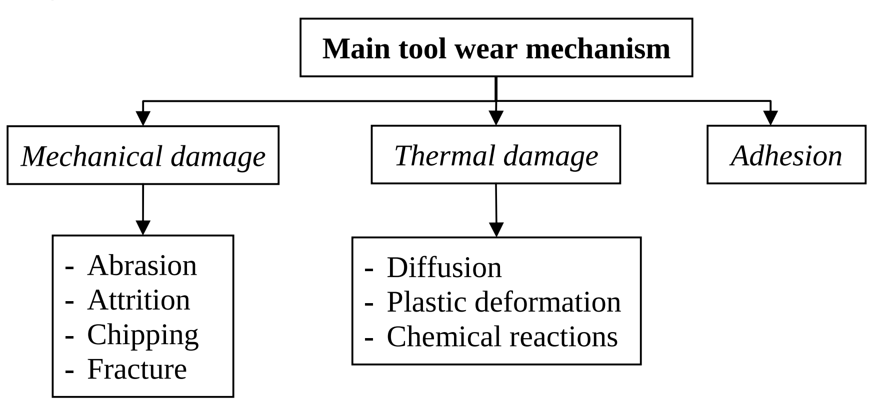


Figure 2. 10 Classification of tool wear mechanisms according to the cause of tool damage (adapted from [42])

These tool wear mechanisms can be described as follows;

***Abrasion*:**

Hard particles from either the work material's microstructure or broken cutting edge that slide against the cutting tool will remove material leaving groove tracks on tool flank face.

***Attrition*:**

Attrition occurs, on a scale larger than abrasion. In this mechanism, as a result of sliding interaction between the tool and workpiece material, micro-fracture mechanically weakens tool grains or particles. These weakened grains facilitate wear.

***Chipping*:**

Critical fluctuation in cutting force leads to weaker parts of cutting tool breaking away.

***Fracture*:**

Fracture has a scale larger than chipping. Depending on its occurrence, it has three stages; early, unpredictable and final [42]. At the early stage, fracture is caused by improper selection of cutting conditions (abusive cutting) or when a defective tool is used. Unpredictable fracture can occur if chatter is detected or there is irregularity of work material. Meanwhile, fracture at the final stage occurs at the end of tool life caused by fatigue due to mechanical or thermal stresses.

***Diffusion*:**

Heat generation in the primary deformation zone and friction between tool and workpiece material generates heat that facilitates unstable atom movement across the tool-workpiece interface. Diffusion modifies near surface properties and can promote other mechanisms of material removal.

***Plastic Deformation*:**

At critically high cutting temperatures, it is possible that tool materials lose their hot hardness and experience deformation.

***Chemical Reactions*:**

At high temperature, chemical compounds can be formed by the reaction of the tool and work material or with other influencing factors such as oxygen in the air or sulphur or chlorine in a cutting fluid. One of the most common chemical reactions is oxidation. The oxidized tool surface is weak and can be easily rubbed away by the chip that is sliding over the rake face, thus leaving an abraded tool surface.

Adhesion

Adhesion is a wear mechanism where the tool and workpiece material have a contact under high pressure and temperature. This condition makes it possible for material transfer between tool and workpiece to take place, and this induces welding between tool and workpiece materials. When the contact progresses further, the welded materials can be removed and lead to a small portion of tool material wearing off the tool faces (normally the rake face).

2.1.5 *Dry machining and semi-dry machining*

The use of cutting fluids to reduce elevated temperatures during machining operations is believed beneficial for improving machining performance. However, the increasing consumption of cutting fluids nowadays has become of great concern to practitioners and scientists in machining industries. This trend triggers economic and environmental issues. The high volume of cutting fluid used on the shop floor will increase the cost of its acquisition, in addition to the treatment costs for its disposal. Nevertheless, quite apart from the economic issues the utilisation of cutting fluid damages the environment and causes detrimental health problems [43 - 46].

Furthermore, the negative effects of using cutting fluid, as previously described, have forced the use of alternative, new technology that is more sustainable and economically feasible; particularly in industrialised countries with strict environmental regulations. This technology is known as the dry machining method. In dry machining no cutting fluids are used. Due to constraints in applying this technology across all the processes, full implementation is restricted to certain processes; however, development of dry machining technology is currently in progress. Near dry machining is another method which has been extensively used and studied. Though not as radical as dry machining, near dry machining uses cutting fluid, but in amounts much lower than that of conventional applications.

2.1.5.1 Dry machining

The term dry machining is associated with machining processes without the presence of cutting fluids. In this technology, the elevated temperature is reduced by lessening the friction at interfacial faces (i.e. tool-workpiece interface and tool-chip interface). The friction reduction in this technology can be achieved by the use of a coating layer on tool substrate materials. The coating layer must have a low friction coefficient. This relies on the choice of coating materials as well as coating technology.

In their study involving dry machining, Cassin and Boothroyd [47] used this method to compare the lubricating action of several types of cutting fluid that were mixed with carbon tetrachloride as an lubricant improving agent. They found that CCL_4 (i.e. carbon tetrachloride) treatment on carefully ground off workpiece material can result in the same cutting force magnitude as in dry machining. This finding indicates that to some extent the application of dry machining is feasible, especially in terms of lowering cutting forces at a low cutting speed of 0.178 m/min. It is apparent that at low cutting speeds, the superior coating layer provides a lower friction coefficient, however, dependent upon the combination of tool type and workpiece material, as the cutting speed increases the heat generated will render the effect of the coating layer inferior.

Accordingly, a study was undertaken to find an appropriate coating material and new technology, which will improve the coating material's characteristics. The study will look at coating materials and on how to coat the substrate material properly to improve performance. As such, coating methods such as Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) have made the prospect of dry machining on the shop floor becoming more feasible. Recently the search for suitable material for tool coating has shown a remarkable uphill trend and many studies are towards the discovery of an appropriate coating material that can be used to improve the performance of the dry machining process [48 - 52]. Thus, the range of cutting speeds that can be applied to the dry machining application can be increased.

Mativenga and Hon [53] identified that a better surface finish on end milling of H13 tool steel can be obtained by appropriate selection of tool coatings as well as coating technology. They suggested that effective tool coatings would enable wear zone protection thus increasing the feasibility of dry machining implementation at higher cutting speeds. Furthermore, Dudzenski [31] highlighted the importance of suitable combinations of tool material and its coating material asserting that the right combination can result in better dry machining performance at different cutting speeds when cutting Inconel 718 alloy.

Diniz and Micaroni [54] found that the careful selection of cutting parameters could improve machining performance in terms of surface finish, tool life and even exhibit superior performance compared to the use of cutting fluid. This principle was confirmed following the turning of two AISI 1045 steel cylinders that were hardened to 55 HRd and 59 HRd respectively. However, as indicated by Galanis et al [55] in a comparison study between dry machining and wet machining of AISI 422 stainless steel workpiece material, there is an optimum condition where the machining performance using dry cutting was acceptable.

On the other hand, heat generation caused by shearing of cutting tools and workpiece material cannot be neglected in analysis of machining performance using a dry cutting operation. It is well known that cutting temperature is cutting speed dependent. As the cutting speed increases, the cutting temperature will increase comparatively hence increasing the heat generated at the contact zone. The heat generated will dissipate through the solid body involved in removal of material, including workpiece material, which will encounter microstructure changes. Consequently, it can lead to weak workpiece material structural integrity, thus it would be possible to increase burr size [56]. Furthermore, it would also affect the strength of machined part/ components due to residual stress as caused by elevated temperatures [57].

From the above-mentioned studies, it is conceivable that successful application of dry machining for a broad range of machining conditions, including workpiece material, can be achieved if the superior friction characteristics of cutting tools can be perfected so that the function of cutting fluid can be completely altered. In addition, it has to be able to surpass part quality and machining time of that which can be achieved when employing cutting fluid [32,33].

Recently, the implementation of a near dry machining that has proved popular is minimum quantity lubrication (MQL). This is supported by commercially available MQL delivering system equipment. The term minimum quantity lubrication (MQL) has become widely used in academia and research. Some researchers use micro litre lubrication [5] and others use near dry machining [73, 74, 98]. MQL is a misnomer because dry machining is feasible and the lower limit for minimum quantity lubrication is dry machining. Ideally, it should be called low quantity lubrication. There is need for international consensus on which terminology to use. Hence, in line with popular terminology, MQL is used in this thesis.

2.1.5.2 Semi-dry machining

Dry machining is a technology believed to be most sustainable. However, constraints in its application due to technological limitations of tooling have prevented full implementation, especially when high cutting speeds are required. While improvements to related aspects of dry machining are being developed, a bridging method is necessary to fill the gap between wet machining and dry machining.

One view about sustainable machining processes has urged further development of a technology widely known as the near dry machining. The terminology of the near dry machining method is associated with the use of the minimal quantity of liquid as a cutting fluid and/ or any type of liquid or gas used to replace existing cutting fluids.

Some technologies have been explored as the prospective candidates for near dry machining methods. Among these are cryogenic machining, high-pressure jet machining (HPJ) and minimum quantity lubrication (MQL). These need study to evaluate the requirement of full mitigation of the use of cutting fluid.

In cryogenic machining, an attempt is made to reduce the temperature as low as possible in the cutting zones by employing liquid gas such as nitrogen, helium, hydrogen, neon, air and oxygen as a coolant. Recently four methodologies were applied in relation to cryogenic machining. These are pre-cooling the workpiece [58], indirect cryogenic cooling, cryogenic spraying with jets and direct cryogenic treatment of cutting tools [59].

Studies to find the best cryogenic machining application have been conducted using different materials ranging from low hardness [60 - 62] to hard-to-difficult materials. Cryogenic machining is fast becoming one of the more feasible methods for cutting difficult-to-cut aerospace alloys and other hard-to-cut materials due to its capability for maintaining temperatures at the cutting interface below the critical temperature of cutting tool materials [63, 64]. In addition, besides having the best cooling capability, using liquid nitrogen in cryogenic machining processes provides a significant reduction in tool-chip contact length thus reducing heat generation on the rake face [65]. Thus, it improves machining of hard-to-cut material at higher cutting speeds.

Although the cooling action in cryogenic machining can offer a significant reduction in temperature at the cutting zone and shorten the contact length there are still some difficulties anticipated in the lubricating action. In order to prove that cryogenic machining using liquid nitrogen can provide lubrication at the cutting interface, Hong and Ding [66] did a sliding test. They found that a combination of various temperatures dependent on a micro scale of hydrostatic effect might have a role to play in achieving a lubricating action. However, it fails to provide a lubricating action as with traditional cutting fluids because liquid nitrogen can easily vaporise due to low viscosity and chemically stable [67].

Furthermore, the lack of lubrication in cryogenic machining cannot stop it being viewed as a sustainable method due to the potential benefits that can be gained by its application. Among those benefits are being environmentally friendly, having a higher material removal rate, longer tool life, higher throughput and improvement to machine part quality owing to a cleaner environment. However, the high investment and operating costs of cryogenic machining makes it impractical for low production volumes [68].

Other sustainable methods that have been attracting interest among machining scientists is high-pressure jet machining (HPJ). This method is similar to the traditional overhead method but uses a different delivery method. In the traditional way, the cutting fluids are transported to the contact zone helped by a little low air pressure, whereas in high-pressure jet machining, the cutting fluids are delivered at higher air pressure. Higher air pressure increases the particles speed hence reducing the particles size. Higher particle speeds and minute particle size will enhance the penetration ability of cutting fluids, thus it is easier for the particles to enter the operational area and establish the lubricating action. In addition, it also increases the cooling capacity of the cutting fluids due to removing heat predominantly by evaporative mode, which is more efficient than the convective mode [1].

The main achievement of high-pressure jet coolant in machining is its ability to improve cutting tool performance. A 250% improvement in tool life was achieved by using cutting fluids such as water-soluble oil [69]. This tremendous achievement was further investigated by Wertheim et al [70] when studying the effect of high-pressure flushing through the rake face of tools, though at the time they only increased the air pressure by up to 25 atm. Moreover, Rahman et al [71] observed that by identifying effective zone high-pressure coolant, a better surface finish could also be obtained.

It should be borne in mind that HPJ machining cannot fully be recognised as a sustainable method due to the use of large amounts cutting fluids as a cooling/ lubricating media. Kovacevic et al [72] suggested applying a narrow jet in order to reduce the amount of cutting fluids usage in high-pressure jet machining. Unfortunately, implementation of this method is still constrained by high investment costs.

Another technology that could be categorised as a bridging method for sustainable development is popularly known as minimum quantity lubrication (MQL). This technology is the most feasible technology that could be implemented on the shop floor. For example, the Ford Motor Company has, since May 2005, fully implemented the MQL system on the shop floor [73]. Despite its feasibility for improving machining performance while using a small volume of cutting fluid, it also benefits from the simplicity of its delivery systems.

2.2 Minimum Quantity Lubrication (MQL)

2.2.1 *The concept of MQL*

In minimum quantity lubrication, a small volume of cutting fluid is transported to the cutting zone assisted by air and converted via orifices into small particles (atomisation). These small particles are delivered to the cutting zone in the form of air borne particles, a gaseous suspension of liquid particles. An idealised condition of MQL can be seen in Figure 2.10.

However, the ideal concept, as shown in Figure 2.10, is hard to achieve due to the air pressure accelerating the small particles and creating a mist. The working principle of MQL can be explained by using simple model depicted in Figure 2.11.

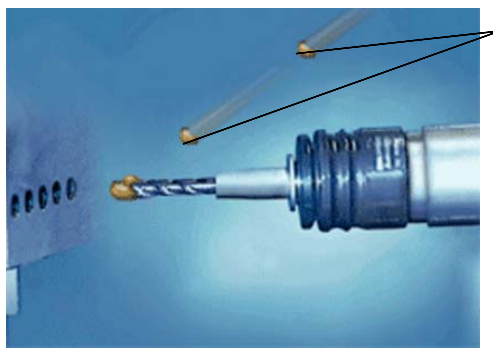


Figure 2. 11 Idealized concept of MQL (after Astakhov [74])

Oil in the reservoir is kept under constant pressure higher than in the mixing chamber. This pressure difference will make the oil flow up to the end of the nozzle where an orifice is located. The orifice has the main function of accelerating the particles' movement. As the particles’ speed increases, the particles' size will be reduced. Smaller oil particles discharged from nozzle tip will subsequently be accelerated by the compressed air hence creating air borne particles. The lubricant in the form of air borne particles will have increased penetrability, especially to intrinsic (i.e. difficult to reach) areas. In this way, minute capillary created by two different surface asperities will help the small size particles of lubricant to gain access to the margined of the sliding and sticking areas. Additionally, the lubricant in the form of air borne particles will increase cooling capacity due to vaporisation of lubricant particles.

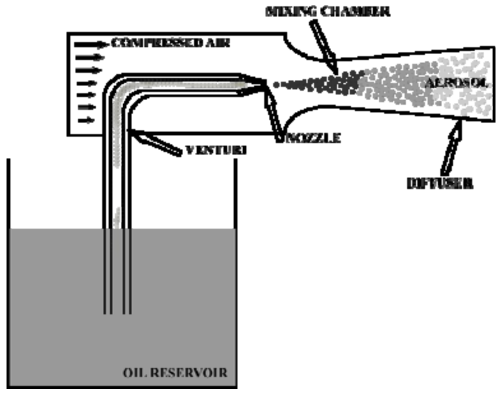


Figure 2. 12 A simple model of MQL systems

2.2.2 *The MQL system*

In general, there are two types of MQL system. The first type is known as an internal system. In the internal system, oil and air is mixed in a mixing chamber before being delivered to the cutting zone through a single nozzle pipe. Meanwhile, the second type, or external system, an oil-air mixture is carried out in the nozzle tip and the air borne particles are formed just after the nozzle tip. The oil is supplied in small quantities through a pipe to the nozzle tip where the air, flowing from a different pipe, will force the oil to the cutting zone. The difference between the external system (T-1) and internal system (T-2) are illustrated in Figure 2.12.

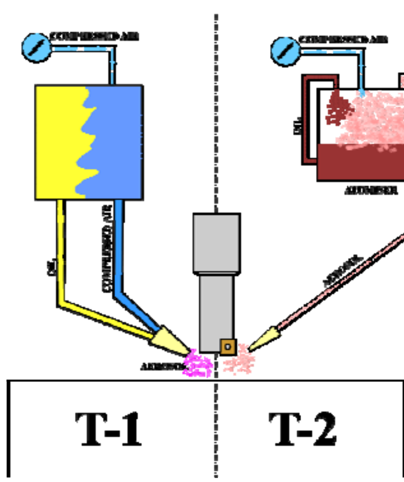


Figure 2.13 Two types of MQL systems
T-1 is external system; T-2 is internal system

As can be seen, from Figure 2.12, both systems work using an external nozzle that moves along in the cutting direction. This becomes a constraint for closed process such as drilling and boring, where the external nozzle will not provide sufficient cooling/

lubricating action deep into the drill tips. To address this obstacle, so that the MQL system can also be used for closed processes, an MQL system with an internal delivery system is the answer. With this system, whether for an internal or external mixing system, the air borne particles are transported to the cutting zone through a specially designed channel that is located inside the tool holder going through to the drill tip.

2.2.3 *Application of minimum quantity lubrication in machining processes*

The application of the MQL method can be found in a variety of machining processes, especially in primary processes such as turning, drilling, milling, and grinding. In addition, cutting of wide varieties of workpiece material, such as aluminium, steel, hardened material as well as hard-to-cut material can also be done using the MQL method.

For instance, Sadeghi et al [75] studied the grinding forces and surface quality properties of surface grinding AISI 4140 using the MQL application. They found that tangential cutting forces were lower using the MQL application compared to flood cooling and better surface finish can also be obtained with this method. In a related study using different workpiece material, 100 Cr6 hardened steel, Tawakoli et al [76] identified that that a combination of the MQL method and resin bond corundum gave the best grinding performance in comparison to wet and dry machining. The two previous results supported the findings underlined by Da Silva et al [77]. In terms of surface integrity (roughness, residual stress, microhardness and microstructures), MQL can be utilised in grinding processes and achieves acceptable surface integrity.

Moreover, drilling processes that are categorised as closed-type processes in machining applications have some constraints in respect of MQL application. This is due to the difficulty of air borne particles providing cooling or even lubrication to the drill tip; particularly during deep hole drilling. The preferred way is for internal cooling/ lubricating channels supplying coolant through an internal supply. These reduce cutting temperature by approximately 50% of compared to external coolant supply [78].

Heinemann et al [79] stated that using an external nozzle for deep-hole twist drilling could be improved if a continuous coolant supply is changed to a discontinuous supply.

This alternative method can further increase the cooling capacity thus helping tool wear reduction. In addition, the use of low viscosity cutting fluid can further improve penetration ability hence enabling cooling and/ lubricating action simultaneously.

It is more feasible to use MQL for drilling high thermal conductivity material, such as aluminium, rather than dry machining. High cutting temperatures, as in dry machining, would affect the hole quality due to thermal expansion. Therefore, MQL is preferable while overhead flood-cooling attempts should be avoided. By appropriate combination of machining variables, the performance can be equal to that of flood cooling for drilling aluminium [80].

Drilling and turning are prominent processes in the machining process due to being frequently used to produce round shaped components/parts. The turning process is classified as a process that produces continuous chips. This means the process will experience elevated temperatures. For decades, overhead flood cooling has been the only option, however, due to more stringent environmental policies, as well as the rising cost of cutting fluid acquisition, the utilisation of this conventional method has been shifted to more environmentally friendly processes such as dry and near dry machining. MQL turning is one of the alternatives in respect of environmental prerequisites.

Dhar et al [81] investigated the influence of MQL application on cutting temperature, chips and dimensional accuracy in turning AISI 1040 steel. They identified favourable tool chip interaction using the MQL application. It was reported by Varadarajan et al [1] that MQL performance better then wet and dry machining on hardened AISI 4340 steel.

The application of MQL can also be found in milling processes. For example, Sun et al [2] reported that MQL enabled better lubrication and cooling actions during end milling of Titanium Alloy. It was demonstrated by longer tool life and cutting force reduction. Moreover, Kang et al [82] also emphasised the feasibility of MQL application even during higher cutting speed regimes. They found that the MQL application in cutting AISI D2 led to better machining performance compared to flood coolant especially if appropriate cutting tools were selected. However, investigations were performed using constant cutting parameters and at defined MQL flow rate.

Interestingly though, full implementation of the MQL application on the shop floor is in doubt due to the need for a cultural change. However, some companies, especially the large-scale manufacturing companies, have fully implemented this method to produce some parts. This implementation has shown some positive results for the future, as reported by Filipovic and Stephenson [83].

2.3 Machining Performance Evaluation for Minimum Quantity Lubrication Application in Milling Processes

To discover the advantages of the MQL application in cutting wide varieties of workpiece materials, comparison studies of MQL and flood cooling, as well as with dry machining, can be found in literatures. In this section, the review will focus on the advantages of the MQL application in terms of the machinability aspects such as tool life, surface finish, cutting forces and cutting temperature particularly in milling processes.

Brinksmeir et al [84] conducted a milling process to cut TiAl6V4 material using a carbide K40 uncoated cutting tool. Constant machining variables used in this study were 210 m/min cutting speed, 0.08 mm/rev feed, 5 mm axial depth of cut and 2 mm radial depth of cut. After analysing the cutting forces, tool wear, surface quality and chip formation resulting from the study, they concluded that MQL application could provide comparable tool life travel compared to that of overhead flood cooling. This performance was obtained by using cutting fluid combined with 7% emulsion. Furthermore, it could be further enhanced by using phosphorus additives.

The use of synthetic ester as in the previously described study guarantees good cooling capability and minimises the lubricating action on the interfacial faces. This is due to the high cooling capacity of cutting fluid, which would increase vaporisation particularly at elevated cutting temperatures that occur during the cutting of low thermal conductivity material such as TiAl6V4. Meanwhile, using an emulsion containing cutting fluid, the cooling capacity is not as good as synthetic ester but they possess considerable lubricant ability that can be utilised to reduce friction. Likewise, the particle size at elevated temperatures is normally decreased. When the cutting temperature increases the viscosity of cutting fluid would be lower thus reducing lubricating ability. However, reduced cutting fluid particles would increase the penetrating ability therefore, as revealed in the above study; by introducing additives, the performance of MQL application can be improved.

That above-mentioned logic also occurs in Rahman's study. Rahman et al [85] evaluated the effect of MQL by milling a block of ASSAB 718 HH steel of hardness 35 HRc. They conducted the experiment using an increased cutting speed as well as increased feed. The cutting speed was increased from 75 m/min to 125 m/min. Three different feeds were selected namely; are 0.01 mm/rev, 0.015 mm/rev and 0.20 mm/rev respectively. Additionally, two depths of cut were selected; 0.35 mm and 0.5 mm. Initially they used EcoCool S-CO5, a fully synthetic water-soluble coolant as the flood coolant and BP CILORA 128, having higher viscosity (75 cSt at 20^{o}C), as MQL oil. Rahman et al found that MQL was effective at low cutting speed and feed rates. When the cutting speed was increased to 175 m/min, high cooling capacity flood coolant contributed to fracture. This was due to the lower specific heat capacity of the type of cutting fluid used. Unfortunately, Rahman et al failed to exploit the possibility of using different MQL parameters to improve the cutting performance of the ASSAB 718HH steel.

Junior et al [86] in their study attempted to identify the mechanism of wear during finished end milling of 15-5 precipitation-hardening (PH) martensitic stainless steel under several cooling and lubrication conditions. Carbide inserts coated with TiAlN were used with four different types of cooling media, which were vegetable oil-based emulsion (VE), low flow of neat vegetable oil (VO), combination between VO and MQL (VO-MQL) and dry machining. Based on preliminary research, the MQL combination was delivered to the cutting zones at a flow rate of 35 ml/h for separated air and oil supplied. The cutting conditions employed for this research were kept at a constant level with a radial depth of cut of 13.33 mm (70% of mill diameter), axial depth of cut of 1 mm; feed per tooth of 0.08 mm/rev and cutting speed of 120 m/min.

In general, of all the cooling and lubrication techniques examined, vegetable oil gave the best result. While MQL-VO existed between the dry and higher flow rate of VO, in addition, wear mechanism occurring in implementation of VO-MQL was reported as similar to that of dry machining, which was a combination of adhesion and abrasion.

The presence of oil in the VO-MQL technique slowed down wear progression because of its ability to reduce friction between the tool and the workpiece. By using the coated tool, it was clear that friction could be significantly reduced, hence preventing adhesion. From these results, it implies that viscosity and the MQL flow rate is important in enhancing the performance of MQL application. One has to realise that the minimum quantity lubrication could not be fully interpreted as the amount of cutting fluids is utilised as low as possible. There is an optimum setting for fluid delivery for every type of workpiece material, so that cutting performance under MQL can be equal to that of generous fluid delivery.

Wu and Chien [3] investigated the influence of the type of lubrication and process conditions on the milling performance of three different materials; P20 tool steel (30 HRc), S45C steel (26 HRc) and NAK 80 steel (38 HRc). Four different milling operations were carried out using a 10 mm diameter tool where two replaceable round inserts were attached. Furthermore, the effects of the type of lubrication and cutting conditions, as well as the relationship between flank wear and cutting forces, the effect of nozzle distance on flank wear, the effect of the type of lubrication on the surface quality of the workpiece as well as the effect of workpiece material on flank wear was analysed. The MQL coolant supply used was Blueber LB-1. In the first experiment, by varying the flow rate from 6, 12, and 24 ml/h and keeping the nozzle distance 100 mm away from tool tip, it was found that MQL with a low flow rate showed the best results for all responses to tool wear, cutting forces and surface roughness. Subsequently, in aiming to find the most effective nozzle position for tool wear, the nozzle position was varied from 20 mm to 200 mm away from the tool tip. They identified that the appropriate nozzle position to promote longed tool life was a distance of 60 mm further from the tool tip. At a constant air pressure, the distance from the nozzle might affect the penetration ability of cutting fluid. Thus, the further the distance the higher the pressure drop. In turn, it would eliminate the possibility of cutting fluid reaching the tool tip for lubricating and cooling provision.

Heisel et al [87] conducted research into milling using dry machining and MQL. Three different milling features were designed for measuring the burr sizes using two cooling/ lubricating methods. The measurement points were set at different entry and exit positions of the C45E workpiece material. A Chemically Vapour Deposition (CVD) coated tool, with TiCN + Al_2O_3 (+ TiN), coating were used. The cutting speed was varied from 150 to 225 m/min, while the selected feed per tooth was 0.05 mm/rev and 0.11 mm/rev. For face milling using a tool of 50 mm diameter, the width of cuts were set at 12.5 mm, 25 mm, and 37.5 mm, while for angle milling were set at 6.25 mm, 12.5 mm and 23.5 mm (i.e. milling process to cut incline surface) and this action was performed using a tool with a diameter of 25 mm. Meanwhile, the depth of cut was kept constant. The MQL application used a special fatty alcohol, Ecocut Mikro Plus 82. Unfortunately, this report did not convey information in respect of the quantity of cutting fluid supplied to the cutting zones.

Heisel et al showed that at a cutting speed of 150 m/min, feed per tooth of 0.05 mm/rev and width of cut of 12.5 mm, the burr size decreased when increasing the MQL supply, especially at the entry side. However, at increased cutting speeds, burr size was comparable for dry and MQL. In contrast, varying the feed per tooth causes significant difference in burr size. Additionally, raising the width of cut seemed to contribute significantly to burr formation, using MQL. This is an explainable phenomenon in respect of increasing width of cut. Larger width of cut would increase the contact area between tool and workpiece thus whichever cutting mode is selected, the cutting fluid penetration would be difficult to determine due to the high compressive stress along that area. Lower penetration ability would in turn minimise the possibility of friction coefficient reduction and increase the occurrence of workpiece hardening that would create large sized burrs due to material side flows. However, with dry machining, because it is running at elevated temperatures, would help to soften the workpiece material therefore, a combination of softening workpiece material with the cutting condition used in this study helped to shorten the burr size.

Liao et al [4] compared the cutting performance between MQL, flood coolant and dry machining. Water-soluble coolant Castrol Superedge B7 with a flow rate of 1,200,000 ml/h was used for flood cutting while Castrol Carecut ES3 and Castrol ES1 were used for MQL. Oil mist was delivered to the cutting zones using a flow rate of 10 ml/h at a pressure of 0.45 MPa. The cutting velocity was set within the range of 300 to 500 m/min. The feed was set between 0.1 and 0.2 mm/rev while the radial depth of cut and axial depth of cut were kept constant at 0.3 mm and 5 mm respectively. The results showed the effectiveness of minimum quantity lubrication (MQL) for end milling of NAK80 mould steel (41 HRc) using TiAlN and TiN coated carbide tool.

Analysis of Variance (ANOVA) results underlined the importance of feed per tooth, cutting speed and cutting environment on tool wear progression. However, only the feed and cutting environment provided advantageous contribution to the cutting forces. Machining of hardened materials by using flood cooling was unsuitable because of thermal crack propagation during the intermittent cutting process. In contrast, MQL had a positive effect on tool wear through the range of cutting speeds. This was the case when the cutting fluids used had different viscosities. At low cutting speeds, low viscous cutting fluid was sufficient to reduce the cutting temperature; adversely higher viscous cutting fluid could improve the cooling capability for cutting at high speeds. Additionally, combining a superior heat resistant, coated carbide tool and MQL prolonged the life of the tool when compared with other methods; this was identified by the absence of welding chips and notch wear. Finally, at cutting speeds ranging from 200 m/min to 250 m/min, surface roughness decreased when using the MQL application followed by dry machining. Although, it is clear that high viscous cutting fluid could improve cooling capabilities when cutting at high speeds, its correlation with the MQL parameters has not been fully explored.

Similarly, Iqbal et al [88] investigated the influence of the cutter's helix angle, workpiece material hardness, milling orientation with regard to prolonging tool life and improving the surface finish using the MQL application and dry machining. Flat end solid K30 carbide cutter with a PVD coated mono layer of TiAlN was used. AISI D2 material with the specific hardness of 52 HRc and 62 HRc was milled. High performance cutting fluid, Unilub 2032 was utilised as the MQL cutting fluid that was supplied at a flow rate of 25 ml/h by using two aerosol ducts, orientating directly to the cutting zones 160^o apart from each other. The experiment conducted was based on a fractional factorial design with 4 factors and 2 levels. This led to eight combination tests in a high speed machining experiment. In addition, cutting conditions were set at constant values; cutting speed 250 m/min, feed per tooth 0.1 mm/rev, radial depth of cut 0.4 mm and axial depth of cut of 5 mm. The experiment showed that a combination of a 50^o helix angle, MQL and down milling could enhance the performance of the tool when cutting AISI D2 with a hardness of between 52 HRc and 62 HRc. Furthermore, the ANOVA analysis revealed that the significant factors affecting surface finish are the milling orientation (i.e. down and up milling) followed by the cooling strategy (i.e. dry and MQL). Finally, the findings for tool wear showed that diffusion, adhesion and oxidation wear, which occurred mostly on the flank face. By not presenting the best results or the effect of the cutting speeds, this experiment did not provide clear information regarding the influence of MQL; but was purely a comparison study to show the benefit of using several cooling strategies such as dry machining and MQL.

Thepshonti et al [89] investigated the performance of minimal cutting fluid application by using a pulsed-jet method in high-speed milling of ASSAB DF3 (51 HRc). Cutting tools with a diameter of 12 mm P20 grade and a TiAlN coated carbide ball end mill insert was used on a two-flute type tool holder. The milling process was carried out using flood, minimal cutting fluid application and dry machining. Water-miscible coolant ECOCOOL 6210 IT at a concentration of 1:10 was applied as a flood coolant at a flow rate of 117 ml/h. A newly developed fluid delivery system was utilised to deliver active sulphurised anti-mist neat cutting oil, RATAK SSN 321 for pulsed-jet cooling, at a pulse rate of 400 pulses/ min, pressure 20 MPa, flow rate 60 ml/h. The nozzle for the pulse-jet was set on the opposite side to the feed. The experiment was conducted on a slot milling feature with machining conditions set at 125 – 175 m/min cutting speed and 0.01 – 0.03 mm/rev feed. The cutting length was 6 m and with 0.2 mm of depth of cut. From the results, Thepsonti et al identified that positive influences of the pulsed-jet method, in relation to tool life, were obtained when higher cutting speeds and lower feed rates were applied. The best surface finish was obtained by selecting low cutting speeds and feed per tooth. However, tool-wear progression when using the pulsed-jet method rises drastically after certain cutting speed levels, whilst flood cooling and dry machining only increased tool-wear progression slightly. In addition, high cutting speeds, as well high feed per tooth, were unsuitable for slot milling when combined with the pulse-jet method because this method could not flush away the chips from the cutting zones. This study underlined the effectiveness of MQL using a pulse jet delivery system. However, the experiment did not follow any definition for higher cutting speed ranges for given workpiece material as defined by Schulz and Moriwaki [23].

By using a two-colour pyrometer, Ueda et al [6] measured cutting temperatures in turning and milling AISI 1045 workpiece material using the minimum quantity lubrication (MQL) method. Comparing the result with the dry machining experiment, they found that MQL generated cutting temperatures 80^{o} C lower. This potential benefit of MQL was obtained when cutting fluid was delivered to the flank face at a rate of 40 ml/h and 50 mm away from the contact area rather than the rake face. Unfortunately, the benefit of MQL application in this study was not defined in terms of other machining performance measured.

Liew [90] used two different tool coatings; TiAlN single-layer and TiAlN/ AlCrN nano-multilayer, on STAVAC type material; a different composition of AISI 420 stainless steel. It was concluded that a combination of a nano-coated tool and MQL oil provided a good surface finish while maintaining reasonably low wear rate. This implies that a tool coating possessing low friction characteristics complemented the lubricating action of MQL, while the oil used as an MQL media had preferable cooling ability. Cooling and lubricating actions, as well as low friction coefficients, simultaneously provided the enhanced temperature reduction in this study.

Using the MQL, the tool life was modelled with a full quadratic equation that was proposed by Priarone et al [91]. This equation was a function of the cutting speed and feed per tooth. Therefore, for harder workpiece materials, tool wear performance can be modelled with the classical models.

Da Silva et al [92] when milling medium carbon steel using a coated cemented carbide did not see benefits of using MQL. However, the negative results in this study are probably due to inappropriate MQL parameter selection. The pressure was too low (i.e. 0.8 MPa) and the distance of the nozzle from the cutting zone was at 30 mm, too far. This result highlights the fact that inappropriate delivery settings for MQL application can affect the effectiveness of MQL.

2.4 Improvement of Minimum Quantity Lubrication Application in Milling Processes

Although the application of MQL in large-scale industries such as the Ford Motor Company has begun, full application in all machining industries still requires some intensive effort. One of the conditions, which need to be addressed, is how to change the traditional culture of the machine shop.

MQL has application for different processes and workpiece materials, as highlighted by Klocke et al [93] in Table 2.1. In addition, Astakhov [94] proposed a global area for improvement of MQL application so that it could be implemented successfully. This area for improvement is depicted in Figure 2.13.

Table 2. 1 Application areas for dry machining and minimum quantity lubrication [93]

Materials	Aluminium		Steel		Cast Iron
Processes	Cast Alloy	Wrought Alloy	High Alloyed Bearing Steel	Free Cutting, quenched and tempered steel	GG20 to GG70
Drilling	MQL	MQL	MQL	MQL-DRY	MQL-DRY
Reaming	MQL	MQL	MQL	MQL	MQL
Tapping	MQL	MQL	MQL	MQL	MQL
Thread Forming	MQL	MQL	MQL	MQL	MQL
Deep Hole Drilling	MQL	MQL		MQL	MQL
Milling	MQL-DRY	MQL	DRY	DRY	DRY
Turning	MQL-DRY	MQL-DRY	DRY	DRY	DRY
Gear Milling			DRY	DRY	DRY
Sawing	MQL	MQL	MQL	MQL	MQL
Broaching			MQL	DRY	

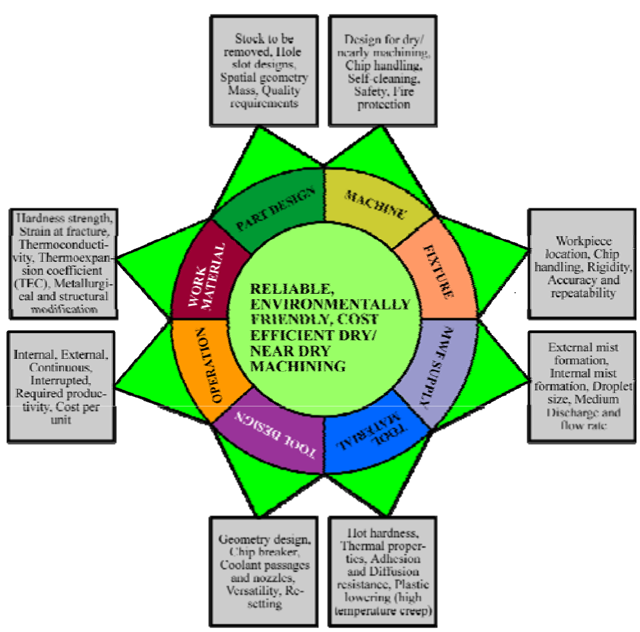


Figure 2. 14 Areas for MQL application improvement [94]

In Figure 2.13, it is clear that many aspects of MQL application need to be addressed for wide scale application. The areas that are considered important for full adoption of MQL are;

- How the MQL works (i.e. mechanism behind the success of MQL application)
- Parameters for improving the feasibility of MQL application
- The supporting methods that can be combined to promote enhanced performance of machining processes using MQL application

2.4.1 Mechanism of minimum quantity lubrication

As discussed earlier, in section 2.1.3.1, there are four mechanisms for flood cooling application. These mechanisms include capillary action, diffusion, volatilisation and the Rehbinder effect. Among these, with regard to the nature of MQL application, the capillary action and volatilisation are more representative of MQL application. Astakhov's [94] view was that the Rehbinder effect is the most plausible method. However, Astakhov's postulation was not supported by any evidence.

As suggested by Williams [95], "*molecular transport within a network of interfacial capillaries could be a significant mechanism that could improve the effectiveness of cutting fluid and as long as they could react with metal surface*". This statement refers to how to create an effective overflow cutting fluid application to enhance machining performance. Therefore, this brings up the question of whether this similar condition could also be applied to the MQL application. MQL, as generally known, uses a very small quantity cutting fluid in the form of air borne particles delivered directly to the contact zones. Thus, it guarantees cutting fluid molecules are smaller than conventional cutting fluid application. However, the reality of this statement would need to be clarified by the presence of actual evidence to prove its applicability to MQL.

Childs [96] reviewed friction contact between tool and chip when modelling friction in metal machining; especially continuous chip formation. Childs reviewed what had been postulated by William [95] and presented a metal machining model for several conditions of cooling methods using different cutting speeds. This model was proposed to help in selecting appropriate conditions when cutting fluid can be applied effectively (Figure 2.14). Unfortunately, this model was based on the conditions mostly used in metal machining which use low cutting speeds and flood cooling applications. The model has limitation for the use of advanced technology or advanced methods in the new era of metal machining, such as high-speed cutting and minimum quantity lubrication. Therefore, this model needs to be justified by employing high cutting speeds and minimum quantity lubrication; because the nature of continuous cutting, as used in Child's study, was different to the nature of interrupted cutting. It is, therefore, still questionable in milling processes using the MQL application. Likewise, the study of Childs used a very low cutting speed threshold of 10 m/min, which is too low for industrial application.

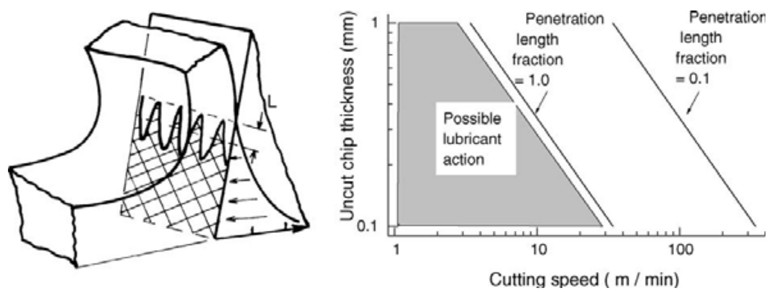


Figure 2. 15 Idealised channels by which lubricant penetrates the lightly loaded part of a chip-tool contact and the consequent limitation of fluid lubrication to low cutting speed (after Childs [96])

Using aluminium as the workpiece material, Itoigawa et al [97] investigated the effect and mechanism of MQL in intermittent turning. They used two types of cutting fluid as MQL media, mineral oil and a combination of synthetic oil and water. The results illustrated that synthetic oil is preferable as an MQL media particularly when it is mixed with water. This combination could eliminate tool damage and material pick-up on the tool surface. This is because water affirmatively possesses good cooling effects that can maintain the film strength rather than producing a film chemical absorption reaction. In addition, by adding water to synthetic ester the cooling-lubricant mechanism could be improved significantly and therefore provide the best performance during application of MQL. This might be due to the cooling and lubrication action working simultaneously. Furthermore, the presence of water could increase the oxygen in the cutting environment and thereby the cutting performance would be enhanced as concluded by Min et al [98] when investigating the absorption behaviour of lubricants using near dry machining.

However, the mechanism proposed in this study correlated with the ability of workpiece material to form a lubricant film that would help MQL to improve its performance. The workpiece material used in this study was aluminium, which is known to have high thermal conductivity. This type of material when heat conduction was stimulated would have good absorption capacity. Therefore, it can be argued that this mechanism cannot be applied to low thermal conductivity workpiece material such as titanium alloy, tool steel etc.

Liao and Lin [99], using minimum quantity lubrication (delivered at a flow rate of 10 ml/h) found that the material diffusion across the tool-chip interface was responsible for weakening the cutting tool. A hypothesis was proposed that if the protective layer could be formed in tool-chip interface then this would retard tool wear. Using MQL provided extra oxygen to the tool-chip interface and promoted the formation of a protective layer. However, it was identified that the stability of the oxide layer was cutting speed dependent and, hence, presented a relatively poor performance at a higher cutting speed of 500 m/min, compared to a lower cutting speed of 300 m/min.

Unfortunately, Liao and Lin did not try to examine the effect of different MQL flow rates and air pressure on the formation of the oxide layer. From Liao's and Lin's work, air pressure combined with oxygen might guarantee the availability of oxygen; but that effect was not explored in the study and therefore, it was not clear whether the formation of a protective layer was caused either by the influence of cutting fluid or air pressure. In addition, they used less viscous cutting fluid, which has less lubricant capacity; so that it would be difficult to maintain the protective layer under severely elevated temperatures, as cutting fluid tends to vaporized easily. Moreover, it might be possible that the protective layer coalesced with a corrosive reaction occurring at the hot surface (i.e. the tool faces) following exposure to the fluid. In general, the cutting tool in milling processes is still exposed to the fluid at the end of the cutting length; therefore, it can form a corrosive layer at the tool face.

Obikawa and Kamata [100] conducted an experiment to investigate the performance of the super lattice coating of TiN/AlN in cutting Inconel 718 using MQL and at high cutting speed regime. They also identified that the presence of oxygen could be a major controlling factor in turning. Synthetic ester was pulverized at a rate of 16.8 ml/h through an internal delivery system. However, they did not mention in their paper how oxygen could exist at the cutting zones, particularly when the cutting speed increases. On the other hand, they reported that increasing the air pressure from 0.40 to 0.60 MPa could increase the oxygen in the cutting environment. The rise in air pressure used in this study was too small, so it cannot be assumed that it could significantly increase the oxygen.

Therefore, it is still unclear why the MQL works, providing an even better cutting performance when compared to fluid cooling. This remains a the challenge in research because understanding the MQL mechanism will lead to significant improvement and help in selecting appropriate types of cutting fluid for given workpiece materials.

2.4.2 MQL and machining parameters

As stated in section 2.2.2, both external types of MQL systems are affordable in terms of system and cost. Therefore, many MQL delivering systems have been made commercially available recently, in a wide variety of design and technology. The simplest one is MQL equipment that is designed to be easily attached to any kind of machine tool. On the other hand, there is MQL equipment that has to be properly installed on the machine tool. The MQL equipment is normally installed on new and advanced technological machine tools. Therefore, the selection of the equipments is dependent on the needs and investment cost constraints.

However, the performance of some of the MQL equipment has been inadequate because the equipment has not been fully adapted for the specific requirement of the shop floor, although the manufacturer has provided all the merits that can be gained by its acquisition. As stated by Astakhov [74], these were intended for promotional effect. Therefore, tests are still necessary to seek the best performance for all specific needs and with this in mind, tests to find the optimum set of MQL parameters (i.e. flow rate and nozzle positions) and the optimum cutting condition for given workpiece material and selected cutting tool yet needs to be undertaken.

Focusing on the use of MQL application in milling operations, the author presents current achievements found in the literature review regarding the best settings for MQL application; either in association with cutting conditions or MQL parameters. These achievements are depicted in Table 2.2.

Table 2. 2 Literature findings regarding cutting conditions for MQL application

Authors	Variables conditions applied	W/P materials	Conclusion
Sun et al [2]	Vc: 40–140 m/min	Ti-6Al-4V alloy	MQL provides the best performance for all cutting condition ranges
Rahman et al [85]	Vc: 75, 100 and 125 m/min	ASSAB 718 steel (35 HRc)	Effective application of MQL found using low cutting conditions
Wu and Chien [3]	Vc: 471 m/min	P20 steel, NAK 80 and S45C	• Oil volume is insignificant for MQL • Nozzle distance is one of important MQL parameters
Liao et al [4]	Vc: 150, 200 and 250 m/min	NAK 80 die steel (41 HRc)	Feed rate was found to have significant effect on the performance
Thepsonthi et al [89]	Vc: 125, 150, and 175 m/min	ASSAB DF3 (51 HRc)	The optimum surface roughness magnitude can be achieved at 150 m/min, and 0.02 mm/tooth
Ueda et al [6]	V: 400,600 m/min	AISI 1045	Position of nozzle plays important role in reducing tool temperature
Iqbal et al [101]	Vc: 175 and 225 m/min	AISI D2 (62-63 HRc)	Cutting condition has substantial contribution to enhancing tool life and surface finish
Iqbal et al [102]	Vc: 172 and 225 m/min	AISI D2 (63 HRc) and X210 Cr12 (60 HRc)	Rotational speed was the most influential parameter
Sasahara et a. [7]	Vc: 2000 m/min)	S45C	• Tool wear reduction can be guaranteed if the selected cutting speed was not more than 750 m/min • Increasing the quantity of cutting fluid supplied can reduce tool wear; however, the rate did not occur proportionally. • The best nozzle position was at the disengage point
Yuan et al [8]	Vc: 220 m/min	50 CrMnMo structure alloy steel	• The distance of 20 mm away from the insert was assumed to be the best. • 120^o from feed direction (or 60^o off exit point) was the best fit for nozzle position
L´opez De Lacalle et al [9]	Vc: 942 m/min	Aluminium alloy	The position of 135^o from disengagement point was identified as the most efficient position to improve penetration ability of cutting fluids under MQL
Liu et al [103]	Vc: 150 m/min	Ti-6Al-4V	• Enhanced oil mist penetration revealed when spraying distance was set at 25 mm away, at 0.6 Mpa of air pressure, and at 135^o (before entry point) of spraying angle when less viscous cutting fluid was used • Reduction of cutting forces as well as cutting temperature was found not proportional to increasing of flow rate
Liu et al [104]	Vc: 60 m/min	Ti-6Al-4V	Spray distance was influenced parameter to reduce cutting forces as well as cutting temperature

Table 2.2, illustrated that most research reports focused on the application of MQL at low to moderate cutting speeds. Although some studies were performed using higher cutting speeds regime. Tools with a bigger diameter were used. Larger tool diameter is used at low RPM and the effect of higher spindle frequency has not been completely assessed.

2.4.3 Improved MQL delivery

In different ways, many studies have been carried out to improve machining performance using the MQL application by redesigning the supply method as well as by combining with the other aspects influencing machining performance such as new coating surface textures or coating layer composition.

Aoyama et al [105] designed a new lean lubrication aimed at improving the cutting performance using the MQL application. This new system was named the direct oil drop supply system (DOS). The benefit of using this system was its capability to avoid the formation of an oil mist, as normally occurs, when using the MQL application. The design for this system is shown in Figure 2.15.

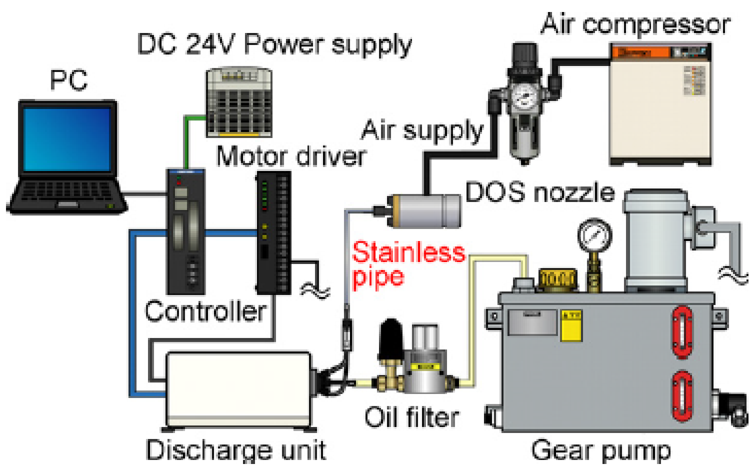


Figure 2. 16 MQL delivery system namely Direct Oil Drop Supply System (DOS) [105]

To avoid oil mist formation, this system used a rotary disk to force air borne particles to be supplied to cutting zones rather than using direct air pressure to transport the oil-air suspension to cutting zones. Accordingly, the density of the oil mist would be lower compared to other methods such as DOS with air, MQL and MQL with vacuum. In addition, to make sure the system definitely produced no mist the nozzle was designed, so that the air and oil transport channels, were separated.

Subsequently, this new method was tested in the milling process for different workpiece material hardness, aluminium alloy and titanium alloy. In milling aluminium alloy, a 10 mm diameter of carbide square endmill was utilised with a selected cutting condition of rotational speed, N: 15,000 rpm; depth of cut, ap: 6 mm; feed per tooth, fz: 0.05 mm/rev and width of cut, ae: 0.5 mm. While milling the titanium alloy, a similar cutting tool type as used to cut the aluminium alloy used slightly different cutting conditions: N: 4780 rpm; ap: 6 mm; Vc: 150m /min; and ae: 0.5 mm. The test results revealed two conflicting facts about two responses; cutting temperature and flank wear build up, where these responses, in fact, should be incorporated into each other due to wear rate being temperature dependent. With the new system, the cutting temperature could be maintained at a lower level than in conventional MQL supply systems. In contrast, the performance of the conventional MQL system, for reducing flank wear progression, was slightly lower than the newly developed system. However, this small fraction of different between the new and the conventional MQL system can assume to be caused by the lack of lubricating action in the new system due to less viscous air borne particles being delivered to the cutting zones.

Furthermore, to improve the performance of the DOS system, a new design nozzle was employed. This enabled the enhancement of the supply system of conventional minimum quantity lubrication for machining processes and the benefits of MQL were more pronounced.

The performance of the new system has been tested by milling two different workpiece materials; aluminium alloy and titanium alloy. A cutting tool of 10 mm diameter was utilised for cutting both given workpiece materials. Meanwhile, cutting conditions were kept constant. All the supply systems were tested using the same flow rate, 20 ml/min. Unfortunately, this new, potential technique was not tested for a suitable cutting speed range, particularly in comparing low cutting speeds to high cutting speeds. Aoyama et al did not try to use the insert type of cutting tool which can cause more cutting fluid deflection when it is reaches the tool faces. Therefore, the performance of this method for different tool geometry is still questionable.

Moreover, Kang et al [106] developed a new type TiAlN and TiAlSiN coating aimed at enhancing the performance of cutting tools in high speed milling of AISI D2 cold-worked die steel. Experiments were performed using 2 mm diameter solid flat end-mill coated with $Ti_{0.75}Al_{0.25}N$ and $Ti_{0.69}Al_{0.23}Si_{0.08}N$. End milling of AISI D2 was conducted using flood cooling, dry with air pressure of 5 kg/cm^2 and minimum quantity lubrication with the amount of oil delivered of 6 ml/h and 5 kg/cm^2 air pressure. Cutting conditions were held constant at 12,000 rpm of spindle revolution, 0.01mm/rev of feed, 0.02 mm of width of cut and 2 mm of axial depth of cut. Test showed that performance of the cutting tool coated with $Ti_{0.69}Al_{0.23}Si_{0.08}N$ is the best for minimum quantity lubrication application due to higher micro hardness as well as oxidation resistance. This research shows that appropriate tool coating could improve the effectiveness of MQL even at high cutting speed rates.

Obikawa et al [5] who investigated the effectiveness of employing minimum quantity lubrication (MQL) showed similar results. They introduced new methods for supplying cutting fluid in very small amounts, namely micro-liter, as well as a new design nozzle. They did a test to investigate these new methods in terms of machining performance on Inconel 718. Three different nozzle designs were utilised in this research. The first type of nozzle was the ordinary type which has a hole positioned below the insert, the second type was almost similar to the first type except that it had a cover around it and, finally, the third type of nozzle had an oblique line and cover around it. To evaluate the performance of these newly developed systems, tests were carried out using a carbide insert coated with a multi-layer CVD ($TiCN/Al_2O_3/TiN$). For all the experiments the cutting condition were set constant at 0.1 mm depth of cut, 0.1 mm/rev feed, and 78 m/min of cutting speed.

The results revealed that the oblique spray nozzle type had a crucial influence in reducing notch wear compared to the other two types of nozzle. However, all the methods that were investigated showed no significant difference to dry machining. Obikawa et al reported that the oblique spray nozzle could be an effective method for delivering cutting fluid in terms of MQL. This might be due to the oblique nozzle design; the size of the air borne particles would be changed and larger particles would be emitted from the nozzle tip than those entering the nozzle. Therefore, in MQL application, the cooling and lubricating action are necessary however, which one is more dominant than the other and what percentage of combination, becomes a challenging area for improving machining performance using MQL application.

Another viewpoint from Pejryd et al [107] and Zhang et al [108] was to improve the machining performance using MQL application by lowering the delivery temperature of cutting fluid. Pejryd et al [107] used room temperature liquid as a cooling media, while

Zhang et al [108] used synthetic vegetable oil maintained at a low temperature (-35^{o}C) by utilising cryogenic compressed air. Application of both methods yielded low cutting forces in comparison to dry machining. Cutting fluids delivered at lower cutting temperatures might enable maintenance of particle size at the specific size where the effect of lubrication is dominant. Normally, when the cutting fluid is supplied at ambient cutting temperature particle size tends to decrease due to accelerating particle speed when air pressure is applied. Thus, the lower the particle size the more the lubricating effect is reduced.

2.5 Environmental Analysis of Machining Processes

The awareness of the global warming phenomenon has been growing rapidly. Many attempts have been carried out to minimise the effect of industrial residue on the environment. The main concern is how to reduce the carbon footprint generated by electricity consumption by focusing on energy efficiency. This is due to most energy is supplied by the electricity grid. Electrical energy is generated from natural resources that in the most part are non-renewable. Natural resources have been declining remarkably. By reducing electricity consumption, it means saving natural resources and reducing the impact residue on the environment.

A machine tool is a piece of electrically driven, motor equipment. Every year the electrical energy consumption to power up machine tools in industries undergoes a significant growth along with increasing machine tool production as well as production of machined parts/components [109]. To decrease electricity consumption used by machine tools, and in consequence decrease carbon footprints, efficient machine tools, in terms of technology and design as well as energy efficient processes become crucial.

Focusing on energy efficient machine tools and processes could in turn help to reduce the carbon footprint (the main cause of global warming). However, global warming is not the only fact that needs to be considered. As it has been realised, machining processes also produce other residues beside CO_2. These residues come from the waste produced because of metal removal processes using cutting fluids. These residues also affect the environment and are categorised as harmful substances. Therefore, a strategy to eliminate the effects of waste in machining processes must be taken into account as well the development of sustainable machining processes.

This section will discuss the current strategies that have been proposed to minimise the energy footprint as well as other aspects of environmental impact. A great deal of environmental evaluation has been carried out using strategies based mainly on impact: such as acidification, eutrophication, photochemical oxidants, human toxicity and ecotoxicity [110].

2.5.1 Energy analysis

Creyts and Carey [111] used the concept of available energy (i.e. exergy) as frequently used in a thermal and chemical analysis to determine the environmental performance of the machining processes. They called this terminology extended energy analysis (EEA). Based on flow stream analysis of machining processes; in this case, aluminium, they calculated treatment of the vapour waste stream, the cutting fluid waste stream, the liquid-solid-waste streams and transportation and handling costs.

The result showed that total exergy increased with the rise in cutting speed. However, separation processes were revealed as the dominant contributory provider. This suggested that waste material removal processes have a notably effect on total exergy at high cutting velocity in comparison with the cutting operation itself. However, this study did not evaluate power requirement, which are a dominant aspect of machining processes.

Draganescu et al [112] studied machine tool efficiency and specific consumed energy in machining using a statistical model. They concluded that specific energy consumed was influenced by cutting power, machine tool efficiency and the cutting parameters and tool cutting capabilities. In addition, it was revealed that higher feed per tooth would rapidly increase the material removal rate hence reducing the energy consumed.

Similar to Dragenescu et al, Avram and Xirouchakis [113] evaluated the use-phase energy requirements of a machine tool system. Assessing the spindle power and feed axes energy requirements based on the spindle movement for cutting and non-cutting operation, they used the following numerical equation;

$$E_{DE} = \int_{t0}^{t1} P_{aY} dt + \int_{t1}^{t2} P_{SY} dt + \int_{t2}^{t3} P_{DY} dt + \int_{t0}^{t3} P_{run} dt + \int_{t1}^{t2} P_c dt \tag{2.1}$$

Where E_{DE} is total energy consumed by spindle and feed axes along tool path (J), P_{aY} is power required to accelerate the spindle in Y-axis direction in watt, P_{SY} is steady state power of spindle in watt, P_{DY} is power to decelerate the spindle in Y-direction in watt, P_{run} is the power required to run the spindle at constant speed in watt, and P_c is counted for cutting forces (F_c) and cutting speed (V_c) in watt. Meanwhile, t_1, t_2 and t_3 are the time necessary to move the spindle from each position along the designed tool path in second.

Based on the cutting power of the tool tip, Schlosser et al [114] evaluated the energy consumption of the drilling processes. They defined the total power consumption as a summation of cutting power (P_c), feed power (P_f) and passive power (P_p). Indeed, as they concluded, these methods were feasible in providing a realistic estimation of machine tool energy consumption. However, this proposed methodology failed to integrate with other aspects of energy consumption in machining processes such as pumping power, etc. In addition, this method might not be appropriate in determining the electrical energy consumption of machine tool during the cutting operation due to mainly based on calculation of mechanical power that is depending on measurement of cutting forces. .

Dahmus and Gutowski [115] identified the area of energy consumption in machining processes using environmental analysis. They stated that the energy consumption in a machining process was driven by direct and indirect energy. Direct energy consumption was the energy required to power up machine tool during the cutting operation. Meanwhile indirect energy can be defined as the energy related to material production.

Continuing the aforementioned framework, Gutowski et al [116 - 118] proposed a now popular method in determining power consumption in cutting processes. Accordingly, they stated that the total energy consumption in a cutting operation would depend on the energy consumption at the ready position (P_o) and cutting energy that is specific to the cutting process, (k) and material removal rate ($\dot{v}$). This was expressed as in Equation 2.1.

$$E = \left(P_o + k\dot{v}\right)t \tag{2.2}$$

Where E is the electrical energy requirements in machining (J), P_o is the power (W) consumed by the machine in ready to cut state, k is the specific machining energy for a selected workpiece material (J/mm^2), $\dot{v}$ is the material removal rate (mm^3/s) and t is the machining cycle time in second.

Extending this model to include the energy consumption for tool changes and energy to produce cutting tools, Rajemi et al [119] proposed a new methodology in assessment of machinability based on minimum energy considerations. This new concept is shown in Equation 2.3.

$$E = P_o t_1 + (P_o + k\dot{v})t_2 + P_o t_3 \left[\frac{t_2}{T}\right] + y_E \left[\frac{t_2}{T}\right] \tag{2.3}$$

This new, extended model enabled the integration of all the areas that have been highlighted by Dahmus and Gutowski [115] in their early study. However, due to focusing on the most sustainable machining processes (i.e machining in dry condition), the power consumption associated with the use of a pump and compressor were ignored. Using this method, Mativenga and Rajemi [120] calculated the optimum cutting parameters and found a 64% reduction in energy footprint using the optimum result compared to following tool supplier recommended cutting conditions.

He at al [121] proposed a new energy model that can be utilised for practical energy estimation in small and medium scale enterprises. This model was correlated with FANUC numerical controlling machine code. Although this model provided a good estimation some element failed to synchronise the power generated by electricity use and the power generated by cutting operations (specific cutting). Therefore, it is conceivable that this method is not robust in determining power consumption.

Furthermore, Li and Kara [122] developed a predictive model for quantifying the energy consumption of manufacturing processes. This model was a combination of tool-tip power consumption and the model suggested by Dahmus and Gutowski [115]. This predictive model is expressed in Equation 2.4.

$$SEC = C_o + \frac{C_1}{\dot{v}} \tag{2.4}$$

Where C_o was the coefficient of the inverse model and C_1 was the coefficient of the predictor, both coefficients were generated from experiments. Thus, this model seems highly dependent on the machining test. It cannot be fully applied as generic model for energy consumption in machining processes. This was revealed by the further studies done by Kara and Li [123]. They utilised eight different machine tools. The eight machine tools generated around eight empirical models. Interestingly they compared two cooling/ lubricating methods; dry and wet and there was no significant difference in the results. Although this model achieved 90% accuracy, it cannot be assumed that this model can be useful in energy consumption prediction as well as in selecting the appropriate machining conditions that can help reduce energy consumption.

2.5.2 Total environmental assessment

Besides the issue of carbon emissions, the machining industries are also facing an issue associated with waste resulting from machining operations such as chips and cutting fluid disposal. Machining industries produce a huge amount of chips as well as cutting fluid residues.

Using an analytical approach, Munoz and Sheng [124] analysed aspects involved in a machining process system. These included process mechanics, wear characteristics and lubricant flows. Assessing the impact of waste streams from a machining process, they calculated utilisation factors of the main output to judge the environmental effect using Equation 2.5.

$$Util = A_1 \frac{E_{Base}}{E} + A_2 \frac{t_{Base}}{t} + A_3 \frac{m_{W,Base}}{m_W} \quad (2.5)$$

Where E is the process energy in Joule, t is production time in second and m_W is weighted mass flow of component waste stream. Meanwhile A_1, A_2 and A_3 are weighting factor for each analysed waste stream output that was determined using a sampling method such as Analytical Hierarchy Process (AHP). Then quantifiable values of the analysis model were put into a prioritisation matrix. However, although this method might be useful, it might be complex. Thus, it would not be practical to use in the planning stage of a machining process.

Choi et al [125] proposed an assessment model of the environmental impact using what is called the '*material balance*' concept. The solid waste, water waste, energy consumption and noise produced as an output of a machining process were estimated using a simple calculation. The value of environmental consequences was evaluated using the value of each aspect (i.e. solid waste, energy consumption, waste water and noise). This, however, failed to show the integrated environmental impact of machining processes due to the analysis being performed separately and additionally, the energy consumption was only determined from driving system. However, this concept might be adoptable as a basic concept in determining the impact of machining processes on the environment.

Narita et al [126] developed an integrated environmental impact assessment. This model was initially proposed to predict the environmental impact of machine tool operation using a Life Cycle Analysis (LCA) approach. The total environmental impact of machine tool operation was calculated from electric consumption (B_E), coolant volume (B_{CF_disp}), lubricant oil volume (B_{Lub_disp}), cutting tools (B_{tool_disp}), volume of metal being removed (B_{chip}) and other aspects of machine tool operation (B_{others}). Including all these aspects, Narita et al [125] expressed the assessment model as in Equation 2.6.

$$B_{en} = B_E + B_{CF\_disp} + B_{Lub\_disp} + \sum_{i \to N} \left(B_{tool\_disp\,i} \right) + B_{chip} + B_{others} \quad (2.6)$$

Where B_{en} is the environmental burden of machining operation (kg-CO_2), B_E is the environmental burden of electric consumption of machine tool (kg-CO_2), B_{CF_disp} is the environmental burden of coolant (kg-CO_2), B_{Lub_disp} is the environmental burden of lubricant oil (kg-CO_2), B_{tool_disp} is the environmental burden of cutting tool that is depending on number of tools used during cutting operation, N, B_{chip} is the environmental burden of metal chips (kg-CO_2) and the environmental burden of other related factors (B_{others}) in kg-CO_2.

Energy consumption was determined from the electricity consumption required to drive a servo motor, spindle motor, spindle cooling system, compressor, coolant pump, chip conveyor, automatic tool change and tool magazine. Additionally, the energy consumption whilst in standby mode was added to show the total electrical energy demand of a machine tool. The machine was assumed not to require more energy for cutting.

From a different viewpoint, Anderberg et al [127] used cost analysis to predict the environmental impact. To calculate the environmental cost generated by the cutting process, the energy consumption was classified into two different studies, which are direct energy (E_D) and indirect energy consumption (E_{ID}). Direct electrical energy consumption was measured from the power driven by the slide movement and rotating spindle. Meanwhile, the indirect electrical energy consumption was defined as the power required during the setup and tool change multiplied by the total duration of one cycle of machine tool operation. Furthermore, in the study the analysis was directed to estimate the cost of carbon footprint for a machining process that was modelled as in Equation 2.7.

$$C_{CO_2} = \left(E_{ID} + E_D\right) \frac{CES}{\left(1000/3.6\right)} \frac{K_{CO_2}}{1000} \tag{2.7}$$

Where C_{CO_2} is carbon dioxide emission cost per unit of product (£), E_{ID} and E_D are indirect and direct electrical energy consumption in kJ, CES^{TM} is carbon emission signature in kg-CO_2/GJ, and K_{CO_2} is carbon dioxide emission cap and trade cost per tonne (£/kJ).

Using the same approach as Anderberg [127], Branker et al [128] built a model to calculate the environmental impact based on Life Cycle Analysis (LCA). This proposed model was actually an adaptation of the concept developed by Narita et al [126]. To quantify the energy consumption demand of a machining process the specific cutting energy and the energy required to activate auxiliary modules was calculated and this model was utilised to determine the optimum process parameter of the milling process [129]. Therefore, there is need for a model that can represent the cutting operation and help in the selection of green process parameters.

2.6 Summary

It has been identified from the literature review that:

- Application of minimum quantity lubrication (MQL) is favourable in situations where dry machining application cannot be fully utilised due to limited capability of cutting tools. Some reports even found that MQL application is more superior in comparison to flood cooling. Thus, they tried to use the smallest amount of cutting fluid as possible to supply the cutting zones without considering the optimum flow rate that might be suitable for given workpiece material. Therefore, a systematic investigation is needed to find the interaction between machining variables and MQL parameters, especially the effect of using different flow rates. Hence, the optimum setting for MQL and machining variables can be used to improve the machining performance for given workpiece material.
- There was no agreement found in the literature in respect of the range of cutting speeds that can be employed so that the effectiveness of the MQL application can be expanded. Indeed, it was suggested that the use of high viscosity cutting fluids could improve machining performance when using MQL at higher cutting speeds.
- Improvements that have been made and reported have focussed on a new design of the MQL delivery system and the correct combination of coating tool layer and MQL media; but few improvements in respect of MQL parameters have been found. The MQL parameters, such as nozzle distance, nozzle position and air pressure are important for effective MQL application.

- Understanding the mechanism behind the MQL application would help to find a suitable strategy to improve performance. One study in this field has been carried out but it was extremely limited and the findings still need to be justified.
- The literature review suggested that the absorption capability of workpiece materials play an important role in the formation of a protective film which would help the MQL application to perform at its best. Thus, it is conceivable that every workpiece material possesses its own characteristics when it is machined using the MQL application. Therefore, machining data for a wide variety of workpiece materials, used in machining processes using MQL, needs to be developed. Interestingly, no data was available in literature for machining hot-worked tool steel, especially H-13, using MQL.
- Improving the MQL application may be essential to meet sustainable development criteria. The literature review revealed very little information on sustainability. Therefore, an environmental analysis has to be undertaken to assess the carbon footprint as well as the environmental burden so that a clear position for the MQL application, in respect of sustainable development, can be identified.

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 Equipment Details

3.1.1 *Machine tool*

The cutting tests performed in this study were conducted using Agie Charmiles MIKRON HSM 400 high speed machining centre. A photograph of the Mikron machine along with details of its capability is shown in Figure 3.1 and Table 3.1.

Figure 3. 1 MIKRON HSM 400

Table 3. 1 Functional capabilities of MIKRON HSM 400

Controller	:	Heidenhain ITNC 530
Maximum Spindle Speeds	:	42,000 rpm
Acceleration	:	1.7 ms^{-2}
Tool Holder Type	:	Type HSK-E 40
X-axis travels	:	400.30 mm
Y-axis travels	:	450.34 mm
Z-axis travels	:	350.27 mm
Maximum Feedrate	:	40,030 mm/min
Maximum Rapid Rates	:	40,030 mm/min
Table Surface	:	320 mm x 320 mm pallets
Maximum Table Load	:	116.12 kg
Spindle Power	:	10 kW
Equipped with	:	• 7-position APC • Chip Conveyor • HSK-40 Touch Probe • Laser Tool Measurement • Oil Mist Extraction • Oil Mist

The reason behind the utilisation of this high-speed machining centre was due to its capability of spindle speeds up to 42,000 rpm. Thus, the effect of rotational speed could be studied. Rotational speed causes centrifugal forces to rise, which would hinder cutting fluid from reaching the target area.

3.1.2 *Minimum Quantity Lubrication system*

The Minimum Quantity Lubrication (MQL) delivery system used in this study is a commercially available MQL fluid delivery system from Unilube A.G. This device was attached to the Mikron HSM 400 machining centre and the mixing of cutting fluid and air happens in an atomisation tank. Thus, the air/fluid particles are delivered through a single pipe and sprayed through a nozzle that has an orifice at its tip. A photograph of MQL system used in this study can be seen in Figure 3.2.

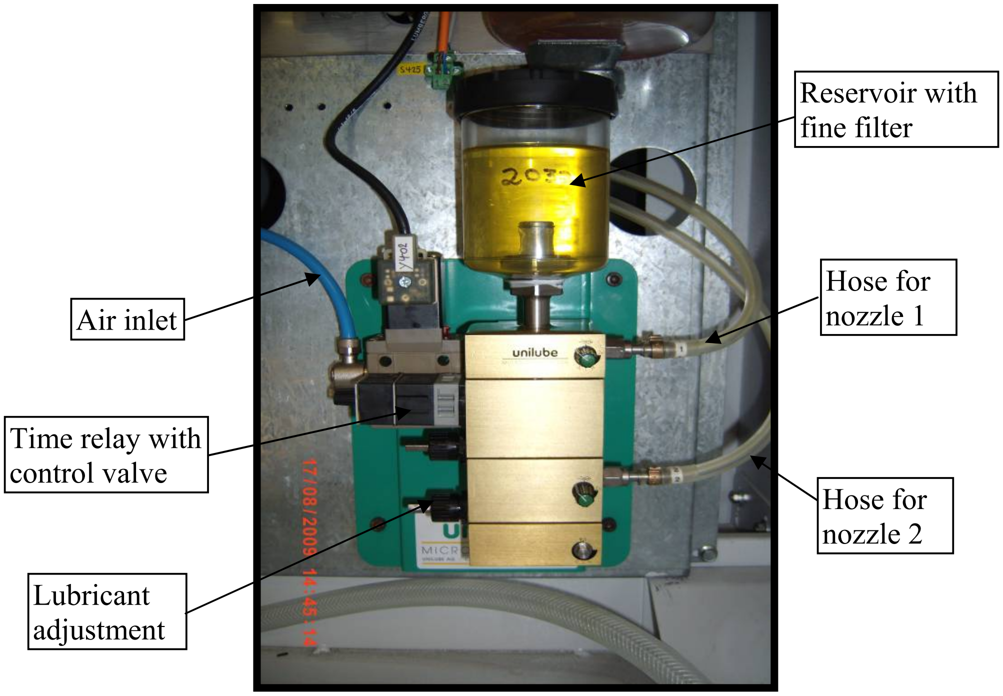


Figure 3. 2 UNILUB MQL delivery system attached to the MIKRON HSM 400 machining centre

The type of cutting fluid delivered by this system is a high-performance lubricant produced by UNILUBE A.G., Unilub 2030. This lubricant is a non water-soluble mixture of ester manufactured from natural fatty acids.

3.1.3 *Surface roughness tester*

To measure the surface roughness on the machined surface of the H13 workpiece material, a Taylor Hobson Talysurf Surtronic 25 was used. The image of the device and its supporting units are shown in Figure 3.3.

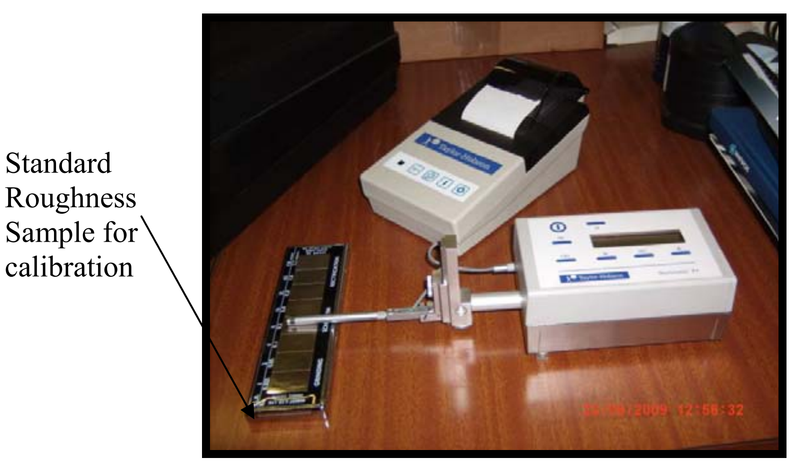


Figure 3. 3 Taylor Hobson Talysurf surface roughness tester

3.1.4 *Optical microscope*

Measurement of tool wear progression was conducted using an optical microscope. The optical microscope used in this study was a Leica DM2500 M optical microscope shown in Figure 3.4.

Figure 3. 4 Leica DM2500 m optical microscope

3.1.5 *Scanning Electron Microscope*

An Hitachi Scanning Electron Microscope (SEM), S-3400 N was utilised to image the flank face and the rake face of inserts and cutting edges. An image of the microscope is shown in Figure 3.5.

Figure 3. 5 HITACHI S-3400 N Scanning Electron Microscope

The SEM device has a resolution of 4 nm at low voltage and 3 nm at high voltage. The accelerating voltage can be raised up to 30 kV, providing clarity in the image taken. In addition, along with the SEM image, a secondary electron detector (SE) and a backscatter electron detector (BSE) provide analysis of the sample.

3.1.6 *Clamp meter*

To measure the current used by the Mikron machine tool, a Fluke 345 PQ clamp meter, as shown in Figure 3.6, was used. This device has the capability to measure flux created by a moving electric current, and is able to measure dc current without the need to break the circuit. The specification of clamp meter is found in Table 3.1.

Figure 3. 6 Fluke 345PQ clamp meter

Table 3. 2 Fluke 345 clamp meter specification for current measurement

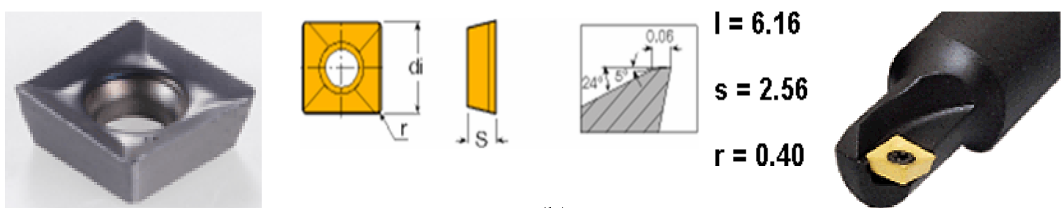
Measuring range	0 to 2000 A DC or 1400 AC rms
Autorange facility	40 A / 400 A / 2000 A
Resolution	10 mA in 40 A range 100 mA in 400 A range 1 A in 2000 A range
Accuracy: AC and DC rms	I > 10 A: ± 1.5 % reading ± 5 digits I < 10 A: ± 0.2 A
Accuracy: AVG	I > 10 A : ± 3 % reading ± 5 digits I < 10 A : ± 0.5 A
Accuracy: Pk	I > 10 A : ± 5 % reading ± 5 digits I < 10 A : ± 0.5 A
Accuracy: AHr	I > 10 A : ± 2 % reading ± 5 digits I < 10 A : ± 0.5 AHr
Accuracy: CF (Crest Factor)	1.1 ≤ CF < 3 : ± 3 % reading ± 5 digits 3 ≤ CF < 5 : ± 5 % reading ± 5 digits Resolution : 0.01
Accuracy: RPL (Ripple)	2 % ≤ RPL < 100 % : ± 3 % reading ± 5 digits 100 % ≤ RPL < 600 % : ± 5 % reading ± 5 digits Resolution : 0.1 % I(DC) > 5 A, I(AC) > 2 A
All measurements dc and 15 Hz to 1 kHz, Maximum overload 10,000 A or rms x frequency < 400,000, Amps rms is a true-rms measurement (ac + dc)	

3.2 Measurement Methods

In this section, the evaluation methodologies utilised in the research are described. These include measurement of cutting-edge radius, surface roughness and flank wear progression.

3.2.1 *Tool edge radius measurement*

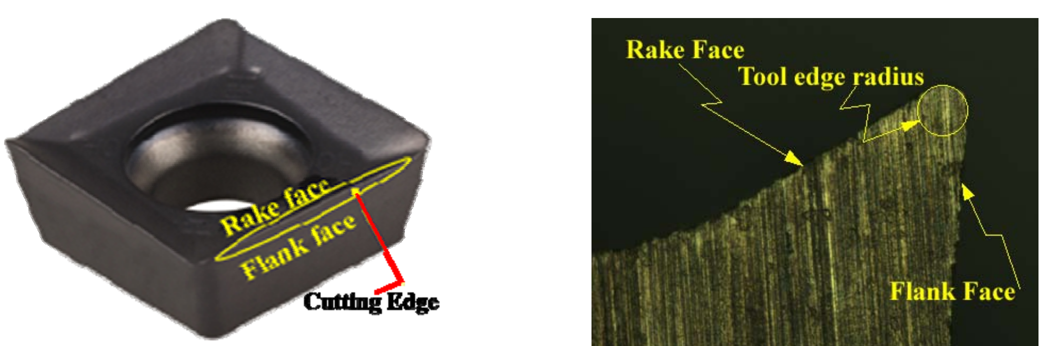
All the experimental work carried out in this study used inserts that were manufactured by ISCAR. The insert is a PVD TiAlN coated tool insert SOMT 060204-HQ (Figure 3.7a and Figure 3.7b). This insert is used for cutting from steel to cast iron (P20-P50; M20-M40; K15-K40). The insert was mounted on an 8 mm diameter single flute Iscar tool holder E90X D08-C10-06 (Figure 3.7c).



(a) (b) (c)

Figure 3. 7 Iscar insert and tool holder
(a) insert (b) insert specification (c) E90 X D08-C10-06 tool holder

The ratio between the undeformed chip thickness and tool edge can be critical if it is equal or less than 1 since a negative rake angle would prevail and this affects machining performance. To understand this impact of relative tool sharpness or so called "size effect", the edge radius of the insert was evaluated for an SEM image of the cutting edge. This was taken from a sectional cut of the cutting tool as shown in Figure 3.8b.



(a) (b)

Figure 3. 8 a. Image of ISCAR's insert, IC928; b. Tool edge radius

The tool edge radius is located at the intersection of the tool rake face and the flank face. By placing the best-fitting circle at that intersection, the tool edge radius can be determined as shown in Figure 3.8b. The size of the tool edge radius for the inserts used in this study was on average 62 μm. A detailed method for measuring the tool edge radius can be found in literature [130-132].

3.2.2 *Surface roughness measurement*

The milled surface roughness for each experimental combination was measured with a Taylor Hobson Talysurf and every set was measured twice. The measurement was taken in the feed direction and width of cut direction. An example of surface roughness measuring is shown in Figure 3.9.

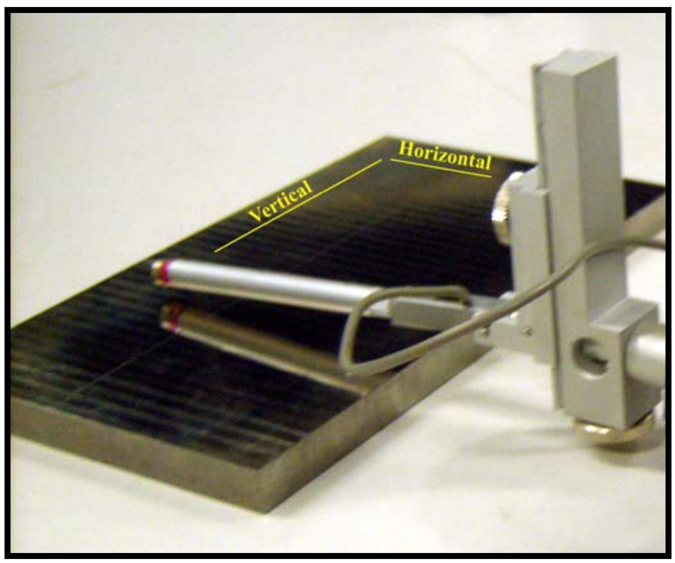


Figure 3. 9 Surface roughness measurement

3.2.3 *MQL flow rates quantification*

A practical procedure was adapted to evaluate the lubricant flow rate. This was done by collecting the fluid delivered over a set period and relating this to the valve opening angle. The results were plotted as in Figure 3.10.

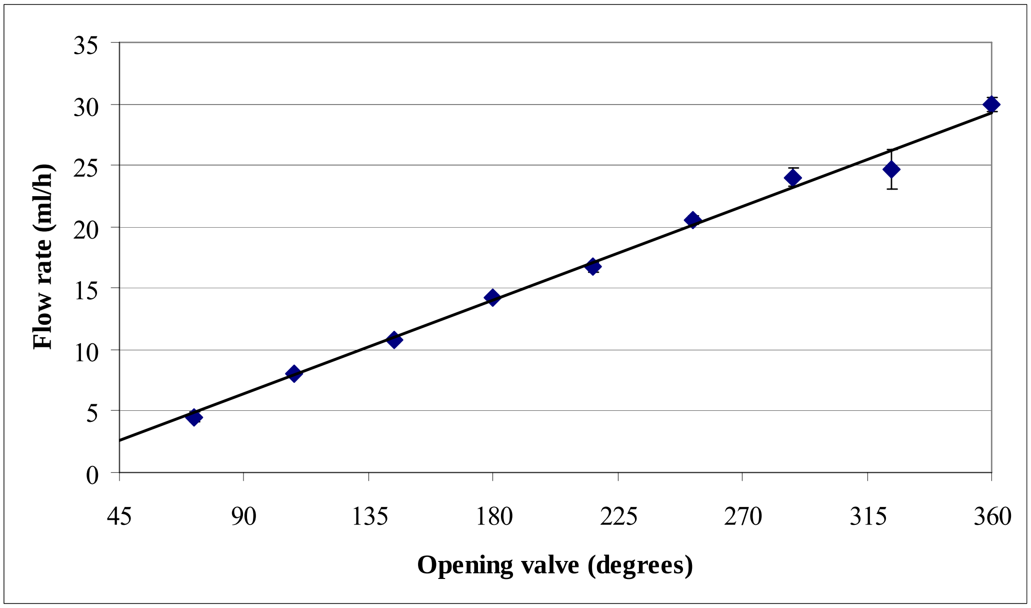


Figure 3. 10 Lubricant flow rate MQL-Unilub for increase valve opening

3.2.4 *Tool wear measurement*

Flank wear was identified as an abraded area on the flank face and was measured from the top of the abraded area to the tool edge. Ideally, the tool edge should still appear even though the adjacent area has been abraded. However, when cutting hard material the tool edge cannot be identified due to the rake face being abraded or chipping on the tool edge. In such cases, an imaginary line based on the geometry of a new tool can be used as a guide. Figure 3.11 illustrates this concept.

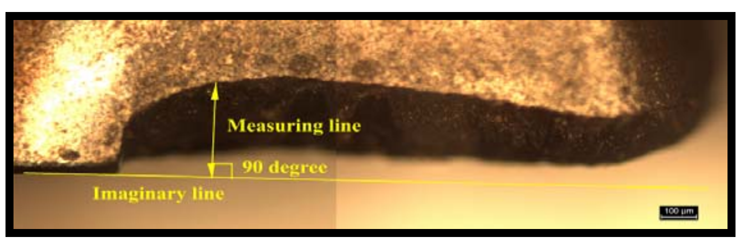


Figure 3. 11 Tool wear measurement

The magnitude of flank wear was determined using the average value of data taken along the abraded area in accordance with ISO 8688-2 [133].

3.3 Experimental Setup

All experiments conducted in this study were performed using a HSM MIKRON 400 machining centre. All of the experiments were setup in a similar way; however, careful attention was paid to setting the cutting tool. The cutting tool had a short overhang (20 mm) in order to eliminate the possibility of causing deflection and vibration. Figure 3.12 depicts the way in which the experiments were set up.

Figure 3. 12 Experimental setup

3.4 Taguchi Experimental Design

Taguchi initially introduced and developed experimental engineering improvement methods based on statistical theory. His method is based on the Orthogonal Array experimental design, which can minimise experimental variation by having optimum settings for control parameters [134]. Therefore, Taguchi Design of Experiments ensures that, for best results, optimal control parameters can be attained. Orthogonal Array design coupled with Taguchi's Signal-to-Noise Ratios (S/N), constitute a strong statistical tool for experiment optimisation in the field of engineering.

Taguchi method permits a minimum of experiments to be undertaken to observe the dominant factors for product quality. The method is less time and resource consuming, significantly reduces the cost of experiments and is easy to adapt into an industry's daily activities [134]. Fraley [135] stated that the Taguchi method was adequate for an intermediate number of variables (3 to 50). Few interactions and only a small number of variables can provide a significant contribution to the result of an experiment.

Furthermore, Fraley described the advantages and disadvantages of using the Taguchi method for experimental activities as follows;

- Advantages
  a. Improved product quality.
  b. Straight forward and easy adoption into many engineering situations, providing the most powerful but simple tools.
  c. Avoids huge numbers of experimentations to observe numerous variations in parameters.
  d. Easy to identify the most important parameters influencing characteristic performance values.

- Disadvantages
  a. The results obtained are not absolute and do not show the highest influencing parameter.
  b. Inhibits all variable combinations to be tested.
  c. Difficult to determine the interaction between parameters. However, by planning the experiment effectively this could be overcome.
  d. Unsuitable for dynamically changing processes such as a simulation study.
  e. Only have benefits in the early stages of an experiment.

Since the Orthogonal Array is the central tenet of the Taguchi Method, selecting an appropriate array is a most important process. Orthogonal array is available on many levels, but for general purposes, two or three levels are adequate. Choosing these levels should be based on the objective to be achieved [136]. Two levels of an orthogonal array are sufficient for a focusing experiment and are more cost-effective in terms of received knowledge. Meanwhile, three levels of experiment are exactly suited for understanding single, continuous and sequential experiments. Single experiments mean the objective can be achieved by completion of one, single experiment that can solve a problem or determine the process settings. Continuous experiment is aimed at continuous improvement and establishing a framework for future process tuning. Additionally, sequential experiments can facilitate the study of processes intensively and incorporate all the variables of interest in one in-depth experiment.

Applying the Taguchi Method is simple, and Taguchi recommended eight basic steps for implementation of this method, which are [136]:

1. Identify the main function, side effects, and failure mode.
2. Identify the noise factors, testing conditions, and quality characteristics.
3. Identify the objective function to be optimized.
4. Identify the control factors and their levels.
5. Select the orthogonal array matrix experiment.
6. Conduct the matrix experiment.
7. Analyse the data; predict the optimum levels and performance.
8. Perform the verification experiment and plan the future action

CHAPTER 4

EFFECT OF KEY PROCESS VARIABLES ON THE EFFECTIVENESS OF MINIMUM QUANTITY LUBRICATION IN HIGH SPEED MILLING

Chapter Synopsis

Great concern about the environmental impact of manufacturing, as well as the need to reduce costs and cycle times, raises interest in dry high speed machining (HSM). Many researchers have reported the feasibility of using minimum quantity lubricants (MQL) in HSM. However, the selection of optimum cutting parameters for MQL application has not been the subject of a systematic study. In this chapter, Taguchi's experimental design was used to define the dominant process parameters and the optimum setting for minimising tool wear and machined surface roughness. The results show that selection of the quantity of MQL required is the most dominant factor for improving wear performance and the use of lower cutting speeds and higher chip thickness to cutting edge radius ratio (more efficient cutting) leads to better wear performance when milling tool steel. This can be a strategy for roughing operations, while the use of feed per tooth lower than the tool edge radius can help improve the surface finish in the finishing operations. This chapter offers an important industrial guide for near dry milling processes and identifies key areas for process improvement.

4.1. Introduction

Cutting fluid plays a significant role in the cutting process. Two main factors of cutting fluid are regarded as important. Firstly, the capability to cool down the cutting tool helps to minimise thermally activated wear. Secondly, lubricating the contact areas where the friction occurs. In addition, cutting fluids help by flushing the chips away from the machining zone. However, extensive use of cutting fluid has a negative impact on the environment and human health [137]. Machado and Wallbank [138] undertook a series of cutting tests using a small quantity of cutting fluid. They concluded that the machining process only requires a certain quantity of cutting fluid depending on the process.

A method that could be employed to mitigate the impact of using cutting fluid is dry machining [139]. For processes such as the intermittent milling process (cyclic cutting hence heating and cooling), dry machining is a promising candidate. Viera et al [140] compared dry machining and wet machining during face milling of H640 steel and reported that dry milling provided the best performance in terms of reducing tool wear and improving surface finish. Thermal cracks were found to be responsible for shorter tool life in instances of cutting fluid due to cyclic heat during the process. The effectiveness of cutting fluid when machining at high cutting speed was questioned.

In high speed machining (HSM), working at higher cutting speeds leads to increased thermal load during the cutting process. Consequently, this increases interface temperature and decreases tool life [141]. Sometimes introducing flood coolant leads to thermal shock and hence the interest in machining dry or machining with minimum cutting fluid. Dry high speed machining for difficult-to-cut materials where traditionally, copious amounts of cutting fluid are used, is a particularly interesting development [23]. It has been noted that more process development is required to achieve widespread use of dry machining in industry [33].

Minimum quantity lubrication (MQL), also known as near dry machining (NDM) can be a favourable machining technology [4, 85, 106], however, there are contradicting results regarding the application of MQL in machining. For example, Rahman et al [85] reported that MQL was suitable for use only at low cutting speeds. While Liao et al [4] reported that MQL was effective for both high and low cutting speed regimes. Several studies have investigated the use of the MQL method, [2, 5, 6, 89, 101, 142, 143] unfortunately, most research into MQL was focused on the benefits and feasibility of this technology [94] and not on performance optimisation.

The aim of this study is to identify the significance of key process variables on MQL performance and fill the knowledge gap regarding optimum settings for machining with MQL.

4.2. Experimental Details

The optimisation of cutting variables in MQL application was done for machining H13 tool steel. Selection of the cutting parameter levels was adapted to suit high speed milling requirements. Therefore, in this work the selected cutting speed was varied from 225 m/min (i.e. maximum cutting speed recommended by tool manufacturer for milling steel workpiece material) to 400 m/min (transition cutting speed for cutting steel workpiece material as recommended by Schulz and Moriwaki [23]. Furthermore, selection of depth of cut and feed per tooth, as given in Table 4.1 was based on consideration of high speed milling application and lighter chip load.

Table 4.1. Factors and their levels using Taguchi's L9 orthogonal array

Parameters	Level		
Cutting speed (Vc), m/min	225	300	400
Ratio of Feed per tooth to tool edge radius (R_f)	0.81	1.13	1.45
Ratio of Depth of cut to tool edge radius (R_{ap})	1.37	1.82	2.42
Flow-rate (Q), ml/h	16.8	22.4	29.9

In high speed milling the practice is to use lighter cuts and higher table feeds. The use of lower depth of cut and feed per tooth implies that the size effect in relation to the tool edge radius needs to be considered. The tool edge radius measured for the inserts used in this study was on average 0.062 mm. The ratio of feed per tooth to tool edge radius in this case defines the effective rake angle and is an important parameter for characterising the process.

The volumetric flow rate levels for MQL parameters were selected according to a preliminary test, which was done to quantify volumetric output of the supply system using the Mikron HSM 400 machine tool. Details of the procedure were given in section 3.2.3. The MQL used was UNILUB 2032 and this was delivered at 4 bar pressure through 2 nozzles at an angle of 45^o to the tool feed direction. Taguchi's L9 orthogonal array was selected as the experimental design. The factors and their levels are shown in Table 4.1. Taguchi's design has been recognised in engineering and industrial research for providing the optimum settings for control parameters [134].

A down milling, end milling operation was performed to cut a H13 workpiece material using a Mikron HSM 400 milling machine. The test was performed using a tool diameter of 8 mm, mounted with rectangular TiAlN PVD coated tool insert (IC928) manufactured by ISCAR. The edge radius of the inserts was evaluated to be 62 μm. Each set of experiments were repeated once.

Surface roughness was measured using a Taylor Hobson Surtronic 3+ Talysurf surface roughness tester. The cut length and the evaluation length were set to 0.8 mm and 4mm, respectively. Furthermore, images of the flank wear area and the rake face were captured using a Leica microscope. Subsequently, the magnitude of flank wear and contact length were measured by using image processing software, Axio Vision Release 4.8. The average flank wear and contact length were calculated from the data collected by taking 15 lines of measurement on the flank wear area of each worn insert. All the measurements either for surface roughness or for flank wear were repeated once for each setting.

4.3. Results and Discussions

4.3.1 Importance of key process variables on tool life

Table 4.1 shows the experimental plan, while the results for flank wear and the signal-to-noise ratio (S/N) are shown in Table 4.2 and Fig. 4.1.

Where R_f and R_{ap} are ratios of feed per tooth and depth of cut respectively to the cutting edge.

The results in Table 4.2 and Figure 4.1 show that a low cutting speed (225 m/min), higher feed per tooth to tool edge radius (R_f=1.45), moderate depth of cut-tool edge radius (R_{ap}=1.82) and a high volumetric flow rate of cutting fluid (29.9 ml/h) gave the least flank wear. The low cutting speed is associated with lower cutting temperatures and hence lower average flank wear. This supports previous reports on the performance of MQL over a range of cutting speeds [85, 89, 101].

Table 4.2. Experimental design and average flank wear response

Vc (m/min)	$\mathbf{R_f}$	$\mathbf{R_{ap}}$	**Q** (ml/h)	**Average Flank Wear (VB average)** (μm)
225	0.81	1.37	16.80	64
225	1.13	1.82	22.40	63
225	**1.45**	**2.42**	**29.90**	**58**
300	0.81	1.82	29.90	63
300	1.13	2.42	16.80	65
300	1.45	1.37	22.40	67
400	0.81	2.42	22.40	68
400	1.13	1.37	29.90	60
400	1.45	1.82	16.80	61

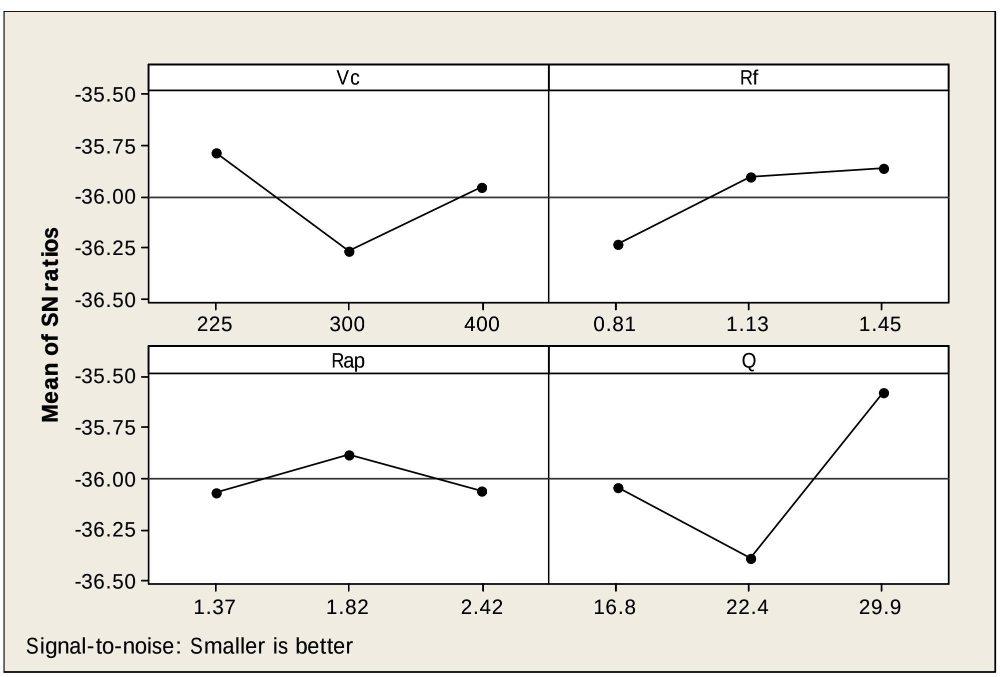


Fig. 4. 1. S/N Ratio analysis for average flank wear

Meanwhile, in this study, higher feed per tooth provided lower tool wear. This is acceptable due to the influence of the edge radius. A lower ratio of feed per tooth to edge radius makes the end milling process undergo a ploughing action that leads to higher cutting energy hence higher tool wear [144]. The higher feed per tooth ratio used in this study provided lower average flank wear; as the ratio of feed per tooth to edge radius used in this study (i.e. 0.062 mm) was higher than one, this implies a more positive rake angle and more efficient chip formation process.

In terms of reducing flank wear, the results of ANOVA (Analysis of Variance) (Table 4.3) show that volumetric flow rates make the highest contribution (60%) followed by cutting speed (21%), feed to tool edge radius ratio (15%) and depth of cut to tool edge radius ratio (of 5%). The dominance of MQL is evident from the large graph gradient. This dominance by MQL reflects the fact that the lubricant reduces friction hence lowering cutting tool temperature and promoting longer tool life.

Table 4.3 ANOVA result for average tool wear

Source	Df	SS	MS	F	Contribution (%)	P
Vc	2	37.8	18.88	2017	20%	1E-12
R_{fz}	2	26.1	13.07	1396	15%	6E-12
R_{ap}	2	8.2	4.11	439	5%	1E-09
Q	2	107.1	53.57	5723	60%	0.000
Error	9	0.1	0.01		0%	1.000
Total	17	179.35	89.64		100%	

Moreover, a subsequent analysis was carried out to predict the possible minimum average flank wear that can be achieved using the suggested optimal settings. By utilising the statistical software MINITAB 15.03, it was found that the minimum value for average flank wear was 56.60 µm. The result is similar to the statistical prediction calculation that was done manually using a 95% confidence level. A confirmation test was then performed and the actual minimum value for average flank wear using the optimum setting was measured at 50 µm. Therefore, compared to the initial experiments, a 13.8 % decrease in flank wear was achieved by applying the optimum setting as was predicted by the Taguchi method.

4.3.2 Importance of key process variables on surface roughness

Surface roughness is one of the important indicators for quality in a machining process. In this investigation, the measured values Ra are shown in Table 4.4 and the S/N ratio is shown in Fig. 4.2. Both sets of data show that a combination of moderate cutting speed, low feed per tooth to tool edge radius ratio, low depth of cut to tool edge radius ratio and a low volumetric flow rate contribute to a better machined surface finish.

Table 4.4 Experimental design and average surface roughness response

Vc (m/min)	$\mathbf{R_f}$	$\mathbf{R_{ap}}$	**Q** (ml/h)	**Ra_average** (μm)
225	0.81	1.37	16.80	0.232
225	1.13	1.82	16.80	0.363
225	1.45	2.42	16.80	0.491
300	**0.81**	**1.82**	**29.90**	**0.223**
300	1.13	2.42	16.80	0.310
300	1.45	1.37	22.40	0.329
400	0.81	2.42	22.40	0.379
400	1.13	1.37	29.90	0.353
400	1.45	1.82	16.8	0.453

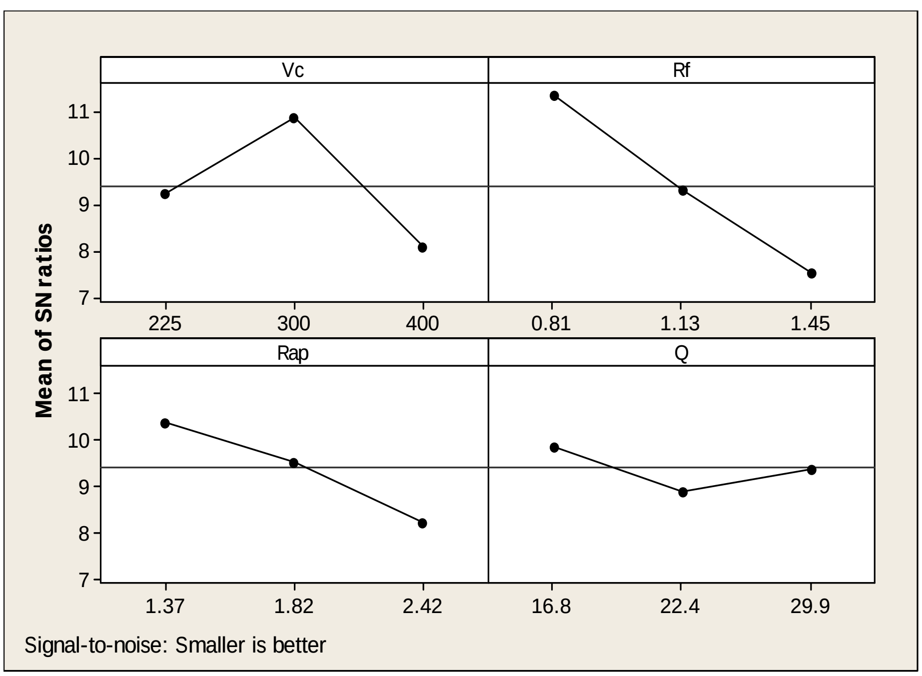


Fig. 4.2. S/N Ratio analysis for surface roughness response

In finishing operations, in order to produce superior surface finish, the quantity of cutting fluid is less critical as indicated in the ANOVA Table 4.5. This supports Da Silva and Wallbank [145] who concluded that only a small quantity of lubricant is required to remove adhering broken off BUE out of the machined surface. The ANOVA analysis result shows that controlling feed per tooth to tool edge radius ratio followed by cutting speed and depth of cut-tool edge radius ratio is the priority to improving the surface finish. The need for a low ratio of feed per tooth to the tool edge radius supports the improvement in surface finish that is obtained by a trade off between shearing and ploughing based cutting modes. This is also associated with the polishing effect.

Similarly, the predicted minimum surface roughness was 0.157 μm Ra and the confirmation cutting test result was 0.150 μm Ra. Thus, comparing the best results from the initial experiment and from the predicted optimum setting, a 33% improvement in surface roughness can be obtained.

Table 4.5 ANOVA result for surface roughness

Source	**Df**	**SS**	**MS**	**F**	**Contribution (%)**	**P**
Vc	2	0.04	0.02	6.3	24%	0.019
R_{fz}	2	0.07	0.03	11.2	42%	0.004
R_{ap}	2	0.02	0.01	4.1	15%	0.055
Q	2	0.00	0.00	0.4	2%	0.666
Error	9	0.03	0.00		17%	
Total	17	0.15	0.07		100%	

4.4. Conclusions

The motivation for this study was to establish optimum cutting conditions for effective machining of tool steel, H13 under MQL conditions. To achieve that objective, experimental design using Taguchi's method was utilised. The following conclusions can be drawn:

- The rate of flank wear in MQL machining is highly sensitive to the quantity of MQL. This is more dominant compared to the impact of cutting speed, feed per tool and depth of cut. In this study, the highest quantity of MQL gave the lowest wear rate.
- In finishing passes, the ratio of feed per tooth to tool-edge radius is the dominant factor to be manipulated in order to significantly reduce surface roughness. This

is so when compared to changing cutting speeds or depth of cut to tool-edge radius ratio or quantity of MQL.

- A strategy for MQL machining of tool steel is to undertake roughing passes at higher feed per tooth and moderate cutting speeds using the maximum quantity of MQL. The finishing pass operation can use the lowest feed per tool in order to exploit the size effect for improving surface roughness.
- The confirmation test results for the optimum setting obtained by the use of Taguchi's method for surface finish has highlighted the possibility of obtaining sub-micron surface roughness of 0.150 µm Ra when machining tool steel.
- The fact that the optimum MQL quantity reported in the study was at the highest level tested suggests that there could be tool wear reduction benefits when setting MQL flow rates at values more than 29.9 ml/hour. This range was not evaluated because 29.9 ml/h was the highest flow rate in the system used. This system is also representative of what is used in industry on the Mikron HSM 400 machine.

CHAPTER 5

RANDOM OR INTUITIVE NOZZLE POSITION IN HIGH SPEED MILLING (HSM) USING MINIMUM QUANTITY LUBRICANT (MQL)

Abstract

High speed machining, the need to reduce environmental impact and manufacturing cycle time has promoted the use of minimum quantity lubricant (MQL) in mechanical machining. However, in MQL, where a small quantity of cooling lubricant is delivered to the cutting zone, the sensitivity of machining performance to nozzle position has hardly been explored in research or noted in industrial practice. In this study of conventional versus high speed machining, the focus was on a systematic study of the effect of nozzle position on tool wear. The study elucidates the effect of spindle rotation speed on the sensitivity of nozzle location in order to enhance machining performance. The work provides some fundamental information regarding the position and orientation of the nozzle in order to maximise the benefits of machining using minimum quantity lubricants. This work is of significant importance for the repeatability of MQL machining operations, and to promote longer tool life in particular for machine shops where nozzles are currently randomly oriented to the cutting zone.

Keywords: minimum quantity lubrication, nozzle position, high speed machining, end milling, tool wear

5.1 Introduction

Historically, machine shops have predominantly employed cutting fluids. As coolant and lubricant, cutting fluid improves machining process performance. Cutting fluids play a significant role in reducing cutting temperature and lowering friction on the interfacial surfaces of a cutting process system (e.g. tool-workpiece interface and tool-chip interface). These interfaces generate heat. Coolant and lubricant cutting fluids contribute to prolonging tool life, obtaining better surface finish and minimising the geometrical error in machined parts. In addition, when cutting fluid is delivered to the cutting zone at high volume and high pressure, it helps to flush chips from the cutting zone. This reduces re-machining of strain-hardened chips and promotes better machining performance.

The superior advantages gained by using cutting fluid have induced uncontrolled use in delivery and the use of copious amounts of fluid. However, the need to reduce thermal shock, the rise in environmental concerns, also linked to the impact of cutting fluid usage on the environment, as well as strict regulation for disposal of cutting fluid waste by a number of industrialised countries has attracted interest in the development of machining processes that avoid the use of cutting fluids [146 - 148]. Alternative strategies are dry machining and near dry machining. Full implementation of dry machining is limited by the need to reduce friction and thermal load [33]. Development of coating materials and a shift to near dry machining technology bridges the gap while alternative methods to flood coolants are developed. One of the most promising near dry machining methods is minimum quantity lubrication (MQL). In MQL, the volume of cutting fluid delivered to the contact zone can be significantly reduced to 1 ml/h [145].

In flood coolant applications, large volumes of cutting fluid are delivered around the machining area, therefore, the possibility of cutting fluid penetrating all the critical interfaces is high. As such, the direction of the nozzle is usually not critical. However, in one study, Diniz and Micaroni [146] found that when using high pressure and high-flow rates, positioning the nozzle towards both flank face and rake face simultaneously was beneficial for prolonging tool life in comparison with directing the nozzle toward only one of the faces. Later, Rahman et al [147] postulated the importance of nozzle position for improving MQL performance.

5.1.1 *MQL supply parameters*

The ultimate goal of using cooling/lubricating media in a machining process is to reduce cutting temperature and friction as much as possible. This becomes the greatest challenge in respect of the MQL method due to the restricted amount of cutting fluid delivered during the cutting operation. Ueda et al [6] measured the tool temperature in end milling by using a two-colour pyrometer embedded in annealed AISI 1045 steel workpiece material. Two nozzles were used to cool down the workpiece-tool contact area. The nozzles were located at a 45^{o} angle (e.g. position B) and 135^{o} angle (e.g. position A) and positioned 50 mm away from the contact point of tool and workpiece material (Figure 5.1).

The result showed locating the nozzle at position A gave a temperature value 50^{o} C lower than locating the nozzle at position B. They assumed that at A, a large amount of oil droplets adhered to the tool face during the cutting process acting as a coolant. While in position B, some of droplets may blow away from the cutting point and decrease the percentage of oil droplets acting as a coolant at the cutting point. Other plausible explanations for the lower cutting temperature when the nozzle is in position A is that in this position the tool has undergone a significant temperature reduction before entering the engagement point and this condition could help the oil droplets to provide effective cooling. Meanwhile in position B, the tool is still experiencing higher temperatures. Oil droplets delivered are only able to reduce the tool temperature when the tool actually enters the engagement point. Taking into account the direction of the tool rotation, Figure 1 shows that position B is the tool exit position. Thus, their work suggested that nozzles should not be located close to the chip evacuation path.

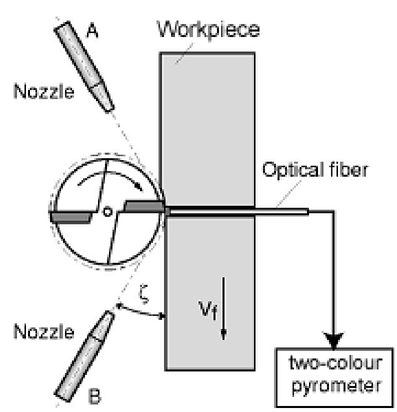


Figure 5. 1 Nozzle position in end milling [6]

Sasahara et al [7] came to a different conclusion about the effect of the nozzle position in high speed cutting of S45C material. They found that spraying the cutting fluid at the exit point (disengagement point) resulted in the longest tool life due to elimination of chip adhesion. Yuan et al [8] evaluated the effect of the nozzle position in an end milling process of 50CrMnMo; a structured alloy steel. The position of 60 degrees away from the disengagement point led to prolonged tool life. Meanwhile, a modelling approach to evaluate tool wear in near dry turning suggested that the nozzle should be directed onto the rake face to give the longest tool life for cutting high-strength low alloys [143]. In contrast, it was suggested that the nozzle position could be ignored when cutting Ti-6Al-4V material since no significant variation in cutting force and cutting temperature was experienced by changing the position of the nozzle [103].

Referring to previous findings described above, it seems that there are some conflicting recommendations regarding nozzle location. One study suggested positioning the nozzle at the tool disengagement point (exit point); however, it could be argued that this zone should be free of interference, as MQL pressure would hinder chip evacuation. This area is where the chip evacuates and chip removal is critical for MQL process effectiveness. Lopez de Lacalle et al [9] simulated the spraying effect of cutting fluid using computational fluid dynamics (CFD) software and concluded that the nozzle should be located before the tool engages the workpiece material to ensure the MQL jet reaches the tool edge.

The location of the nozzle has to balance the need for effective MQL fluid delivery (fluid trapping), the requirement not to retard chip evacuation and the effect of MQL application on the thermal regime and safety considerations.

5.1.2 *Research motivation*

When minimum quantity cutting fluids are used, the delivery of the fluid and hence, the position of the nozzle is important [147, 148] in order to maximise the benefits derived from limiting the volume of cutting fluid. There was no consensus in literature regarding the optimum position for MQL nozzles. Neither was there significant awareness that this is a key process variable in industrial machining. The motivation for this work was to determine the effect of nozzle position in high-speed milling of tool steel in order to maximise the benefits of using MQL.

5.2 Research Method

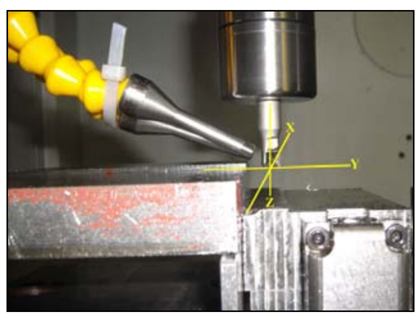
Cutting tests were performed on a Mikron HSM 400 high speed-milling machine to evaluate the best location for the MQL nozzle. The material used in this study was a 150 mm by 100 mm by 100 mm block of H13 tool steel. Initially, cutting tests were conducted on the workpiece material in its ‘as-delivered’ state; and in this condition, the hardness was measured to be 13 HRc. The second test was performed on the material after the hardness had been increased to 45 HRc achieved by vacuum heat treatment. The cutting inserts were PVD TiAlN coated supplied by Iscar with code name IC928. The geometry for the inserts was SOMT060204-HQ. The inserts were mounted on an ISCAR 8 mm diameter tool holder E90XD08-C10-06. This tool holder accommodates only one insert. This was specifically selected in order to study the process in single tooth cutting mode. The cutting speed was varied from 350 m/min to 700 m/min, following the manufacturer’s recommendations for the type of inserts used in this experiment. This range of cutting speed spanned the transition to the high cutting speed region as defined by Schulz and Moriwaki [23]. The feed per tooth (f_z) and axial depth of cut (a_p) were kept constant at 0.05 mm/min and 1.5 mm respectively. A width of cut of 4 mm for the ‘as received’ workpiece condition was used and this was reduced to 0.6 mm for the harder workpiece to take into account the greater machinability challenge. The selected feed per tooth and depth of cut were considered in order to minimise tool wear rate especially when the cutting speed is increased to high-speed. In addition, the low chip load avoids higher cutting forces [25].

For the end milling of the H13 workpiece material using the MQL application, 29.9 ml/h of high-performance lubricant UNILUB 2032 (lubricant properties are specified in Table 5.1) was delivered to the cutting interface using a pressure of 4 bars (e.g. maximum operating pressure for MQL system used in this study is 8 bars). The quantity of cutting fluid delivered was verified by collecting the delivered fluid in a container for a monitored duration. The 29.9 ml/h flow rate used was the highest possible on the machine and this value was found to be the best in terms of tool wear performance based on a prior Taguchi process optimisation [149]. End milling was performed twice for every experimental run.

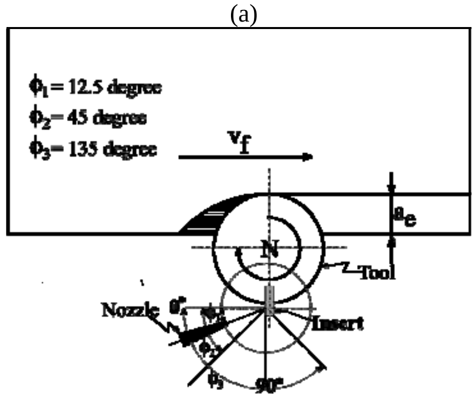
Table 5. 1 Properties of high-performance lubricant UNILUB 2032

Pour point	< -30 ^{o}C
Flash point	> 250 ^{o}C
Vapour pressure	< 0.1 kPa
Density (at 20 ^{o}C)	0.902 g/ml
pH-value aqueous solution (at 20 ^{o}C)	5.6
Viscosity (at 20 ^{o}C)	56 mm^2/s
(at 40 ^{o}C)	22 mm^2/s

In this study, the nozzle was held in a constant position 60 degrees to the spindle and tool axis as shown in Figure 5.2a. From the workpiece end milled face and the tool entry point the nozzle was located at 12.5^{o}, 45^{o} and 135^{o}. The set of nozzle positions are illustrated in Figure 5.2b. The nozzle discharge tip was positioned 4 mm away from the tool to avoid increasing the spraying angle that can lower the fluid particle pressure hence minimising effective application of MQL [150]. A longer distance also promotes excess mist [151]. The nozzles were aligned in these positions to enable assessment of the fluid trapping effect and the need to avoid obstruction of chip evacuation by the MQL jet.



(a)



(b)

Figure 5. 2 (a) Nozzle position relative to spindle axis and (b) nozzle position relative to tool entry position and workpiece end milled face

In this study, the nozzle was not located towards the exit side or tool disengagement point. The highest temperature of the tool was reported to be at the tool exit point [152, 153] and avoiding this point helps to reduce the chances of the tool experiencing thermal shock and cracking [154], it also ensures that the fluid flow does not hinder chip evacuation. Additionally, at the tool engagement point it is difficult to maximise the fluid trapping as fluid is carried away by the rotational force.

A Leica optical microscope was utilised for taking images of the tool clearance face and flank wear. Average tool wear was measured for two experimental runs for each test condition. This was done using AxioVision Rel 4.8 image-processing software. In evaluating the tool life, the tool wear criterion was set at 0.3 mm of average flank wear [133]. Meanwhile, a Hitachi Scanning Electron Microscope, S-3400 N was utilised for capturing details of the condition of flank face and rake faces.

5.3 Results and Discussions

5.3.1 *Nozzle position impact on tool wear and tool life H13 steel in annealed state*

Figure 5.3 shows the tool wear and tool life as a function of nozzle location for a spindle speed of 13,934 rpm (i.e. equal to a cutting velocity of 350 m/min). The nozzle was located at three different positions of 12.5°, 45° and 135° from the tool-workpiece initial engagement side.

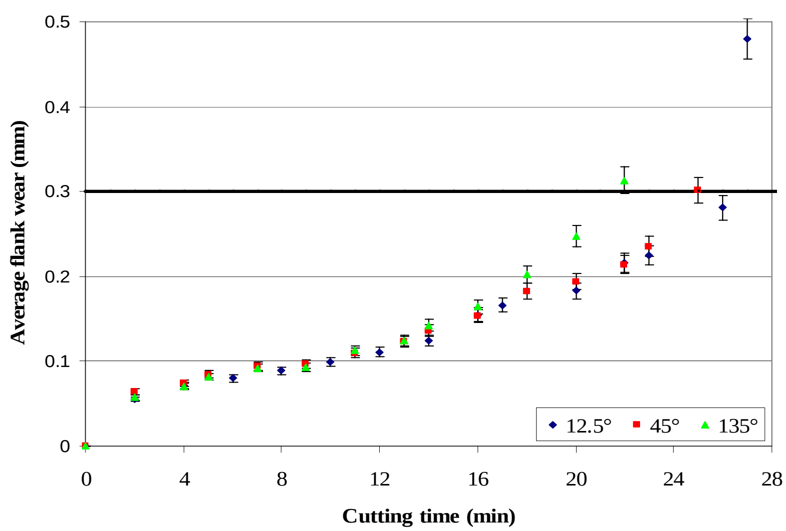


Figure 5. 3 Nozzle position and tool wear progression under MQL application at 13,934 rpm

The results show that when 135° was used, flank wear increased faster than when the other smaller angles were used. This is particularly evident from 16 minutes to 27 minutes of cutting time. In principle, the closer the nozzle is located to the sidewall of the workpiece material the better the tool performance in terms of tool wear. When the MQL fluid is applied to the surface of a cutting tool, it follows the momentum of the tool. Aligning the nozzle closer to the entry point of the cutting tool helps trap the fluid, thus providing the lubricating action. Figure 5.3 also shows that the location of the nozzle is more critical in extended periods of cutting, when the tool has experienced advanced wear and its cutting effectiveness is reduced. This is evident from data points diverging at longer cutting times.

5.3.2 *Effect of nozzle position when machining hardened H13 workpiece material*

The study described in the previous section showed that when machining annealed tool steel, the nozzle should be positioned toward the rake face and closest to the workpiece sidewall at the tool entry position. A follow-on study was done based on hardened tool steel and assessing the 12.5 and 45 degree positions which had given better and comparable tool wear performance when machining the as received tool steel. The 135-degree having shown a higher wear rate was not pursued. In many applications, such as dies and moulds, the tool steel workpiece is in a hardened state. Hot-work steel is extremely tough and has the ability to withstand wear and cracking. Hardening this type of tool steel can result in more challenging machinablity. Figure 5.4 shows the tool wear progression in respect of the two nozzle alignment angles when machining hardened tool steel.

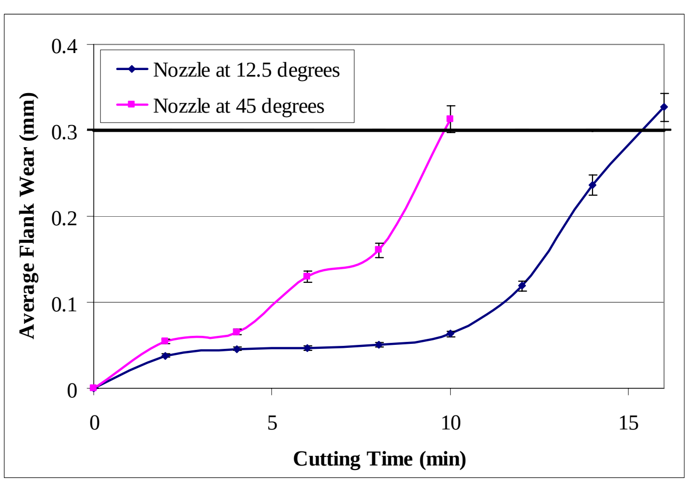
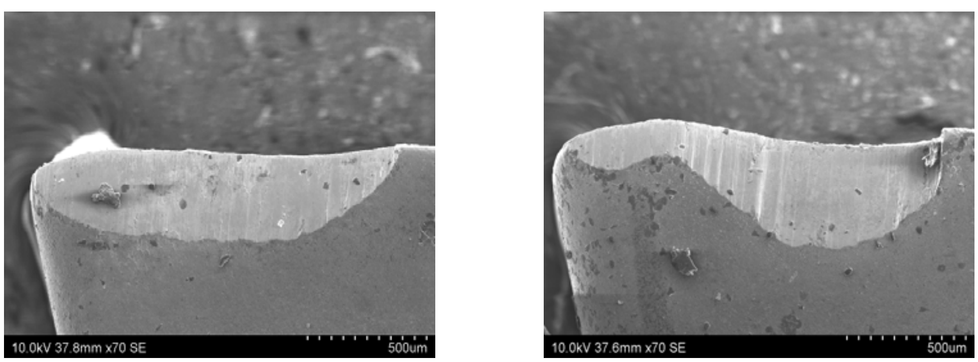


Figure 5. 4 Effect of nozzle positions in end milling of hardened H13 tool steel at 13,934 rpm

If Figure 5.4 is compared to Figure 5.3, the reduction in tool wear rate and tool life due to the increased hardness of the workpiece material is evident. When the material was hardened to almost four times its annealed state (from 13 HRc to 45 HRc), positioning the nozzle closer to the workpiece face at an angle of 12.5^o significantly improved tool life in comparison to orienting the nozzle at an 45^o angle. Thus, simply shifting the nozzle from a 45^o angle to a 12.5^o angle at the end-milled face leads to a massive 55% increase in tool life. When machining hardened steel, the temperature is quite high and in this case, the nozzle position appears to be very critical and a dominant key process variable (KPV) that has to be controlled. This is a step change in the knowledge of process behaviour, as the nozzle position is rarely considered critical in machining.

In order to explore why the 12.5^o angle prolonged tool life performance in comparison to an angle of 45^o, an analysis using SEM microscopy was conducted. The flank face and rake face were examined and these images are shown in Figure 5.5 and Figure 5.6 respectively. Figure 5.5 reveals that, with the nozzle angled at 12.5^0, flank wear had a uniform pattern along the depth of cut line; when the nozzle was angled at 45^o, the pattern was irregular and became enlarged close to the end of the depth of the cut line. In addition, in Figure 5.5b, a sharp notch is distinct at the flank face of the cutting tool for MQL with the nozzles at a 45^o angle. The images show that locating the nozzle closer to the workpiece appears to result in uniform tool wear. This could suggest improvements in lubrication and/or cooling effect.



(a) (b)

Figure 5. 5 SEM images of flank face after cutting exposed by cutting fluid from nozzle at position (a) 12.5^o and (b) 45^o

Closer observation of the rake face, as depicted in Figure 5.6, shows that the lower the angle of the nozzle the more uniform the tool wears. For machining harder tool steel workpiece material, a more effective supply of lubricants is required.

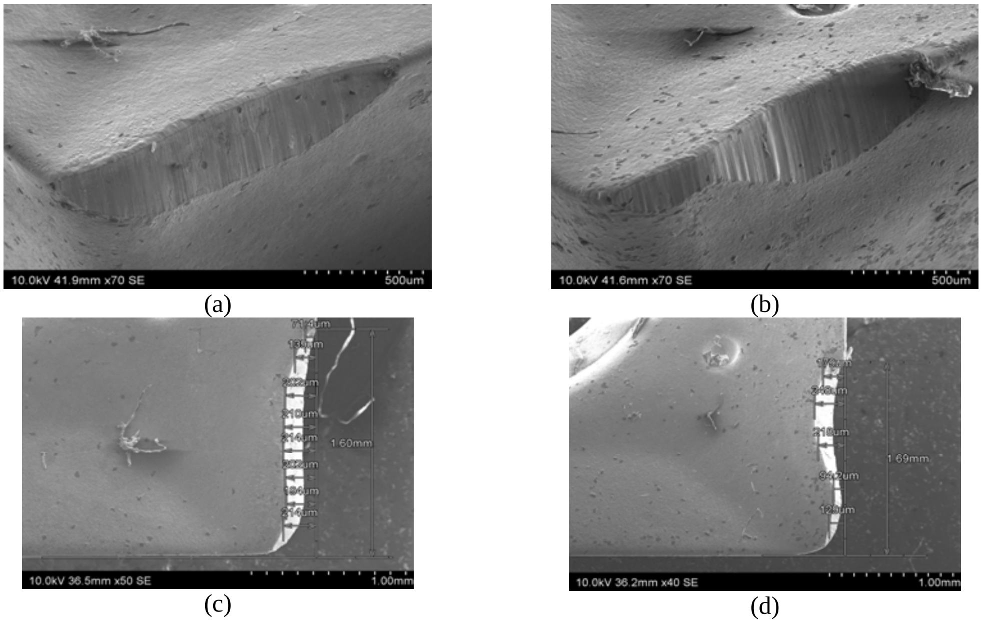


Figure 5. 6 SEM images of TiAlN insert after machining after MQL delivered from different positions. (a) 3D insert image for insert used at 12.5°, (b) 3D insert image for 45°, (c) image of the rake face for 12.5° and (d) image of the rake face for 45°

5.3.3 *Assessment of fluid trapping at different nozzle positions*

The effect of the rotation of the tool on fluid trapping was investigated using the method illustrated in Figure 5.7. This involves the use of a fluid soaking device (sponge) to assess the quantity of cutting fluid delivered to a particular location. In the method, the volume of droplets trapped in sponge 1 (representing the sidewall of machined workpiece material) and sponge 2 (parallel to the feed direction) was quantified. The distance from outer diameter of the rotating tool to both sponges was kept constant at 4 mm and similar to the cutting tests. This offset was useful to make sure that the tool would not cut or push the sponge.

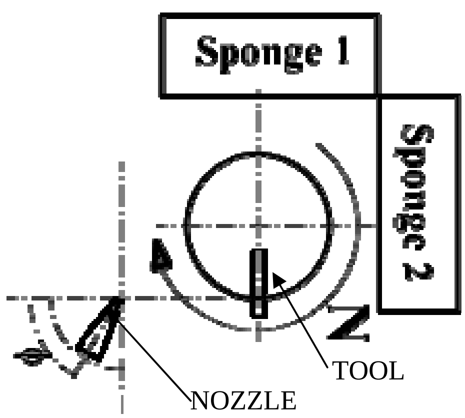


Figure 5. 7 Method for quantifying MQL fluid trapping

Initially the weight of the sponges was recorded and then the spindle was run at selected rpm with the nozzle directed to different orientations. The quantity of fluid collected by the sponge was evaluated from the measured mass of the fluid soaked sponge minus the dry sponge. The weight measurement for the sponges was done using a weight balance that had an accuracy of one milligram.

The fluid trapped in the sponges at both directions was measured after running the MQL nozzle flow for 30 minutes. Figure 5.8 shows the fluid trapped for different positions when running the spindle at 13,934 rpm. For each set, the experiment was conducted twice and there was very little variation between the repeats as shown in the range bars in Figure 5.8.

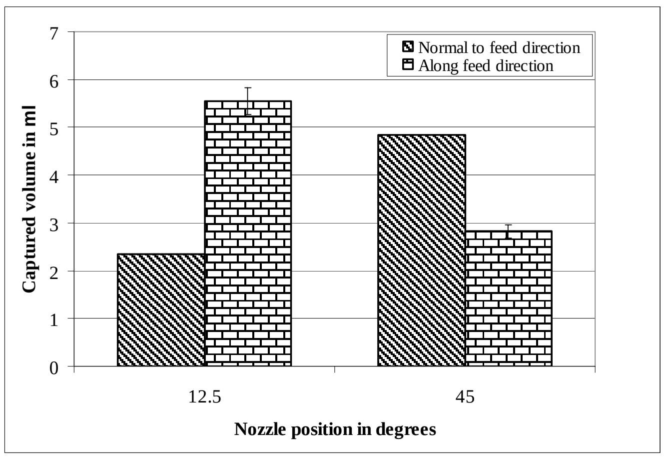


Figure 5. 8 Effect of different nozzle positions on the possibility of fluid trapping using a rotational speed of 13,934 rpm

From Figure 5.8, it is clear that by positioning the nozzle at an angle of 12.5^o relative to the feed direction there is more possibility that the rake face will receive more lubrication rather than when the nozzle is positioned at a 45^o angle while using a rotational speed of 13,934 rpm. This is intuitively reasonable because at the lower angle to the entry position more fluid is directed onto the tool engagement point thus increasing the chance of MQL effectiveness. Thus, better fluid trapping supports improved tool life performance at 13,934 rpm when using a 12.5-degree angle orientation of the nozzle from the entry point and cutting plane. This can increase the effectiveness of the cutting fluid.

5.3.4 *Effect of rotational speed on nozzle position of hardened H13 material*

High rotational speed was identified as a key factor that influences the performance of the MQL application [4, 102]. Figure 5.9 shows the effect of increased rotational speed to 27,867 rpm on tool wear progression. In this study, the nozzle was located at an angle of 12.5^o toward the rake face, close to the end-milled face and tool entry position. This position was the most suitable for providing the longest tool life at a rotational speed of 13,934 rpm according to previous results. As can be seen in Figure 5.9, flank wear at a cutting speed of 700 m/min rapidly increased after 2.8 m into the cutting length. The results illustrate the difficulty of introducing cutting fluid to provide a lubricating action when the spindle is operated at high frequency. Additionally a higher cutting speed would lead to higher cutting temperatures and this can activate and or accelerate wear modes.

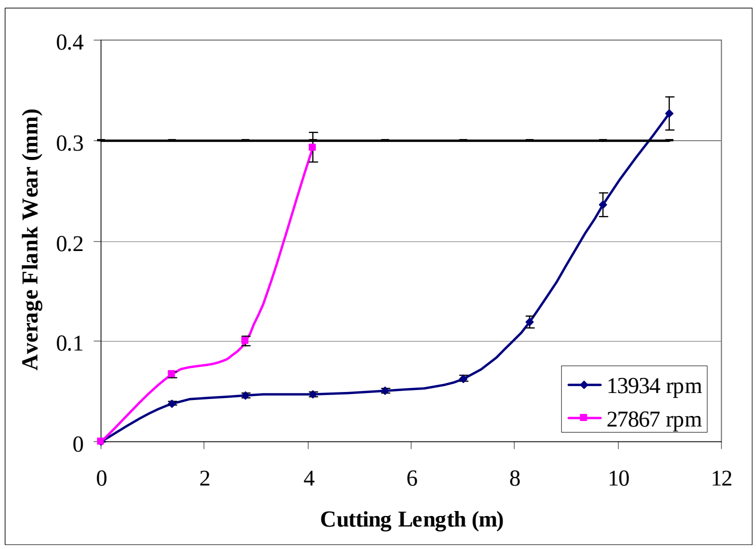


Figure 5. 9 Effect of rotational speed on tool wear progression using a 12.5^o nozzle orientation

In order to explore process improvement, the nozzle was re-aligned in four different positions located further away from the engagement point: at 25^o, 35^o, 45^o and 60^o. The average tool life for these new measurements can be seen in Figure 5.10. Employing the nozzle position at 45^o achieved a tool life of approximately 5.7 minutes, which is higher compared to the other positions (i.e. 12.5^o, 25^o, 35^o, and 60^o). These other positions attained tool life of 2.9 minutes, 3.8 minutes, 4.7 minutes and 2.3 minutes respectively. This improved result can be partly explained by the wiping effect being a dominant mechanism for transporting lubrication to the rake face. In addition, the wiping effect was supported by the appropriate penetrating angle for fluid delivery; which in turn can guarantee fluid particle trapping on the rake face. This theory was explored by using a similar method as described in Section 5.3.3. The results are shown in Figure 5.11 where the angle of 45 degrees resulted in the largest amount of fluid trapped.

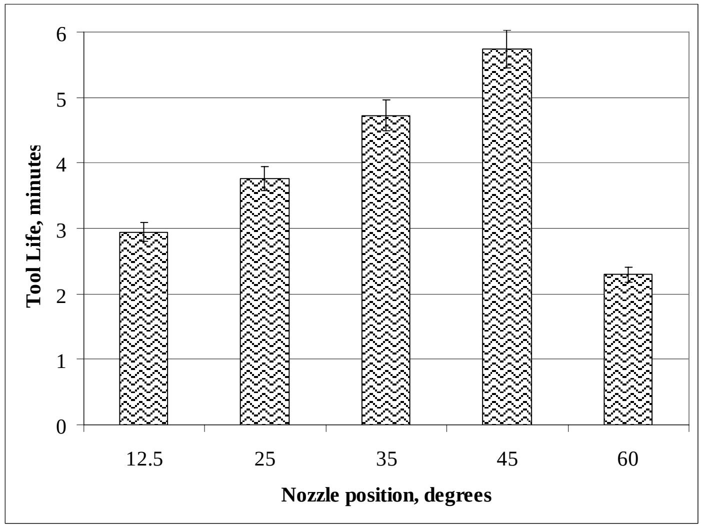


Figure 5. 10 Tool life using different nozzle positions at a rate of 27,866 rpm

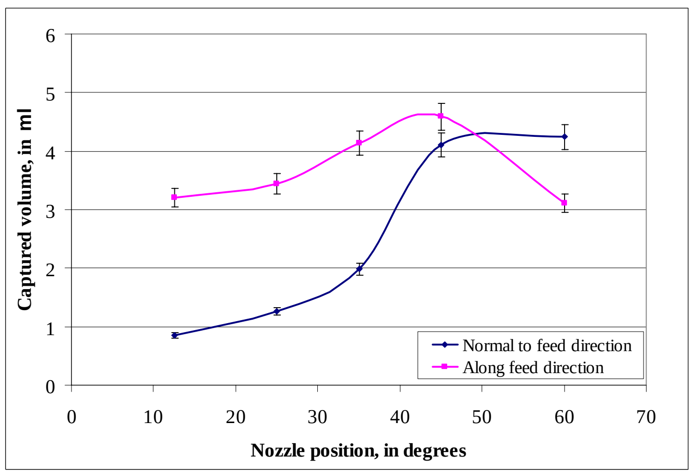
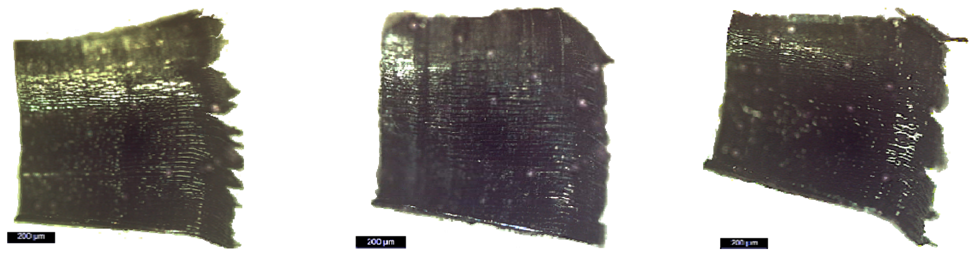


Figure 5. 11 Effect of different nozzle positions on the possibility of fluid trapping using rotational speeds of 27,868 rpm

The results shown in Figure 5.11 support the results shown in Figure 5.10. The quantity of MQL delivered to the cutting zone is important. In milling, the spindle frequency is high and fluid is delivered over a shorter time window according to the nozzle orientation. Increasing the nozzle angle compensates for the reduced trapping time and reduced trapped volume that is experienced at higher rpm. This strategy is only valid at acute angles where trapping is effective. This explains why 60 degrees is worse compared to 40 degrees and 12.5, 25 and 35 degrees are worse compared to 45 degrees at higher rpm as shown in Figure 5.10. The tool wear results in Figure 5.4 and 5.10 agree and are supported by the fluid trapping data in Figure 5.8 and 5.11.

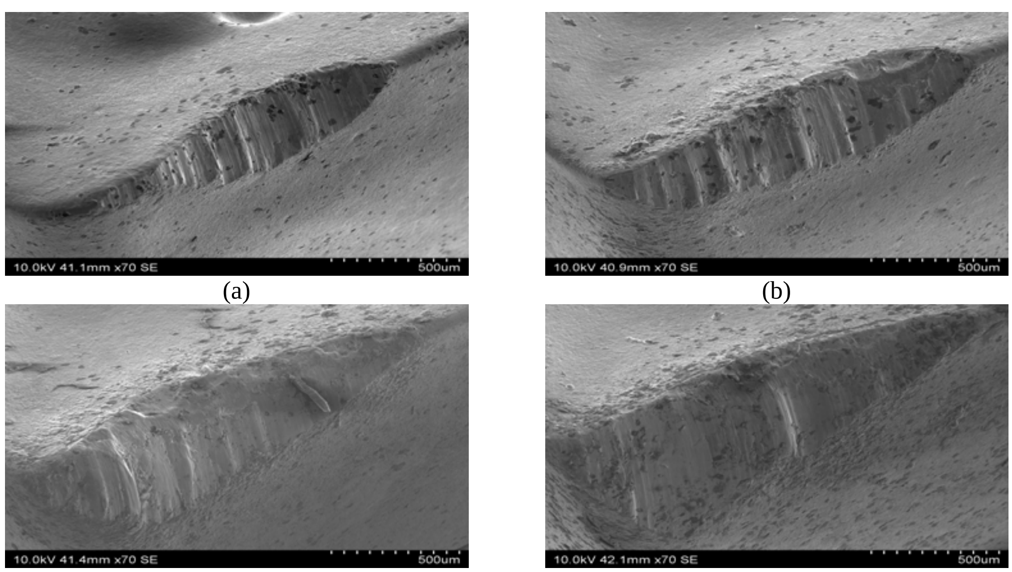
In addition, interesting characteristics in Figure 5.12 were observed from the morphology of the chips produced by end milling using nozzles at position of 35^o, 45^o and 60^o. At nozzle position of 35^o and 60^o, end milling produces segmented chips compared to at position of 45^o where the optimum tool life was achieved. The cases were segmentation occurred could be linked to increasing the chip-tool interface temperature due to high friction force generated on the tool rake face [155]. Thus, it is conceivable that effective lubricating action and better thermal control was obtained by aligning the nozzle at a position of 45^o.



(a) (b) (c)

Figure 5. 12 Image of the chip produced by end milling using nozzle at position (a) 35^o, (b) 45^o and (c) 60^o

To add further insight into the cutting tool's performance at the highest cutting speed, microscopy analysis was undertaken on the inserts using SEM and the observed images of the flank face and the rake face of the inserts are shown in Figure 5.13. Again, the best tool life performance is linked to uniform wear patterns thus supporting effective lubricating action.



(c) (d)

Figure 5. 13 SEM images of flank face of the insert used for end milling with nozzle position at (a) 12.5^o, (b) 45^o, (c) 35^o and (d) 60^o at 27,866 rpm

5.3.5 *Effect of increasing the fluid delivery pressure on tool wear progression*

To observe the effect of increased fluid pressure at different nozzle orientation, a subsequent test was carried out where the fluid delivery pressure was increased to the maximum pressure (i.e. 8 bar). The tool wear progression using the higher pressure is plotted in Figure 5.14 alongside to that at 4 bar. From the graph, there is no strong evidence that increasing MQL pressure can significantly prolong tool life. Thus, changing the nozzle position is a more effective and more important strategy for increasing tool life than supplying MQL at higher pressure.

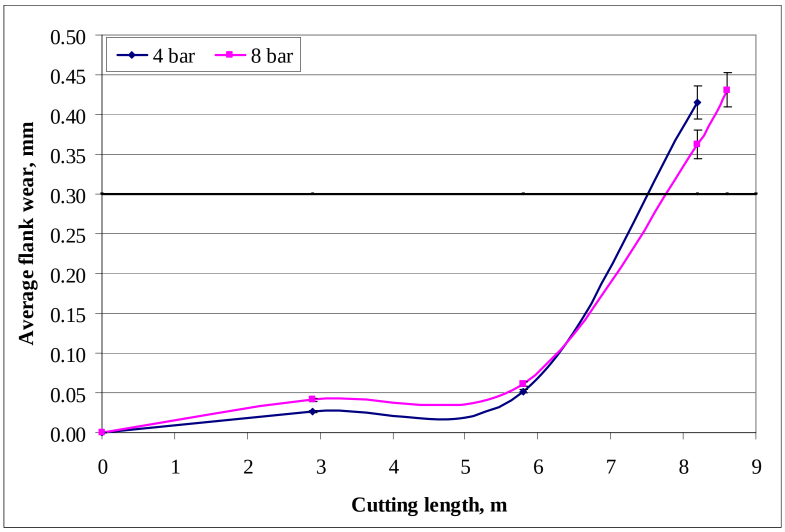


Figure 5. 14 Effect of increased fluid delivery pressure on tool wear progression

5.4 Conclusions

An investigation was conducted to study the effect of nozzle position on tool life in end milling of tool steel. This study yielded some important findings that could be transformative in improving the ability for controlling machining performance and improving the effectiveness of MQL in the machining processes.

- In mechanical milling of tool steel in an annealed state, using MQL, there was some benefit for extending tool life by locating the nozzle closest to the end-milled face and tool entry point. This supports effective fluid delivery through a trapping action. For hardened tool steel (45 HRc), moving the nozzle from a 45^{o} back to a 12.5^{o} angle increased tool life by 50%. Thus, the position of the MQL nozzle is a critical process variable that needs to be controlled in end milling hardened tool steel.

- The quantity of fluid collected by a soaking device aligned to the tool feed plane, positively correlated with tool wear observations in MQL. Thus to improve the effectiveness of MQL in machining it is important to ensure that the maximum cutting fluid volumetric flux is delivered to the tool entry point and feed plane.
- The wiping effect and penetrating angle are predominant factors in the effective delivery of MQL at high rpms. Positioning the nozzle at a 45^o angle relative to the rake face and tool entry position doubled tool life compared to 12.5^o and other positions (25^o, 35^o and 60^o). Thus, when machining at high and ultra high spindle speeds the nozzle needs to be rotated away from the workpiece feed plane. This can deliver a high volume of fluid particles to compensate for the short tool-workpiece interaction time.
- The optimum location of the nozzle, in relation to the rake face, correlates well with uniform flank wear land.
- The nozzle position in MQL end milling of hardened tool steel at high spindle speeds is a critical consideration, which significantly affects tool life and machining performance. The nozzle should be not randomly positioned.

CHAPTER 6

TOOL LIFE AND ENVIRONMENTAL BURDEN ANALYSIS OF MILLING PROCESS USING MINIMUM QUANTITY LUBRICANT (MQL) CONDITIONS

Chapter Synopsis

Limited availability of natural resources and the negative environmental burden of industrial processes are driving environmental awareness and resource efficiency improvements in manufacturing. Issues of concern in mechanical machining arise from the significant use of electrical energy and oil-based coolants/lubricants. Process innovation through high speed machining has enabled manufacturing cycle times to be reduced and in some cases promoted dry machining or the use of minimum quantity lubrication. However, the environmental assessment of these innovations has hardly been explored. In this study, the tool life performance in machining tool steel using dry, flood coolant and minimum quantity lubrication (MQL) were evaluated. The work then assessed the energy and hence the environmental burden of these three machining lubrication alternatives. The work is fundamentally important in assessing the direct energy and the environmental credentials of machining processes.

6.1 **Introduction**

A mechanical machining process is performed on a machine tool, which can be viewed as an energy converter, converting electrical energy into mechanical energy required for machine tool motion and the chip formation process. The amount of electrical energy used to run a machine tool is very substantial. The electrical energy can be generated from either renewable or non-renewable energy sources. Most electrical energy is derived from non-renewable energy sources such as crude oil, coal and gas (i.e. fossil-fuel resources). As demand increases along with industrial activity, the availability of non-renewable energy sources becomes a critical issue. For example, in the UK, the Department of Energy and Climate Change reported a 3.6% increase in energy consumption in 2010 [156]. However, this increasing demand was not matched by an increase in the production rate for primary fuel required for energy generation, in fact the total production of primary fuel in the UK declined by 6.8%.

The energy used by a process can be linked to the CO_2 footprint derived during the generation of energy. Jeswiet and Kara [157] presented a model to evaluate carbon emissions as shown in Equation 6.1. In this equation, the "Carbon Emission Signature" (CES^{TM}) is used to determine energy generation derived carbon emission which is measured in kg of CO_2.

$$\text{Carbon emissions } [kgCO_2] = E_{part}\ [kWhr] \times CES^{TM}\ [kgCO_2/kWhr] \qquad (6.1)$$

where E_{part} is the energy consumed to produce a component or manufactured product and CES^{TM} is the carbon emission signature as calculated for the energy mix. The UK uses an "average carbon intensity factor for electricity fixed at 0.43 kg-CO_2/kWhr" [157]. Thus, reducing energy demand contributes to energy efficiency, cost control and improved environmental performance through reduced CO_2 emission [158].

In machining, sustainability can be addressed through reduction in energy consumption, longer tool life and improved functional quality of machined products through surface integrity performance [159]. The use of copious amounts of cutting fluid in machining must be taken into consideration as well. It is not only because of its waste disposal but also its effect on the health of machine operators and shop floor workers [44, 46]. The environmental burden of cutting fluid can be assessed through measures of ecotoxicity, acidification, human toxicity, eutrophication and photochemical oxidants [10]. It is assumed that to reduce the environmental burden of cutting fluid, dry and minimum quantity lubrication could be the alternatives [32].

Energy efficiency and restricting the use of cutting fluid are key challenges facing scientists and machinists developing sustainable machining processes. The machining process is complex and hence, analytical methods are important in assessing energy efficiency as well as the environmental burden of a machining process [160]. The models have to be able to capture the relationship between the process parameters and the outcomes [127].

*6.1.1 **Energy modelling in machining***

There are a number of models now emerging for the evaluation of power and hence, energy requirements in machining processes. Kara et al [123] and Neugebauer et al [161] used the specific cutting energy of machining processes in determining cutting process energy efficiency. While these models can be useful in comparing the machinability driven aspect of energy efficiency, the models in themselves do not separate the chip removal process (tip energy) from machine tool resource energy (start-up and ready state energy). Anderberg et al. [127] and Dahmus and Gutowski [115] also argue that specific energy based on tip energy evaluation does not provide the full information for actual energy demand and total system requirements for material removal processes. Empirical and statistical based models [117,123,162,163] have also been used for evaluating energy in machining. These are limited to different types and/or brands of machine tools, workpiece materials and methods. Other approaches have used software such as KERS [162] and MTConnect [163] for automatic evaluation of the energy consumption used in machining processes. The use of such software is useful for real time monitoring of energy usage during machining.

Dahmus and Gutowski [115] classified the energy consumption of a cutting process into two groups. This covered the constant energy used for start-up operations and the energy used in actual material removal processes. Energy is required to power machine modules and to cut a workpiece material [117]. Li and Kara [122] and Mori et al [164] adopted this approach to study the fixed power demand of machine tools.

Rajemi et al [119] proposed a new idea for dealing with optimisation of machining processes from the energy perspective. By applying minimum energy considerations, they built a novel concept for selecting a feasible combination of machining variables that can fulfil the requirements for minimum energy criterion and process constraints [120]. However, due to the focus being environmentally friendly processes such as dry machining, the model does not explicitly model other aspects of machining processes such as cooling/and lubricating energy characteristics.

Using a Life Cycle Analysis (LCA) approach, Narita et al [11] proposed an analysis tool that can be utilised to determine the environmental burden of a machine tool operation (B_{en}) as expressed in Equation 6.2.

$$B_{en} = B_E + B_{CF\_disp} + B_{Lub\_disp} + \sum_{i \to N} \left(B_{tool\_disp_i} \right) + B_{chip} + B_{others} \qquad (6.2)$$

Where B_{en} is the environmental burden of machining operations in kilograms of gas (kg-GAS). This is determined by the environmental burden of electricity consumption by machine tools, B_E (This includes all the machine's main components that are used to ensure the machine operated functionally such, as servo motors, spindle motor, cooling system of spindle, compressor, coolant pump, lift up chip conveyor, chip conveyor, automatic tool changing (ATC), and tool magazine motor), the environmental burden of coolant, B_{CF_disp}, the environmental burden of lubricant oil, B_{Lub_disp}, the environmental burden of cutting tools, $B_{tool\_disp_i}$ (This depends on the number of cutting tools N used during a machining operation), the environmental burden of metal chips, B_{chip}, the environmental burden of other factors related to machine tool operation, B_{others} such as automatic pallet changing, etc.

6.1.2 ***Research motivation***

There has been an interesting study in evaluating the environmental burden of machine tools [162]. However, the environmental burden of the machining process with regard to MQL, dry and flood coolant has not been fully explored. Therefore, the aim of this study was to evaluate the environmental burden caused by application of minimum quantity lubrication compared with dry and flood coolants with particular consideration of tool life performance. In this study, the evaluation would be focused on electrical energy demand using an improved direct energy model that is going to be developed in this study.

6.2 Direct Energy Model

A machine tool needs an amount of energy to power specific modules (E_{setup}) such as energy to start up the computer, fans, motor etc, to position the spindle in the position 'about to cut' (E_{ready}), to cut a workpiece material (E_{cut}), to drive servo-motors for performing a tool change task ($E_{tool-change}$) and to pump coolant/ lubricant and to deliver it to the cutting zones (E_{cool}). These can be mathematically modelled as in Equation 6.3.

$$E_{Tot} = E_{setup} + E_{ready} + E_{cut} + E_{tool\_change} + E_{cool} \qquad (6.3)$$

The energy E_{setup} can be evaluated from the machine's power consumption during machine idling (P_o). The energy consumed during the cutting process E_{cut} can be evaluated from the energy used to power machine modules and to convert a workpiece material into the final product. Gutowski et al [117] modelled this as detailed in Equation 6.4.

$$E_{cut} = (P_o + k\dot{v})t_2 \qquad (6.4)$$

Where P_o is the energy used to power machine modules in kW, k is the specific cutting energy in Ws/mm^3, $\dot{v}$ is material removal rate (mm^3/s) and t_2 is the duration of the cutting operation in seconds.

Figure 6.1 to Figure 6.3 shows the measured power profile in machine tool. This shows that the ready state energy should be used as the basic energy demand by the machine tool and Equation 6.4 can be modified as expressed in Equation 6.5.

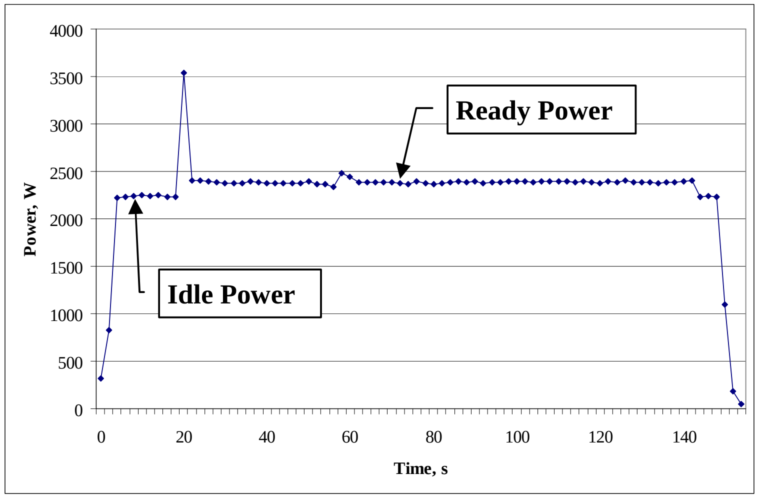


Figure 6. 1 Power profile of the Mikron HSM 400 as spindle was rotated at 11,943 rpm

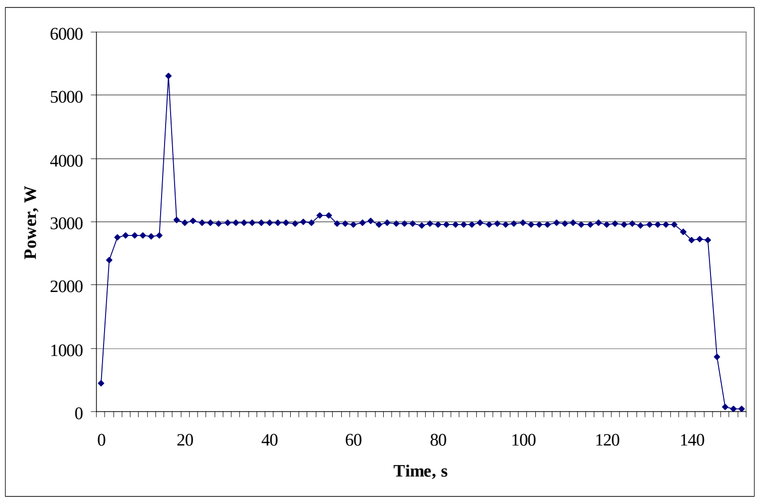


Figure 6. 2 Power profile of the Mikron HSM 400 as spindle was rotated at `15,924 rpm

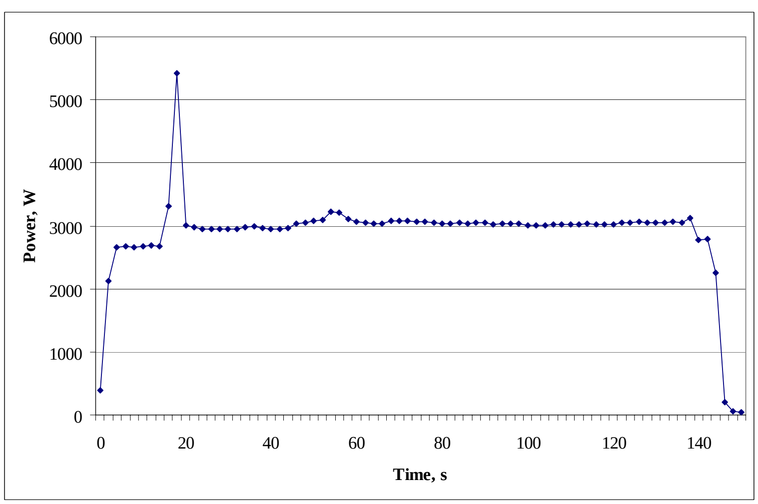


Figure 6. 3 Power profile of the Mikron HSM 400 as spindle was rotated at `19,905 rpm

$$E_{cut} = \left(P_{ready} + k\dot{v}\right)t_2 \tag{6.5}$$

In order to identify the change in power for different speed, tests were conducted for cutting speeds of 100 m/min, 200 m/min, 300 m/min, 400 m/min and 500 m/min. The relationship between cutting speed and ready power were then plotted in Figure 6.4

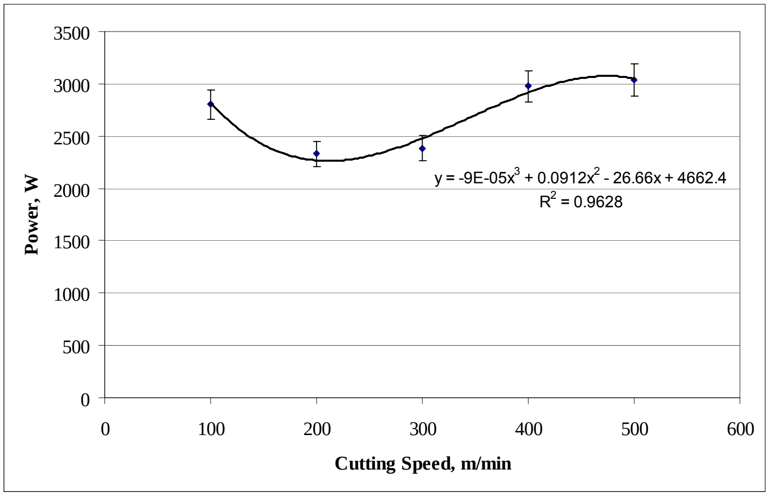


Figure 6. 4 Power characteristics of different cutting speed selection

Based on statistical analysis, the power characteristics of different cutting speed selection can be compared with a third order polynomial function that will give a correlation value of 0.96. This correlation magnitude shows that data were well distributed to the function mentioned above. Therefore, the function that was expressed in Equation 6.6 can be utilised to evaluate the ready power (P_{ready}).

$$P_{ready} = 4662 - 26.7V_c + 0.09V_c^{\ 2} - 9x10^{-5}V_c^3 \tag{6.6}$$

Figure 6.4 shows that there is fluctuation of power over the range of observed cutting speed. This is apparent at the rotational speeds ranging from 3,981 rpm to 15,924 rpm (i.e. 100 m/min to 400 m/min of cutting speed). According to the power-speed characteristics of the Mikron HSM 400 machine tool that is using a HSK-E40 chuck [165], the maximum available spindle power linearly increases with rotational speed up to 14,780 rpm and becomes constant at higher rotational speeds. It has been shown before (Figure 6.1 to Figure 6.3) that the power required depends on selected spindle speed and is influenced by the power-spindle speed characteristics of the machine (spindle design).

The energy to change a tool after it attains the end of its service life $E_{tool-change}$ can be evaluated from the power of the motor servo to activate the automatic tool change function. This task will require electrical power if a prerequisite condition is fulfilled. In this case, cutting time (t_2) must exceed the service life of the tool (T); otherwise, tool change energy would be zero. Details of tool change energy can be modelled by Equation 6.7.

$$E_{tool-change} = P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right] \tag{6.7}$$

Finally, coolant/lubricant is delivered to the cutting zones by utilising pumps and/or compressors. Energy consumption to control the cutting temperature (i.e. cooling energy) depends on the cutting environment. If dry machining was selected, then the cooling energy would be zero. However, if compressed air or coolant/lubricant were utilised, then the electrical power used by the compressor and/or the pump would have to be taken into account. For modern machine tools, they would only be activated during cutting operations. Cooling power (P_{cool}) is dependent upon the pump's and/or compressor's idle power (P_{pump_o} and P_{comp_o}), operating power (P_{pump_ops} and P_{comp_ops}) and running time (i.e. equal to cutting time (t_2)).

From the above discussion, the direct energy of a machining process can be evaluated using Equation 6.8.

$$E_{Tot} = P_o t_1 + P_{ready} t_{ready} + \left(P_{ready} + k\dot{v}\right) t_2 + P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right] + P_{cool} t_2 \tag{6.8}$$

Where ;

- P_o is electricity consumption driven by machine modules in kW,
- P_{ready} is electricity consumption driven by movement of rotating spindle to the ready to cut position,
- k is specific cutting energy in Ws/mm^3, and $\dot{v}$ is material removal rate (mm^3/s).
- t_1 is setup time, t_{ready} is ready time, t_2 is cutting time and t_3 is tool changing time. All the time is in seconds.

The tool is normally changed to begin a cut and then changed again when the cutting time reaches the tool life. Hence, the number of tool changes is calculated as one plus an integer value derived from a ratio of the total cutting time to the tool life. Furthermore, to reduce cutting temperature during the process a compressor or cooling pump can be used; generating electrical energy consumption for cooling (P_{cool}) in kW. The magnitude is influenced by the type of cooling method selected and the running time of the equipment to support that selection (t_2) in seconds (e.g. pump and/ compressor).

When fluid cooling is selected, operating power (P_{pump_ops}) is practically determined from its hydraulic power (P_{hyd}) in W, which is proportional to fluid flow rates (Q) and hydraulic pressure gradient (Δp) and inversely proportional to pump efficiency (η) and conversion factors (c). Using that formulation, the relationship between flow rate and power was established and the effect of different hydraulic pressure and power was also modelled. Results were plotted in Figure 6.5.

Accordingly, the total power of cooling if a pump is utilised can be modelled in Equation 6.9.

$$P_{cool} = P_{pump\_o} + Q\Delta p\eta \tag{6.9}$$

Where P_{pump_o} is the energy demanded to activate the pump (in W), Q is fluid flow rate from the nozzle tip (litre/hour), Δp is hydraulic pressure in Pa, and η is the mechanical efficiency of the pump motor shaft.

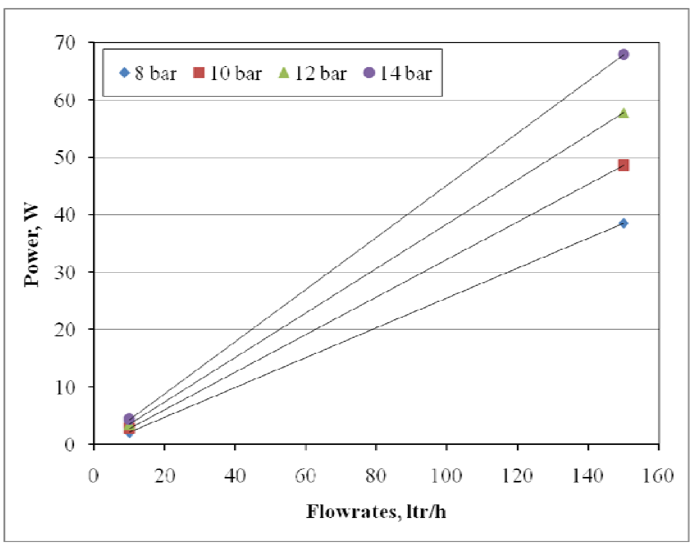


Figure 6. 5 Relation between fluid flow rate (Q) and hydraulic pressure (ΔP) on electric power consumption of pump

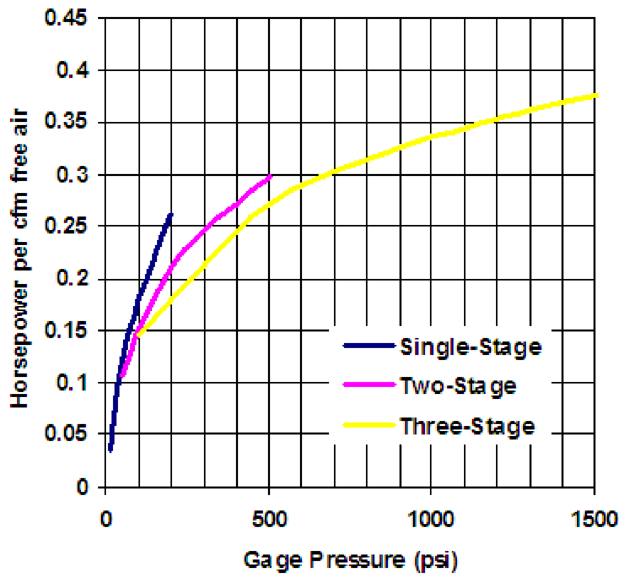


Figure 6. 6 An increase in power demand for compressed air at certain pressures [166]

Meanwhile, if machining processes utilise air-cooling to reduce tool interface temperature then the compressor will be activated. The electric power used by the compressor during its operation is an accumulation of standby power or idle power (P_{comp_o}) and power for compressed air or operating power (P_{comp_ops}). It should be noted, most types of compressor used in industry are adiabatic compressors [166]. Therefore, in determining the operating power, this study focussed only on adiabatic compressors. For adiabatic compressors, the operating power can be evaluated using a generic formula as expressed in Equation 6.10 [167].

$$P_{comp\_ops} = \left[\frac{N P_o Q x}{746(x-1)} \left\{ \left(\frac{P_1}{P_o} \right)^{\frac{(x-1)}{Nx}} - 1 \right\} \right] \tag{6.10}$$

Where, P_{comp_o} is the standby power of the compressor in W, N is the number of stages for the compressor running at different rates, P_o is absolute initial atmospheric pressure in Pa, P_1 is absolute final pressure after compression in Pa, x is the adiabatic expansion coefficient, which has value of 1.41 and Q is the flow rate of compressed air in the reservation tank at atmospheric pressure in m^3/s.

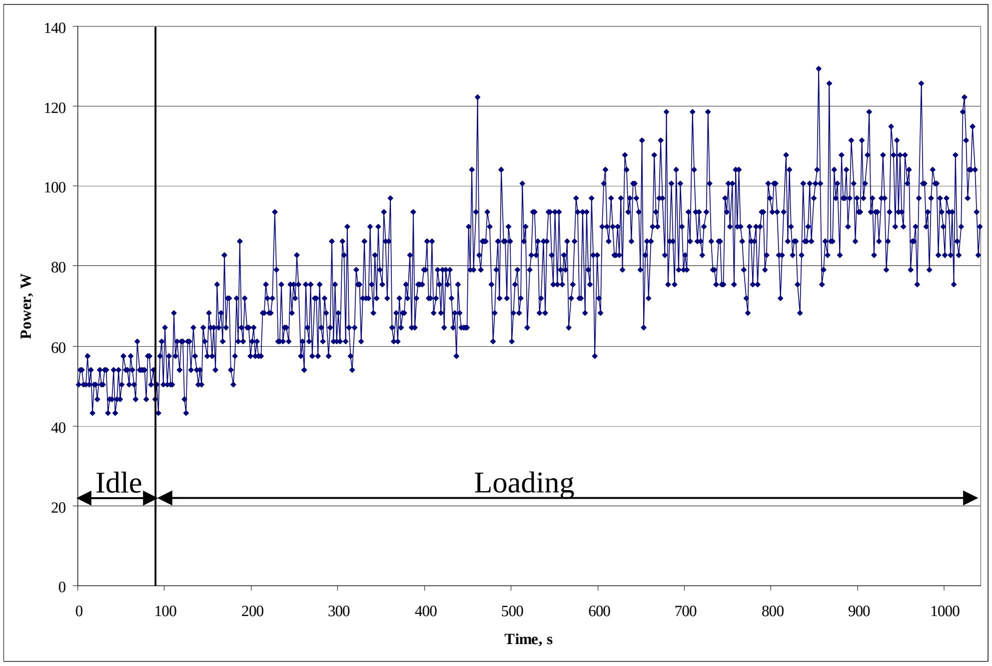


Figure 6. 7 Power profile of compressor at idle and loaded state

Using Equation 6.10, the increase in power demand when the compressor is in loading stage would follow the trend as shown in Figure 6.6. In order to validate that trend, the electric power drawn by the compressor when it was in idle stage and loading stage was measured. Accordingly, the power profile for those stages was plotted as in Figure 6.7. This measurement was carried out when the compressor was compressing the air from 0.76 MPa to 0.83 MPa and the measurement was stopped after the final pressure was achieved so, Figure 6.7 will not give a complete cycle of compressor operation.

Based on the results revealed in Figure 6.7, the trend shows a similarity with the trend resulting from the calculation used in Equation 6.8. Therefore, this validates the effectiveness of Equation 6.10 for calculating the energy demand of the compressor at loading stage. In addition, the power profile shown in Figure 6.7 also indicates the total power demanded to compress a volume of air at a certain pressure requiring a basic power (idle power/steady power) and loading power (operating power). Thus, the total power required to compress a volume of air at a certain pressure is given by Equation 6.11.

$$P_{cool} = P_{comp\_o} + \left[\frac{NP_o Q(x-1)}{746} \left\{ \left(\frac{P_1}{P_o} \right)^{\frac{(x-1)}{N}x} - 1 \right\} \right] \quad (6.11)$$

It should be noted, Q can be calculated from Equation 6.12.

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{1.41} \tag{6.12}$$

Where P_1 is air pressure in the reservation tank in pascal, P_2 is the outlet air pressure in pascal (or air pressure measured from the outlet section of the nozzle). Meanwhile V_1 is volume of air in reserve tank that needs to be compressed to its final pressure in m^3 and V_2 is the volume of the air supplied through the nozzle in m^3.

6.3 Experimental Details

6.3.1 Mechanical machining test details

A study was conducted on minimum quantity lubricant machining and to benchmark it to dry machining and machining using flood coolant and assess electrical energy requirements. End milling cutting tests were performed on H13 steel (192 BHN) on a MIKRON HSM 400 high speed milling centre. AISI H13 is used to produce die-casting, extrusion, trimmer, hot gripper and header dies, and hot shear blades. It is a hot worked tool steel with high chromium content. Composition of the alloy is shown in Table 6.1.

Table 6. 1 Composition (% by weight) of H13 Tool Steel

C	Mn	Si	Cr	V	Mo	Fe
0.40	0.40	1.00	6.25	1.05	1.25	Min 90.95

A cutting speed of 350 m/min was used for a tool 8 mm diameter to study tool life in dry machining, MQL and flood coolant method. This was the maximum cutting speed recommended by ISCAR for IC 928 inserts, according to the process window. This cutting speed magnitude was selected to make sure the process ran at a speed close to the high-speed regime (transition). Therefore, the difference in tool life of the three different cutting environments would be obvious. The inserts were TiAlN coated. The geometry of these inserts was SOMT 060204-HQ. After pilot tests, a moderate feed rate of 0.05 mm/rev was set in order to give a reasonable tool life. The depth of cut and width of cut was set to 1.5 mm and 4 mm respectively.

The workpiece used in this study had a length of 150 mm, a width of 100 mm and thickness of 100 mm. For a cutting pass, the total length of cut was 100 mm. After every 11 passes of cut, the insert was taken for tool wear measurement to a Leica microscope. The measurement for flank wear was done at 15 positions along the flank face using Axio Vision Release 4.8 image processing software. Each cutting condition was repeated using a new cutting edge and the result represents an average of the wear measurements.

6.3.2 Specific energy constants for H13 tool steel workpiece material

In this study, a series of experiments were conducted to obtain a specific energy constant (k) of machining hardened H13 material using three different cutting environments; dry machining, minimum quantity lubrication and flood cooling. The cutting conditions selected are depicted in Table 6.2. The selection of cutting conditions was based on the allowable cutting speed recommended by the insert manufacturer for cutting steel and avoiding the possibilities of tool wear propagation.

Table 6. 2 Cutting conditions for obtaining specific energy constants of machining H13 tool steel

No	V_c (m/min)	a_e (mm)	a_p (mm)	f (mm/tooth)	l_t (mm)	MRR (mm^3/s)	Net Power (W)		
							Dry	MQL	Flood
1	100	0.6	0.5	0.05	100	1.00	260.83	258.22	256.96
2	125	0.6	0.5	0.05	100	1.24	262.38	258.52	257.70
3	150	0.6	0.5	0.05	100	1.49	263.72	260.41	260.24
4	175	0.6	0.5	0.05	100	1.74	266.72	262.84	262.27
5	200	0.6	0.5	0.05	100	1.99	268.04	264.89	263.39

For each cutting environment, a series of end milling tests at different cutting speeds were repeated twice and current drawn by the machine tool during each process was measured using a clamp meter, Fluke 345 PQ. The measured current was then converted into power using the electrical power equation in Equation 6.12.

$$P = \sqrt{3} V I \tag{6.12}$$

Where V is the voltage in volts (V), and I is the current in ampere (A)

The calculated power value was then deducted from the idle power and other power figures related to the cutting process, such as pump power and/compressor power to obtain the net power and the net value was plotted against the material removal rates at different cutting speeds. Figure 6.8 shows the evaluation results for different cutting environments.

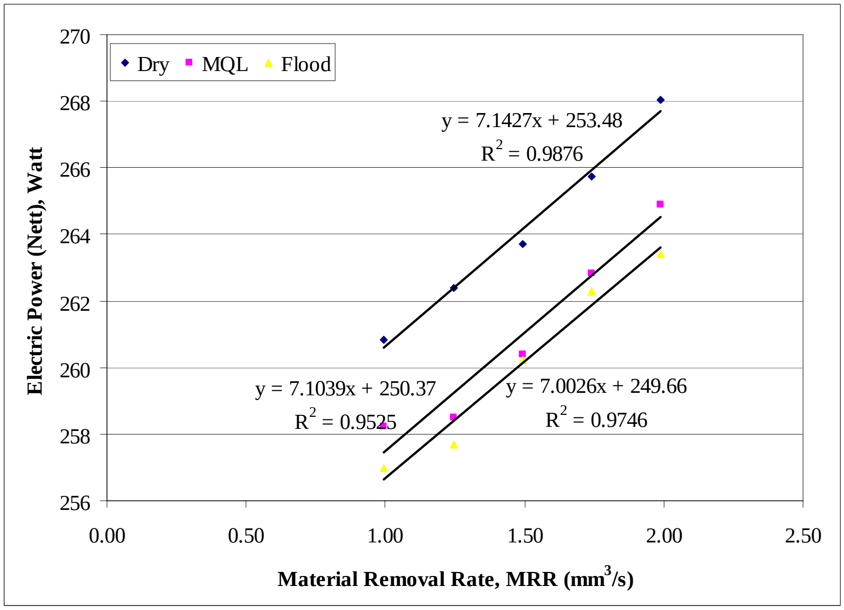


Figure 6. 8 Variation of power with material removal rates for different cutting environments

From the results shown in Figure 6.8, it can be evaluated that specific energy constants (k) is the gradient of the power and material removal rate relationship [168]. The inference that can be made from that figure is that for cutting a H13 tool steel workpiece, the specific energy constants for dry machining, MQL, and flood cooling are 7.14 Ws/mm^3, 7.10 Ws/mm^3 and 7.00 Ws/mm^3, respectively. Comparing these results with the specific energy requirement in cutting operation for steel that is given by Kalpakjian and Schmid [41], the values for each cutting environment are shown to be in the range (Table 6.3).

Furthermore, the different cutting environments selected cause the difference in specific energy constants for the same material. For dry machining, the value is higher compared with the other two methods. This is due to a lack of additional friction reduction media. This leads to higher cutting force being required to cut a workpiece material compared to other cutting environments. However, the study shows that the use of coolants does not significantly change the specific energy for workpiece materials. Compared to flood coolant, MQL and dry machining increased the specific energy constants by 1.4% and 2% respectively.

Table 6. 3 Specific cutting energy range for different materials [41]

Material	Specific cutting energy (k), Ws/mm^3
Aluminium alloys	0.4 – 1
Cast irons	1.1 – 6.4
Copper alloys	1.4 – 3.2
High-temperature alloys	3.2 – 8
Magnesium alloys	0.3 – 0.6
Nickel alloys	4.8 – 6.7
Refractory alloys	3 – 9
Stainless steels	2 – 5
Steels	2 – 9
Titanium alloys	2 – 5

6.4 Results and Discussions

6.4.1 Direct energy model validation

Before the model developed in this study can be utilised to evaluate the three different cutting environments, the model needs to be validated. To do so, the total energy required to cut a block of H13 workpiece material using flood environment condition was taken into account. Cutting tests were conducted using the parameters provided in Table 6.4. Electric current drawn during the process was measured continuously using a clamp meter, Fluke 345 PQ and converted to power using Equation 6.12. Data was then plotted to create a power profile for machining the workpiece material using flood environment conditions as in Figure 6.7.

Table 6. 4 Parameters set to calculate total energy demand using direct measurement and direct energy model for cutting a block of H13 workpiece material

Parameters	Magnitude
Cutting speed, Vc	350 m/min
Feed per tooth	0.05 mm/rev
Depth of cut	1.5 mm
Width of cut	0.6 mm
Basic power	2.86 kW
Energy constant	7.0026 Ws/mm^3
Cutting time	922 s
Ready time	4.2 s
Pump idle power	1.52 kW
Pump flow rate	30 l/min
Pump hydraulic pressure	3 bar
Pump efficiency	80%

The total energy required to cut a block of H13 workpiece material using flood environment conditions can be determined by calculating the area under the power-line curve graph. From Figure 6.9, the total energy required is 4,666 kJ. Meanwhile, using the same data as in Table 6.4, the total energy required to cut H13 workpiece material using the direct energy model in Equation 6.8 is approximately 4,208 kJ. It means there is approximately 10 % error using this model. However, this error might be caused by variations in cutting time. It was identified that there is approximately 7.8 % of error in calculating cutting time between the theoretical cutting time used in the evaluation and the real cutting time in direct measurement. Therefore, the real error of the model is only about 2.6 %, which is a reasonable magnitude for an evaluation model. Thus, it can be concluded that the direct energy model developed in this study is a feasible model for energy evaluation.

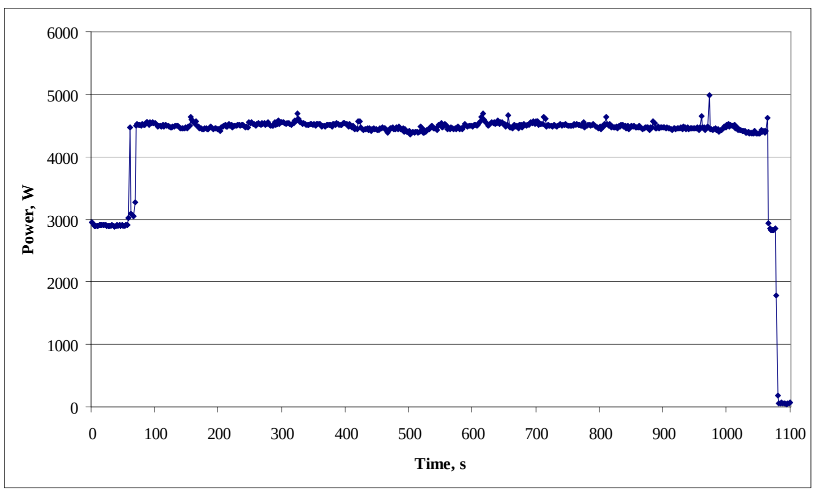


Figure 6. 9 Power profile of cutting a block H13 tool steel workpiece material using flood environment methods

Note that the total energy calculated from the direct energy model in this evaluation excluded the tool-change energy demand due to the test being carried out within the service life of the tool.

6.4.2 Tool wear progression for dry, MQL and flood coolant

Figure 6.10 shows the flank wear progression for the three different cutting environments. By considering tool wear data and tool life criterion based on the average flank wear of 0.3 mm [132], the tool life was 15.3 minutes, 25.0 minutes and 29.7

minutes for dry machining, MQL and flood coolant respectively. It is interesting to note that for 23 minutes of machining the wear performance of MQL was comparable to that of the flood coolant method. Moreover, while the tool life for dry machining was significantly low, the tool life for MQL was relatively closer to that of the flood coolant method. An interesting aspect was to evaluate whether the tool life compromise, in shifting from flood to MQL machining, was done at improved environmental performance.

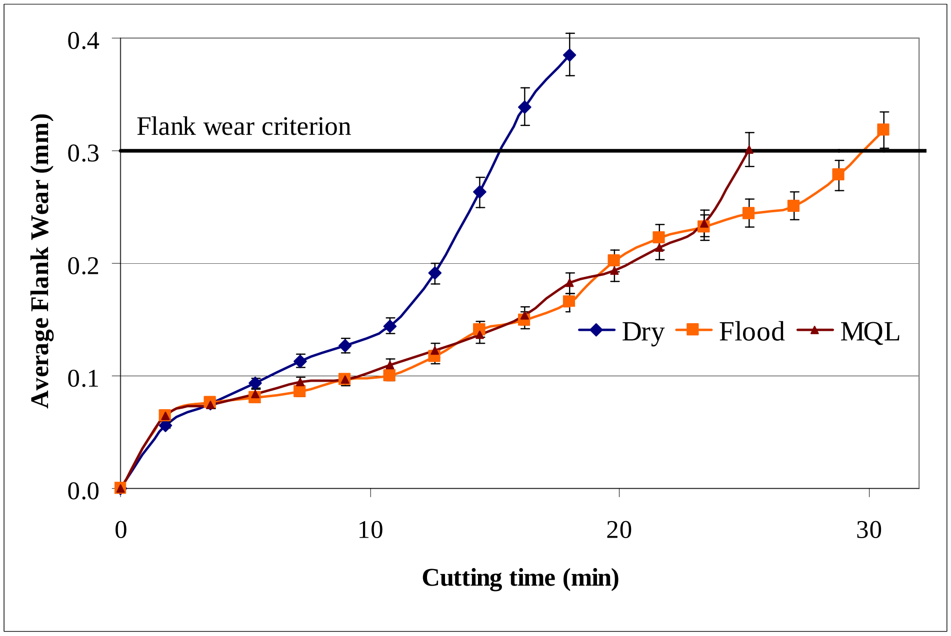


Figure 6. 10 Average flank wear progression for the tool utilised in milling using dry, MQL and flood

6.4.3 Evaluation of environmental burden: direct energy requirement

Energy consumption in machining is relevant for evaluating the environmental sustainability of manufacturing processes. This is because the energy used can be directly linked to energy costs and the carbon footprint associated with the quantity of electricity from power stations. Energy used during the machining process was characterised by measuring the current drawn by the process. The measurement was done using Fluke 345 PQ Clamp meter. It was found that the power required for sustaining the machine in a running state at zero loads was 2.86 kW. The power required by the coolant pump, air compressor and MQL system was 1.52 kW, 0.05 kW, and 0.002 kW respectively.

For comparison purposes, two cases were considered in order to evaluate the effect of cutting time and energy consumption. The first case was to produce a single small mould design as depicted in Figure 6.11. The second case was to produce a dozen nested components, similar to case 1; in one setup (schematic figure of nested component is shown in Figure 6.12. The time to machine one single component was 2.58 minutes. The tool transfer time in machining many components in one set-up was neglected. This time can be reduced to a very short duration if rapid feeds are used.

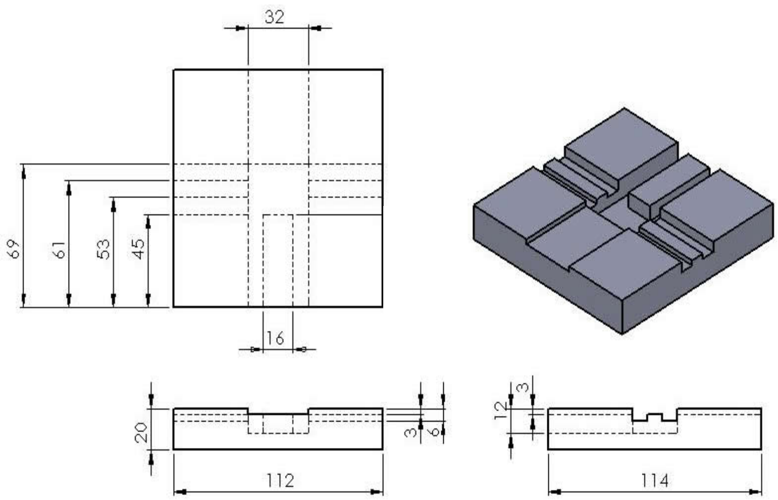


Figure 6. 11 A simple mould design (all dimensions are in mm)

The direct energy used by a machining process is of importance to industry because it can be correlated to the cost of the electricity required to run the manufacturing process. This direct energy does not take into account the energy embodied in material inputs such as workpiece material, cutting tools and lubricant. The direct energy is important in manufacturing because it represents a quantity that industry can control. The direct energy for machining processes as indicated in Equation 6.8 was considered to be the electrical energy used by the machine during set-up, before cutting and while cutting, for tool change and energy required, where applicable, for pumping the coolant. Figure 6.13 shows the direct energy required to machine 12 components shown in Figure 6.11 that were arranged according to configuration shown in Figure 6.12.

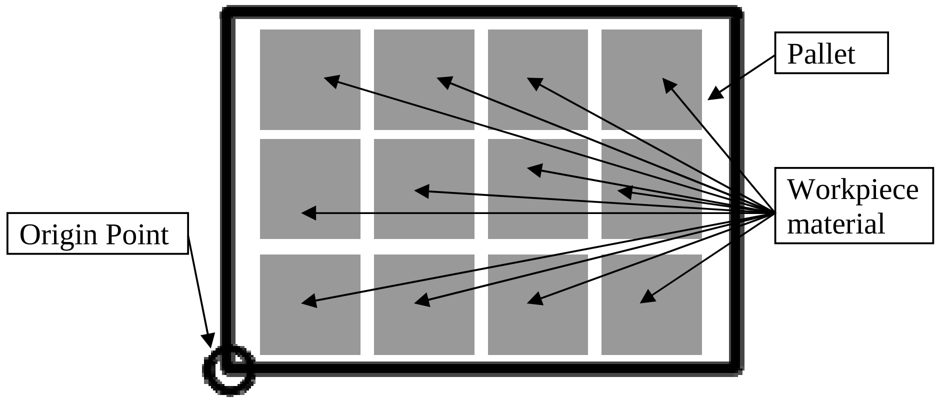


Figure 6. 12 Schematic figure of twelve nested component arrangement

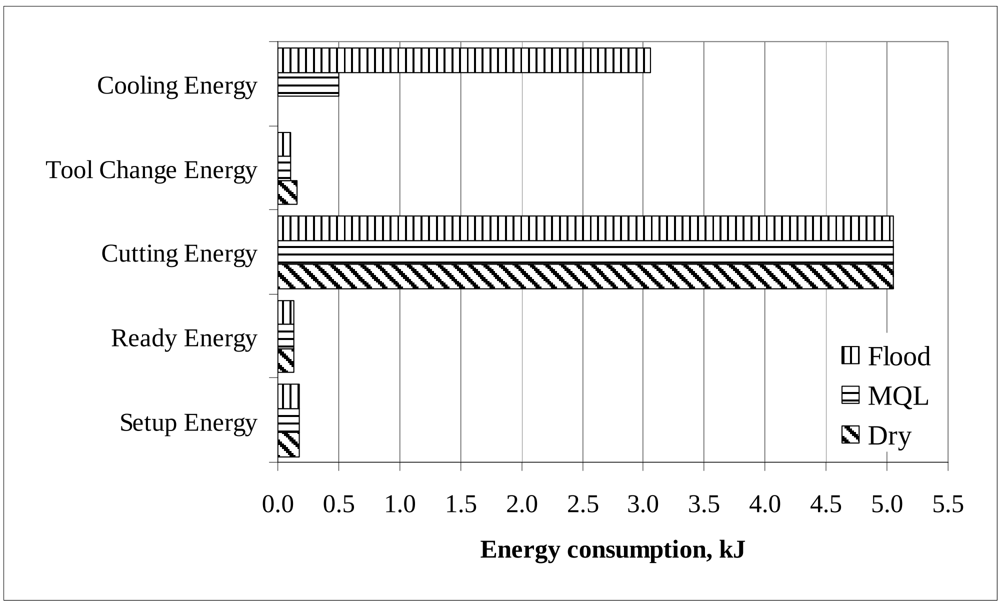


Figure 6. 13 Total energy consumption for three different cooling/ lubricating methods, based on the direct model for machining twelve nested components at one setup, as in Figure 6.11 and Figure 6.12.

As shown in Figure 6.13, the set-up, and the ready and cutting energy are not affected by the machining environment if unified cutting conditions are considered. Meanwhile, the energy required for tool change in dry machining is almost double that required for flood cooling and MQL. Interestingly, tool change energy for MQL and flood cooling is the same. This is due to tool life of either MQL or flood cooling being almost the same hence, the possible number of tool changes would also be the same. However, the portion of tool change energy is only around 3%, 2% and 1% of total energy demand for dry, MQL and flood cooling respectively. Thus, no significant effect can be expected for the cases used in this study. The significant difference in energy footprint arises from the flood-pumping requirement. Both MQL and dry machining reduce the total direct energy requirement compared to flood coolant by 30% and 35%, respectively. This reduction is simply due to reduced and no energy demand for flood coolant.

6.4.4 Effect of multiple components and longer cycle time

The influence of the cutting time over energy consumption in machining was examined. The time analysis was conducted for twelve nested components. The total time for machining twelve components was estimated to be 30.96 minutes. Increasing cutting time beyond the tool life means that tool change has to be considered and more energy is attributable to the tool changes. Figure 6.14 shows that machining using flood coolant conditions still carries the highest direct electrical energy usage compared to dry and MQL when considering both short and long cycle times for cutting. From the above discussion and Figure 6.14, it can be inferred that cutting time plays a significant role in differentiating the energy intensity of machining processes. For both short and long cycle times, the differences in the direct energy required for dry, MQL and flood coolant is dominated by energy demand in fluid pumping. The environmental sustainability of flood coolant can be improved by more energy efficient cutting fluid pumping and delivery.

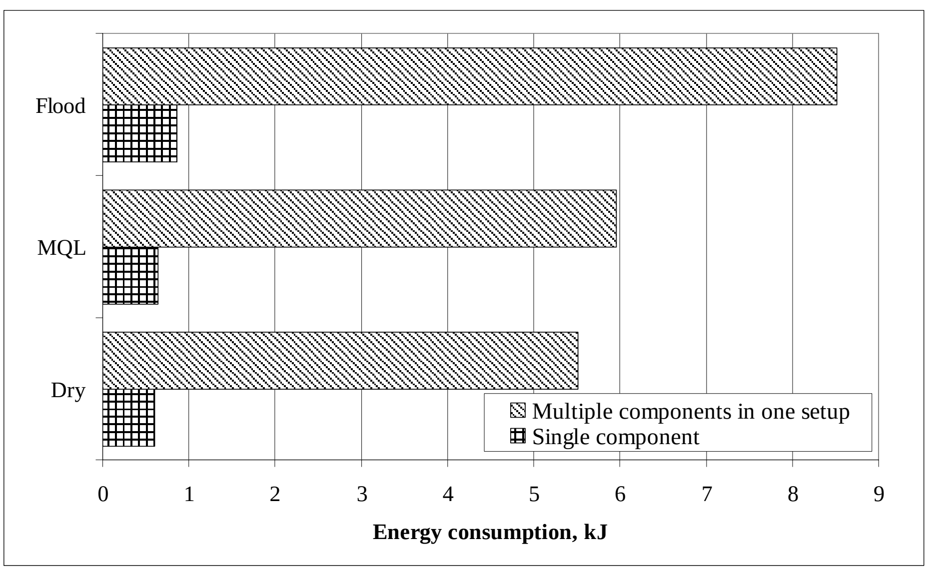


Figure 6. 14 Total energy consumption of different machining strategies

The study also considered the impact of machine activities on energy consumption. A time ratio approach was introduced as expressed in Equation 6.13. Equation 6.13 shows a productive machine utilisation ratio, S. Where t_2 is the actual cutting time and t_1 and t_3 are setup and tool changing times. If S is larger than 1, the machine is utilising electricity resources predominantly for actual value added activities. If S is less than 1, the set-up and tool change dominate the cutting cycle and the difference between MQL and dry machining is not significant when considering direct energy requirements; as can be seen in Figure 6.15

$$S = \frac{t_2}{\left(t_1 + t_3 + t_{ready}\right)} \tag{6.13}$$

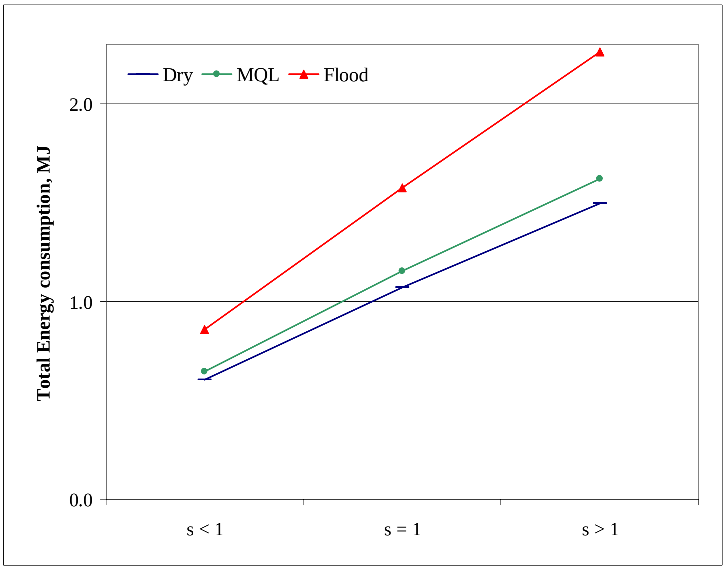


Figure 6. 15 Time ratio effect on total energy consumption

Interestingly, the trend for both MQL and dry machining is similar at low and moderate productivity levels when cutting time is lower and equal to setup time. However, during high productivity times, the cutting process is dominant and total energy consumption of machining processes using MQL is slightly higher when compared with dry machining.

6.4.5 *Considering other environmental impact categories*

Narita et al. [10] in their study reported that six categories were used as environmental an indicators. These impact categories are global warming, eutrophication, acidification, photochemical oxidant, human toxicity and ecotoxicity. Figure 6.16 shows global warming potential in grams equivalent to CO_2 for machining methods evaluated from Equation 6.8 using the UK CES of 0.43 kg-CO_2/kWh. Indeed, flood coolant increases the total global warming potential when compared to dry or MQL conditions. Shorter tool life experienced by the use of dry machining does not significantly effect the total energy consumption of dry machining, thus still lower carbon footprint compared to other cutting environments.

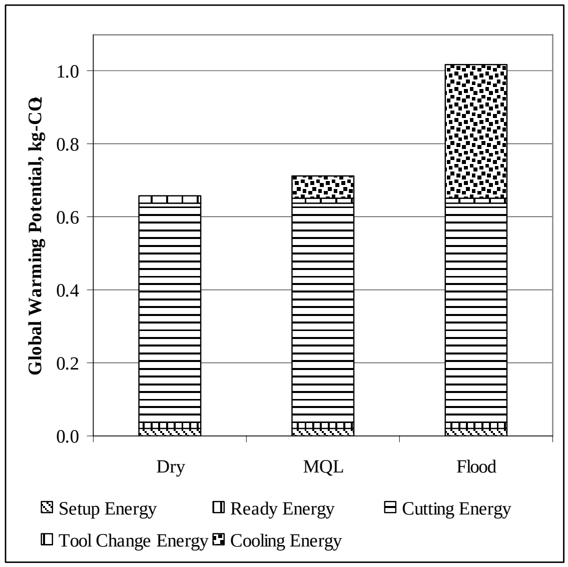


Figure 6. 16 Comparison of global warming potential of dry machining, MQL and flood cooling

Acidification represents the amount of SO_2 and NO_2 emitted into the environment. These substances are dangerous and hence, it is desirable to reduce their emission into the environment. A 350 μg/m^3/hour (i.e around 1.34 x 10^{-5} g-SO_2 for conditions applied in this study) has been declared by The European Union [169] as threshold of SO_2 emission. Human toxicity affects people who are working around the area of electric energy generators. This is due to exposure to dichlorobenzene (1.4 $C_6H_4Cl_2$), which is harmful.

Figure 6.17 shows the total acidification of dry machining, MQL and flood cooling as evaluated using Equation 6.8 and the tool life information shown in Figure 6.8. The flood coolant cutting condition has the highest level of acidification, and although the level of MQL and dry machining are below that of flood cooling it is still high. According to the Environmental Protection Agency of US government, the air quality emitted by SO_2 can cause several health problems ranging from breathing problems to cardiovascular related problems [172]. Therefore, reduction of acidification is an important consideration.

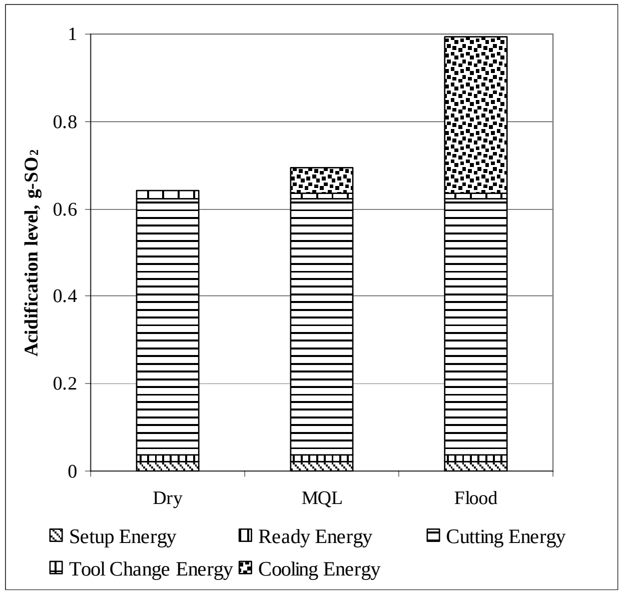


Figure 6. 17 Comparison of acidification level of dry, MQL and flood

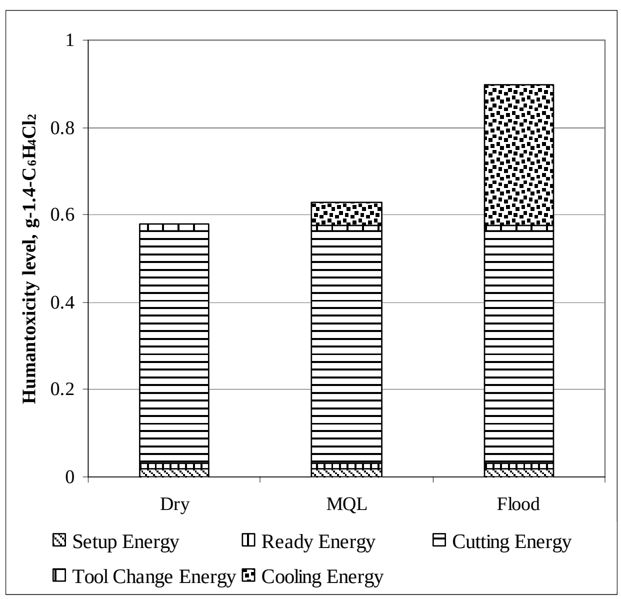


Figure 6. 18 Comparison of human toxicity level of dry, MQL and flood

Figure 6.18 shows the human toxicity level for machining using dry MQL and flood coolant conditions as evaluated using equation 6.8 and the tool life information shown in Figure 6.10. The human toxicity for machining using flood coolant conditions is higher than that for dry or MQL machining. This is due to the energy requirements for pumping cutting fluid.

The information presented in this analysis (Figures 6.16, 6.17 and 6.18) shows that in terms of the mass of dangerous gases, the global warming potential (approx. 1 kg-CO_2), for the three machining environments is higher than the acidification (< 1 g SO_2) or the human toxicity(< 1 g 1.4-$C_6H_4Cl_2$)levels.

6.5 Conclusions

This study conducted an evaluation of the energy footprint as well as the environmental burden of an end milling process based on tool life information and electrical energy requirements when machining using dry, minimum quantity lubrication and flood coolant.

- When using flood coolant a tool life of 29.7 minutes was achieved compared to 25 and 15.3 minutes for MQL and dry machining respectively. The use of MQL significantly enhanced the machining performance in respect of tool life when compared to dry machining and the performance was very close to machining under flood coolant. Thus, MQL plays a vital role as an intermediate method to mitigate the use of copious amounts of cutting fluid.
- Machining cycle time has a significant effect on electricity requirements during machining operations. The effect of non-productive activities such as machine set-up and tool change has to be considered. These productivity factors are more critical compared to the choice of machining environment, when the energy requirement for machining components within a cutting time frame is comparable to the set-up or tool change time. This case is typical of machining single small components.
- The energy footprint for dry machining and MQL are at a comparable low to moderate productivity level. At higher productivity levels, dry machining demonstrated its capability as the most environmentally friendly method. Therefore, the only obstacle to the application of dry machining is associated with the production budget (i.e. tooling cost).
- Compared to human toxicity and acidification, the environmental burden in terms of global warming potential dominates the energy footprint of the machining process. Hence, climate change and reducing CO_2 emissions are relevant drivers for environmental optimisation of machining processes.

- Selecting MQL can be an intermediate strategy for reducing direct energy requirements, global warming potential, human toxicity, and acidification in machining processes compared to machining using flood coolant. MQL also provides a good compromise, in terms of tool life, when compared to dry machining.
- The study reported here relates to the environmental burden arising from direct electrical energy usage. It does not, and was not, intended to address the life cycle or environmental burden of all associated inputs and outputs. In this analysis, the machine tool is the boundary. This work is important for the manufacturing industry in that it reports on activity that occurs inside the plant and is within the control of the manufacturing department.

CHAPTER 7

ENVIRONMENTAL BURDEN ANALYSIS OF END MILLING PROCESS - AN IMPROVED ENVIRONMENTAL EVALUATION TOOL

7.1 Introduction

A mechanical machining process system is governed by inputs, the machine tool and outputs as shown in Figure 7.1. The process inputs are a combination of electrical energy, workpiece material, cutting tool, tool holder and cutting conditions as well as other related parameters, such as cutting fluid flow rates etc. The machine tool is made up of modules and also equipped with supporting parts such as fixtures, jig etc., to ensure a mechanical machining process can be successfully performed. Machining process outputs relate to all products and by-products of the process. In mechanical machining process, products can be classified as value-added products such as components and/parts, gas emission and waste products such as chips, cutting fluid residue and used insert or cutting tool.

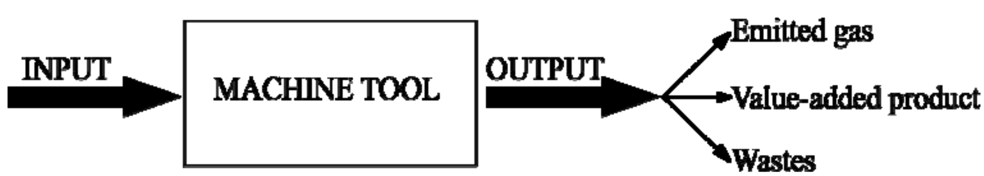


Figure 7. 1 A mechanical machining system

Input elements are important and have to be controlled or specified to ensure produced parts and/components that have high surface integrity and close dimensional and geometrical tolerance. The output elements, such as gas emissions and waste, result in environmental burden for the industry.

The CO_2 emissions, attributable to power generation for the quantity of electricity required in machining, are of concern due to global warming. Meanwhile, machining process waste needs extra caution in its disposal to minimise negative environmental impact. This raises costs, for example in preparing chips and insert/cutting tools for recycling and ensuring that cutting fluid residue is disposed of safely in the environment.

Many environmental performance evaluations are based on life cycle analysis (LCA). However, in LCA the integrity of data needs to be improved. While LCA helps to identify environmental hot spots it is not geared to local process improvement to ensure that the optimum operating conditions of processes, based on environmental criteria, are be obtained [120].

7.2 Environmental Analysis of Mechanical Machining

Munoz and Sheng [124] carried out analytical and qualitative analysis of different aspects of a cutting operation. Choi et al [125] proposed a model for environmental impact assessment. This model was based on Life Cycle Analysis (LCA) of a manufacturing process. Data was gathered from direct measurement of inputs. Creyts and Carey [111] used an extended energy concept to evaluate the environmental performance of a machining process. However, within this model, there was no consideration or explicit modelling of cutting conditions in building up the environmental characteristics of the process.

Narita and Fujimoto [11], proposed a more process level approach, based on LCA analysis, to model the environmental burden of a machining process. This model was focussed on the machine tool. Using an economic based model, Branker et al [128], included the model developed by Narita and Fujimoto in estimating the cost of environmental compliance. Other researchers [171,172] have used Narita and Fujimoto's model [11], and it is clear that the model proposed by Narita and Fujimoto is a good basis for process level environmental analysis.

7.3 Research Motivation

The model proposed by Narita and Fujimoto [11] can estimate the environmental burden of a machine tool operation instead of the cutting operation. The model was based on life cycle analysis, and the indirect inputs and their embodied environmental impact were also integrated into the model. In this study, the motivation was to evaluate the environmental burden of the end milling process using three different cutting environments; dry machining, minimum quantity lubrication (MQL) and flood coolant, from the cutting operation viewpoint or the 'effect', considering not only energy consumption but also the waste stream. Due to inappropriate evaluation models currently available, an improved and integrated model could be the key for evaluation of the environmental burden made of the machining process.

7.4 Development of an Improved Environmental Burden Analysis Tool

The environmental burden of the mechanical machining process B_{en} can be evaluated as the environmental impact of energy usage, B_E, environmental burden of cutting fluid disposal, $B_{CF-disp}$, environmental burden of cutting tool and tool holder disposal, B_{tool_disp} and environmental burden of chip disposal, B_{chip}. Integrating all these elements will yield a model for the environmental burden as shown in Equation 7.1.

$$B_{en} = B_E + B_{CF\_disp} + B_{tool\_disp} + B_{chip} \tag{7.1}$$

The environmental burden attributable to consumption of electrical energy by a machine tool can be defined as the total energy consumption of a machining operation (E_E) in kWh multiplied by the emission signature (ES^{TM}) in kg-GAS/kWh. In Chapter 6, an extended direct energy model to calculate total energy consumption during the machining process, was developed and tested. This model was built from setup energy, which involves machine idle power (P_o) and setup time (t_1), from cutting energy, evaluated from the utilisation of idle power and cutting power during the cutting operation, from tool change activity and from required power necessary for pumping coolant to the workface to reduce cutting temperature. Therefore, the total energy consumption E_E can be detailed as in Equation 7.2.

$$E_{Tot} = P_o t_1 + P_{ready} t_{ready} + \left(P_{ready} + k\dot{v}\right)t_2 + P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right] + P_{cool} t_2 \quad (7.2)$$

To note, Equation 6.8 is repeated here as Equation 7.2 for purposes of clarity.

Where $\boldsymbol{P_o}$ is the electrical power consumption required by machine modules in kW when the machine is running at no load, $\boldsymbol{k}$ is specific cutting energy in Ws/mm^3, and $\dot{\boldsymbol{v}}$ is material removal rate (mm^3/s). In a machining process, the compressor or cooling pump can be used and has a power requirement (P_{cool}) in kW. The P_{cool} magnitude can be calculated by using Equation 6.9, Equation 6.11 and Equation 6.12 as revealed in section 6.1.4. The energy is calculated from a product of the P_{cool} power, the fluid running time (t_2) in seconds. Meanwhile, the electrical energy consumption for machine setup and tool changing activity are influenced by set-up time (t_1 in seconds) and tool changing time (t_3 in seconds) as well as achievable tool life (T is in seconds).

The tool is normally changed at the start of a new job, and then it is changed when the cutting time reaches the tool life. Hence, the number of tool changes is calculated as one plus an integer value derived from a ratio of the total cutting time to the tool life.

Extending Equation 7.2 to be a model for environmental burden estimation of electrical energy consumption, the equation had to be divided by a time conversion factor of 3600 (from J to Wh) and multiplied by emission intensity for a given gas and/ chemical substance (ES^{TM}). Thus, the environmental burden estimation of electrical energy consumption can be expressed as in Equation 7.3.

$$B_E = ES^{TM}\left[\left(P_o t_1 + P_{ready} t_{ready} + \left(P_{ready} + k\dot{v}\right)t_2 + P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right] + P_{cool} t_2 \right)/3600\right] \quad (7.3)$$

Meanwhile the environmental burden of cutting fluid usage is calculated from the ratio of cutting duration (t_2) and the useful life of cutting fluid (t_{CF}) and multiplied by the volume of cutting fluid used over the period of cutting and this is multiplied by the environmental factor of cutting fluid disposal (C_{DE}) in kg-GAS/kWh. The equation for the environmental burden of cutting fluid disposal for machining is detailed in Equation 7.4.

$$B_{CF\_disp} = \frac{\sum_{i=1}^{N} t_{2i}}{t_{CF}} \left[\sum_{i=1}^{N} (Q_i t_{2i}) \right] C_{DE} \tag{7.4}$$

Where t_2 is cutting duration, t_{CF} is the life of cutting fluid before it is disposed of, Q is the flow rate (l/min) of cutting fluid delivered to the cutting zone and C_{DE} is the environmental factor of cutting fluid disposal in kg-GAS/l. While i is number of processes that are taken into account for accumulation the total volume of cutting fluid disposal

Furthermore, the volume of cutting tool disposal that can be a burden on the environment (E_{Tool_disp}), can be calculated from the used cutting tools/inserts and from tool holder. However, because the service life of the tool holder is normally sufficiently long, thus for estimated low batch size production, this environmental burden can be low. Therefore, the environmental burden of the cutting tool can be expressed as in Equation 7.5.

$$B_{Tool\_disp} = \left(W_{Tool}\ INT\left[\left(\frac{t_2}{Tz} \right) + 1 \right] C_T \right) + \left(W_{TH} \left[\frac{\sum_{i=1}^{N} t_{2i}}{nTz} \right] C_H \right) \tag{7.5}$$

Where W_T and W_{TH} are tool weight and tool holder weight respectively in kg, t_2 is cutting time, T is tool life, z is number of available cutting edges, t_{TH} is the utilisation period of the tool holder in minutes and n is the life of the tool holder expressed in number of insert cutting edges used before holder end of life. C_T and C_H are the environmental burden factors of the cutting tool and tool holder material respectively.

Finally, the environmental burden caused by chip disposal can be explained as the total weight of the chip produced during the machining process multiplied by the environmental factor of chip disposal. Thus, the environmental burden formulation for chip disposal can be expressed as in Equation 7.6.

$$B_{chip} = [\dot{v} t_2 \rho] C_{ch} \tag{7.6}$$

Where $\dot{v}$ is material removal rate in mm^2/s, ρ is density of workpiece material in cm^3/kg, t_2 is cutting time and C_{ch} is environmental factor of chips disposal.

Therefore, based on the formulation developed in Equation 7.1, the detailed model for the environmental burden of the machining process, taking into account inputs and outputs can be developed as expressed in Equation 7.7.

$$B_{en} = ES^{TM} \left[P_o t_1 + P_{ready} t_{ready} + \left(P_{ready} + k\dot{v}\right) t_2 + P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right] + P_{cool} t_2 \right]$$
$$+ \frac{\sum_{i=1}^{N} t_{2i}}{t_{CF}} \left[\sum_{i=1}^{N} \left(Q_i t_{2i}\right) \right] C_{DE} + \left(W_{Tool}\, INT\left[\left(\frac{t_2}{Tz}\right) + 1\right] C_T \right) + \left(W_{TH} \left[\frac{\sum_{i=1}^{N} t_{2i}}{nTz} \right] C_H \right) + [\dot{v} t_2 \rho] C_{ch} \tag{7.7}$$

7.5 Environmental Burden Evaluation of the End Milling Process

The input data required for environmental burden analysis were obtained from the end milling process of a twelve-nested component of H13 tool steel workpiece material, as depicted in Figures 6.9 and 6.10 on the Mikron high speed milling machine. The end milling process was conducted using TiAlN coated inserts attached on an 8 mm diameter tool holder, manufactured by ISCAR. The cutting process was performed using dry, flood and MQL application. All the data gathered from the experiment is given in Table 7.1. This was used for environmental burden analysis.

Furthermore, using an improved environmental burden model as in Equation 7.7 and information given in Table 7.1, the environmental burden of the end milling process is evaluated. The evaluation was carried out based on the environmental impact categories such as global warming potential, acidification, human toxicity, eutrophication, photochemical oxidant, and human toxicity [110].

Table 7. 1 Data used for environmental burden analysis

Po = power consumed by machine modules without the machine cutting	:	2.86	kW
V_c	:		
a_p	:	1.5	mm
a_e	:	0.6	mm
f_z	:	0.05	mm/rev
k = specific cutting energy	:		
Dry		7.143	Ws/mm^3
MQL		7.104	Ws/mm^3
Flood		7.0026	Ws/mm^3
$\dot{v}$ = material removal rate	:	10.45	mm^3/s
t_1 = idle time	:	60	second
t_2 = cutting time(s)	:	30.96	second
t_3 = tool change time(s)	:	1	second
t_r = ready time	:	4.2	second
T = tool life			
Dry	:	15.3	min
MQL	:	25	min
Flood	:	29.7	min
P_{ocool} = power consumed by cooling/ lubricating equipment before activated			
Pump	:	0.87	kW
Compressor	:	0.051	kW
MQL	:	0.002	kW
Q = cutting fluid flow rate			
MQL	:	29.9	ml/h
Flood	:	0.5	l/s
t_{CF} = coolant life		3000	h
z = number of cutting edges available or number of regrinding processes	:	2	
WT = cutting tool weight	:	4.5	gr
ρ = density of workpiece material		7.75	kg/cm^3
n = the life of the tool holder	:	400[173]	

7.5.1 *Environmental burden evaluation for end milling of annealed H13 tool steel material based on impact categories*

The impact categories of global warming: acidification, eutrophication, photochemical oxidant and human toxicity were used in this analysis. Meanwhile, the impact signature data in respect of emission intensity was obtained from Department for Environmental, Food and Rural Affairs (DEFRA) [174] and the study by Narita and Fujimoto [11].

Global warming potential

A volume of dangerous gas emitted to the environment is a measure of global warming potential. Carbon dioxide (CO_2) is the most dominant gas found in the atmosphere, and this is a common environmental burden indicator.

Figure 7.2 shows the global warming potential of different cutting environments. It is revealed that flood cooling has the highest environmental burden magnitude while dry machining and minimum quantity lubrication (MQL) have a comparable environmental burden. Although the use of cutting fluid promotes longer tool life, it failed to bring CO_2 emission environmental benefits. Meanwhile, the evaluated environmental burden for dry machining and MQL, in this study, are comparable and in agreement with environmental burden evaluation done by Narita and Fujimoto [11].

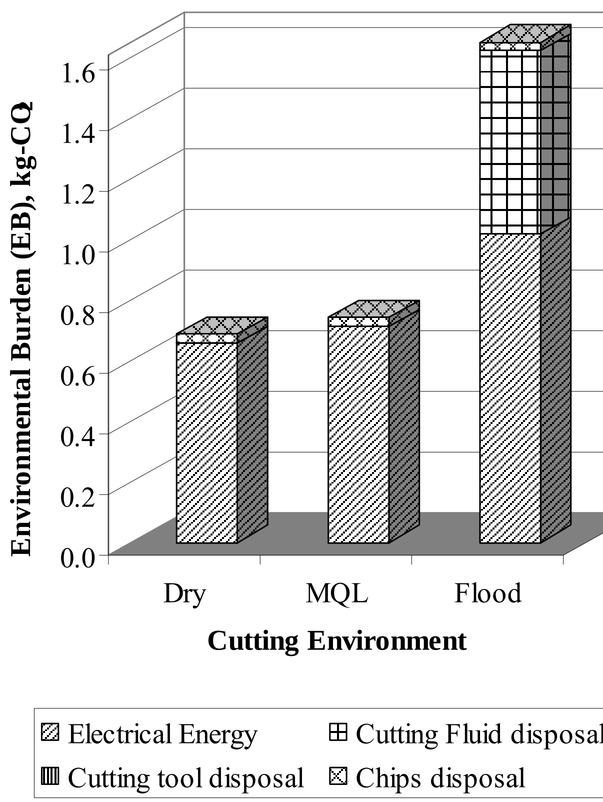


Figure 7. 2 Environmental burden of dry machining, MQL and flood cooling based on global warming potential

This study reveals that environmental burden caused by disposal of cutting tools is almost the same for all three cutting environments. This is due to the fact that there were no cutting tools to be disposed of. This can be explained by considering the measured machining time of 30.96 minutes in this study. Meanwhile, the measured tool life for this study are 15.3 min, 25 min and 29.7 min for dry machining, MQL and flood respectively; and the cutting tools used in this study pose two cutting edges. Thus, there would be only one tool change task and no cutting tool to be disposed of; and this situation applied to all the cutting environments. In addition, the ratio of cutting time to tool life was less than 2, which would not have a significant effect on the environmental burden.

Table 7. 2 Environmental burden estimation for cutting a 12-nested component in one setup

No	Environmental burden criterion	Environmental burden of Dry (gr-CO2)	Environmental burden of MQL (gr-CO2)	Environmental burden of Flood (gr-CO2)
1	Electrical Energy	658.00	712.00	1017.00
2	Cutting Fluid disposal	0.00	0.00	604.00
3	Cutting tool disposal	0.03	0.02	0.01
4	Chips disposal	29.00	29.00	29.00
	Total	688.03	741.02	1650.01

It is obvious from Figure 7.2 and Table 7.2 that electrical energy generation derived emissions dominate the process accounting for almost 90% of the environmental burden magnitude for dry and MQL while around 37 % of total environmental burden for flood cooling is contributed by the waste stream of cutting fluid. Nevertheless, in general for all cutting environments, domination of electrical energy is obvious. This can be understood because the electrical energy required to power up the machine tool and supporting modules and to convert workpiece material to its final shape is high when compared with the waste produced during the process within the range of cutting times and tool life used in this study.

Furthermore, from this evaluation, the effect of cutting fluid usage does show a negative effect on the environmental burden although Blasocut BC 25 cutting fluid used in this study. Blasocut BC 25, is a water miscible cutting fluid that has a long life (i.e. 3000 hours) compared to the total cutting time used in this study (i.e. 30.96 minutes). Thus, it is clear that the negative effect of cutting fluid usage would affect the environment not only when the production volume is high (i.e. mass production) but also when the production volume is quite low.

Acidification

Acidification can be defined as a natural process that converts a gas into an acid. Sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) are the gases that are responsible for acidification. Therefore, the environmental burden of acidification can be calculated from one of these two gases. Data used for analysing the environmental burden of acidification was obtained from DEFRA [174] and the study by Narita and Fujimoto [175].

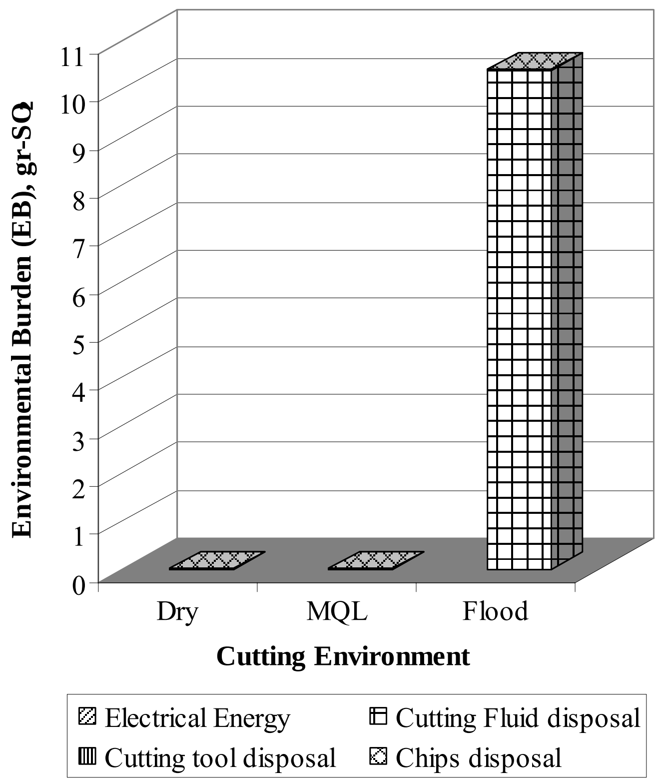


Figure 7. 3 Environmental burden of dry machining, MQL and flood cooling based on acidification category

Figure 7.3 shows the result of the acidification analysis for all three cutting environments. The figure illustrates that flood cooling is the worst cutting environment for promoting acidification. This is due to the high volume of waste cutting fluid disposal in flood machining. Disposing of waste cutting fluid would be detrimental to the environment, especially to land because waste cutting fluid is acidic. Thus, special attention has to be paid to treat waste cutting fluid before it can be disposed of safely. However, this treatment is costly [32] and it would be a burden on the industry.

Furthermore, the evaluation also revealed that there is no significant difference between the environmental burden of acidification for dry machining and machining using MQL. This might be because almost all of the cutting fluid used in MQL application is vaporised hence producing no waste.

Eutrophication

Eutrophication is the process that is responsible for the growth of algae and cyanobacteria, which decreases the oxygen supply. From this definition, it is clear that eutrophication would be attributable to contaminated chemical substance. In machining processes, this is predominantly caused by utilising cutting fluid for reducing cutting temperature. Figure 7.4 shows the eutrophication assessment and it becomes evident how detrimental cutting fluid waste is for environment. Dry and MQL machining use only small amounts of cutting fluid creating little wastage negating the issue of eutrophication, their biggest contribution to environmental degradation is the use of electrical energy.

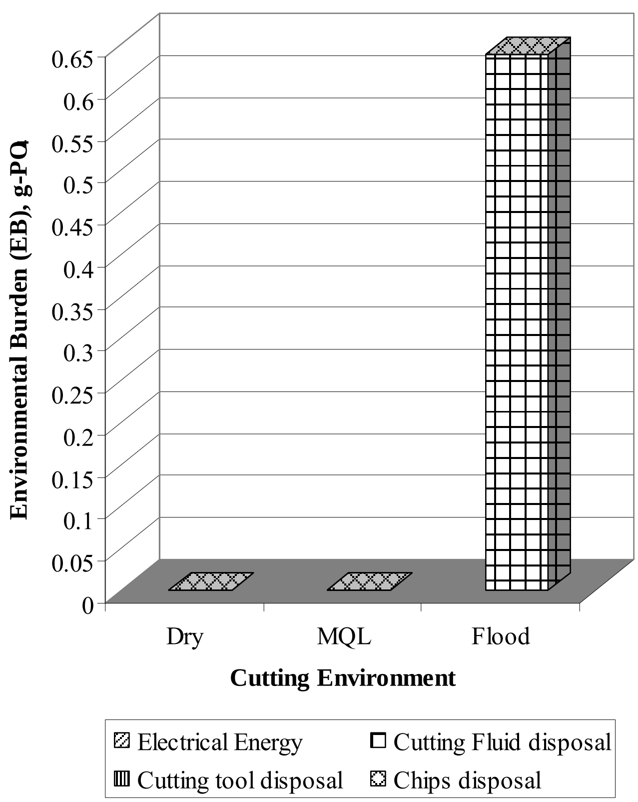


Figure 7. 4 Environmental burden of dry machining, MQL and flood cooling based on eutrophication category

When contaminated substances are disposed of in the environment, they will react with other atmospheric chemical substances, thus, creating chemical substances that would deteriorate in the ecosystem and reduce the level of contained oxygen.

Photochemical oxidants

The presence of photochemical oxidants in the environment has a detrimental effect on soil and plants. Therefore, chemical substances that are capable of forming photochemical oxidants, such as sulphur dioxide, carbon monoxide, acetaldehyde, acetone, benzaldehyde, butyraldehyde, isobutyraldehyde, propionaldehyde, methane, benzene, toluenae, ethylbenzene and formaldehyde should be avoided. In the case of environmental performance analysis, this impact category can be determined by calculating the equivalent C_2H_4 emission.

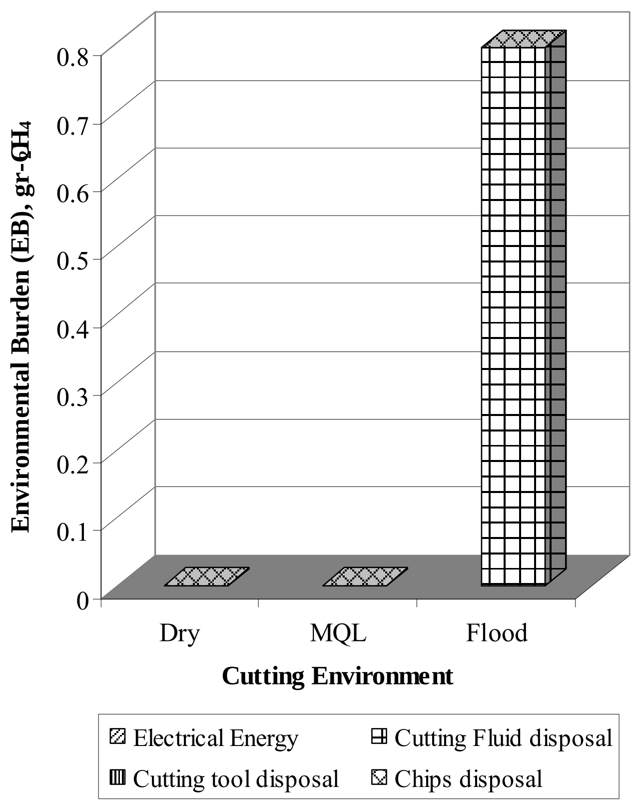


Figure 7. 5 Environmental burden of dry machining, MQL and flood cooling based on photochemical oxidant category

Analysis results of the environmental burden caused by photochemical oxidants depicted in Figure 7.5 illustrates the influence of cutting fluid in creating a photochemical oxidant footprint. Reducing the amount of cutting fluid usage minimises the environmental burden of photochemical oxidant substances.

Human toxicity

One of the consequence of using chemical substances and electrical energy is to cause health problems for people who are work in machining areas and who live in the vicinity of facilities for purifying waste machining products. The environmental burden of human toxicity can be calculated from the equivalent 1.4-$C_6H_4CL_2$ emission.

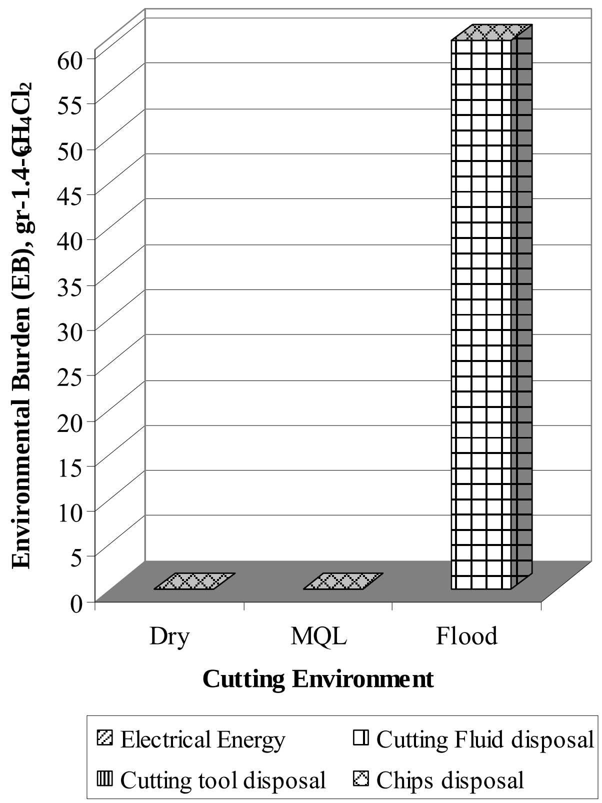


Figure 7. 6 Environmental burden dry machining, MQL and flood cooling based on human toxicity category

The results in Figure 7.6 show that the human toxicity burden of machining using flood coolants has the highest magnitude compared to dry or MQL machining. Therefore, the high human toxicity of flood coolants in machining is caused by the use of cutting fluid.

The analysis results discussed above reveal the significant differences of global warming potential when comparing flood, dry, and MQL conditions. In addition, using the environmental burden model to evaluate the differences between cutting environments has pointed out the importance of energy utilisation in mechanical machining processes. In fact, although, cutting fluid, chip and cutting tool disposal will increase the environmental burden caused by mechanical machining the low volume of waste produced during mechanical machining is insufficient to make a significant contribution to environmental burden impact. The full analysis of the environmental burden is dominated by the requirement for electrical power, which explains why there is such a huge difference between the results revealed in this study compared with the results revealed in the study by Narita and Fujimoto [11].

In using the Life Cycle aspect of machine tools, Narita and Fujimoto [11] used emission signatures or multiplying factors that considered production and disposal aspects.

Finally, based on the analysis results revealed in section 7.5, it can be concluded that for milling processes and for small production batch, the environmental burden is dominated by the demand for electrical energy during the process rather than the waste stream produced. Therefore, the environmental burden model can be generalised as in Equation 7.8

$$B_{en} = GES^{TM} E_T \tag{7.8}$$

Where B_{en} is the environmental burden based on impact category (in kg-GAS), GES^{TM} is the gas emission signature in kg-GAS/kWh, depending on the country and type of electrical grid. Meanwhile E_T is total energy consumption in kWh. E_T can be calculated by using the extended energy model proposed in Chapter 6.

7.5.2 *Effect of reduced cycle time on the environmental burden for end milling hardened H13 tool steel material*

With reference to the results revealed in the analysis in section 7.5.1, a subsequent analysis was done to determine the environmental burden, focusing on the effect of reduced cycle times that are associated with high speed machining. Additionally, the influence of improved MQL performance, due to the effective nozzle position, was also taken into consideration. All the calculations were done using Equation 7.7 and the evaluation was based on the global warming potential only, due to the importance and dominance of this category in quantifying the environmental burden of the process. The data gathered from previous experiments was exploited.

Longer processing times would increase the energy consumption. High speed machining would reduce the cycle time and in turn, reduce energy consumption. Desmira et al [176] found that high speed machining could help in reducing the energy demand. However, their results showed that the environmental burden tended to be higher after the spindle speed was increased to more than 8,000 rpm. The dominant factor of this trend was found to be wear of the tool and their analysis revealed that increasing the spindle speed/cutting speed was detrimental to the tool. This might because of the solid high-speed steel tool used in their study has limitation in respect to longer tool life at higher rotational speed. A solid high-speed steel tool has a limited capability for withstanding for excess heat generation as in high speed machining. Therefore, in this study, the evaluation considered cutting tools, which performed better when compared with high-speed steel tools.

This study focused on effect of increasing cutting speed. Cutting speed has a significant impact on reducing cycle times. For example, increasing the cutting time from 350 m/min to 700 m/min will give a two-fold reduction in cutting time. Meanwhile, increasing the feed per tooth from 0.05 mm/tooth to 0.07 mm/tooth, the reduction in cutting time was calculated as a 1.43 fold reduction. Additionally, if cutting speed and feed per tooth are increased together, a 2.5 fold reduction in cutting time could be expected. However, setting the cutting speed and feed per tooth at a higher rate at the same time is inappropriate in this case as it would increase cutting forces hence, avoiding chatter that would promote progressive wear [4].

Table 7. 3 Cutting conditions used for analysing the effect of cutting speed on the environmental burden

Cutting condition	Condition 1	Condition 2
Cutting speed (V_c), m/min	350	700
Radius of cut (a_e), mm	0.6	0.6
Depth of cut (a_p), mm	1.5	1.5
Feed (f_z), mm/tooth	0.05	0.05
Tool life (T), min	10.61	4.10

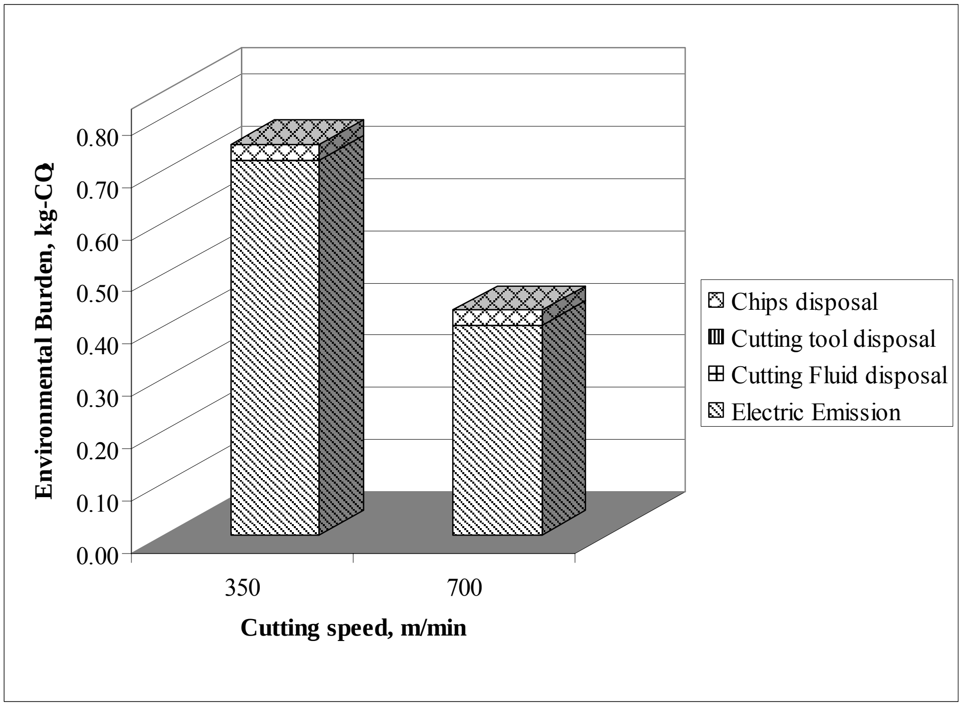


Figure 7. 7 Environmental burden of increased cutting speed

From Figure 7.7, it can be seen that increasing the cutting speed reduced the environmental burden. This result agrees with previous findings found in literature [174,175] in respect of the use of high speed machining. Increasing the cutting speed reduces cycle times, reducing energy consumption and the environmental burden.

Table 7. 4 Environmental burden estimation of increased cutting speed

No	Environmental burden criterion	Vc=350 m/min ($kg-CO_2$)	Vc=700 m/min ($kg-CO_2$)
1	Electric Emission	0.72	0.40
2	Cutting Fluid disposal	0.00	0.00
3	Cutting tool disposal	0.00015	0.00017
4	Chips disposal	0.03	0.03
	Total	0.747	0.430

The environmental burden criterion distribution as the cutting speed increased, is depicted in Figure 7.7, the estimated result is given in Table 7.4. Table 7.4 reveals that the demand for electrical energy made a significant contribution to the environmental burden reduction due to a two-fold increase in the cutting speed. This result has confirmed the importance of electrical energy in the environmental footprint analysis and the environmental burden estimate.

7.5.3 *Effect of improved MQL application of end milling hardened H13 tool steel material on the environmental burden*

The position of the nozzle is a paramount parameter for effective MQL application. The appropriate nozzle position would enable prolonged tool life. To find what substantial benefit can be gained by repositioning the nozzle to enable the tool life to be prolonged, a further analysis was done. The cutting speed (V_c), feed (f_z), depth of cut (a_p), width of cut (a_e) used in this analysis were 700 m/min, 0.05 mm/tooth, 1.5 mm and 0.6 mm respectively. The nozzle was positioned in different places. These positions were 12.5^o and 45^o relative to the feed direction and directed toward the rake face to give a possible lubricating effect. Those positions gave tool life data of 2.9 minutes and 5.7 minutes for the positions 12.5^o and 45^o respectively.

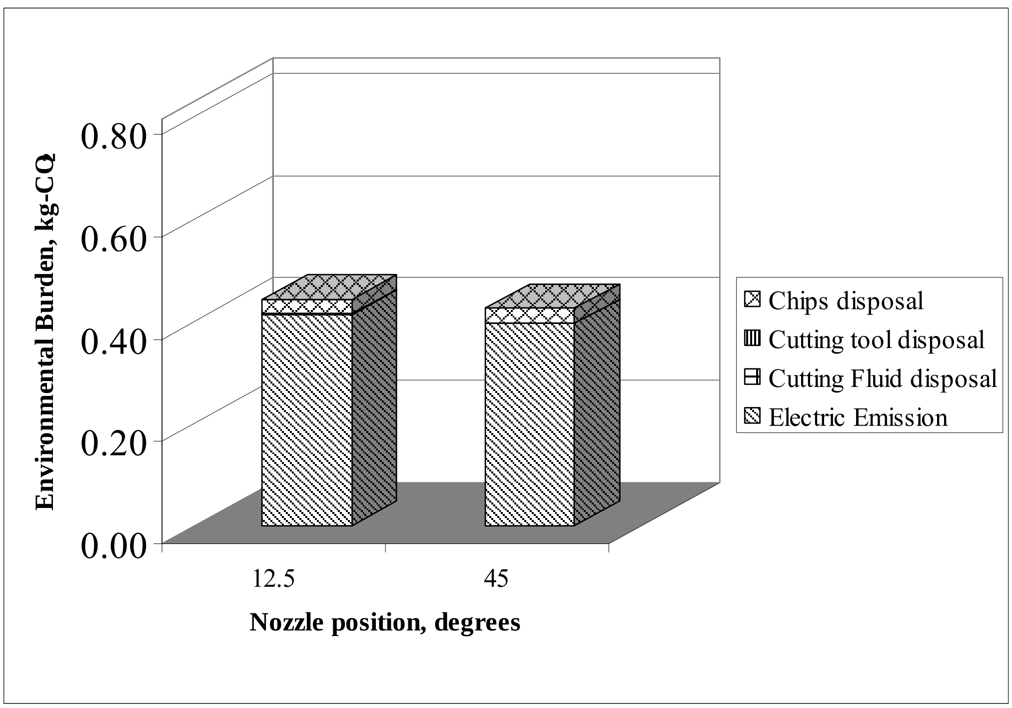


Figure 7.8 Environmental burden of MQL application for nozzles in different positions when machining 12-nested components

Figure 7.10, reveals that improved machining performance has no significant effect on reducing environmental performance as there is a two-fold increase in tool life. As shown in Table 7.5, improved cutting performance affects tool life and, however, only reduces the environmental burden slightly. As in reduced cycle time, the environmental burden is also dominated by the demand for electrical energy. Therefore, it can be concluded that improved cutting performance has no significant effect on the magnitude of the environmental burden compared to reduced cycle time, especially in respect of the electrical energy required.

Table 7. 5 Environmental burden estimation for improved cutting performance

No	Environmental burden criterion	Nozzle position	
		12.5 degrees ($kg-CO_2$)	45 degrees ($kg-CO_2$)
1	Electric Emission	0.41	0.39
2	Cutting Fluid disposal	0.00	0.00
3	Cutting tool disposal	0.00024	0.00015
4	Chips disposal	0.03	0.03
	Total	0.443	0.424

7.6 Conclusions

An improved environmental evaluation tool has been developed in this study. The environmental analysis of the impact categories of different machining environments was evaluated. Additionally, using the environmental evaluation tool, the effect of reduced cycle times and improved cutting performance on the environmental burden has been set and it opens an approach for selecting the appropriate cutting conditions that will help in reducing the environmental burden. From the analysis, there are important conclusions;

- The environmental burden of end milling is dominated by the use of electrical energy. Meanwhile, chip, cutting fluid and cutting tool disposal are relatively insignificant. The environmental burden caused by disposal of cutting fluid is significant in terms of acidification, eutrophication, photochemical oxidants and human toxicity, but it is relatively marginal compared to global warming potential. Therefore, it is conceivable that the global warming potential is the major consideration necessary in the energy footprint evaluation.
- For all impact categories, the end milling process using flood cooling shows the highest magnitude for environmental burden, in terms of either electrical generation or waste streams. This conclusion has, indeed, affirmed the impact of cutting fluid usage on the environment.
- Increasing the cutting speed and feed per tooth in a cutting operation would help in reducing the environmental burden. Significant reduction can be obtained when the cutting operation is performed at higher cutting speeds and feed per

tooth. However, this condition is limited by the capability of the tool to withstand high cutting temperatures.

- Furthermore, manipulating the material removal rate is an effective strategy for reducing the environmental burden associated with the direct impact of a machining process. This conclusion is based on the machine tool being the boundary and the embodied environmental burden of machining inputs has not been considered as this is taken as outside the machine shop boundary and beyond the control of the machinist.
- Finally, the study has shown that the environmental burden is mostly dominated by the demand for electrical energy. Thus, in estimating the environmental burden, evaluation of the demand for electrical energy in the cutting operation is sufficient to distinguish the effect of cutting conditions on the environmental burden. Additionally, based on the electrical energy evaluation, it can help in selecting cutting conditions for environmentally friendly or green cutting processes.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

8.1 Conclusions

Dry High speed milling is increasingly important for significantly cutting down manufacturing cycle times and reducing the environmental burden of machining processes. Near dry machining can be implemented through the use of minimum quantity lubricants (MQL). The knowledge gap addressed in this investigation relates to the selection of optimum cutting conditions for HSM with MQL, defining an optimum setting for the MQL nozzle and evaluating the environmental burden of the machining processes.

Interesting and significant findings that contribute to the advancement of knowledge in the area of machining using MQL application were reported. These key findings are;

- The most significant process variable for improving tool life in HSM roughing operations was the need for higher MQL flow rate. Thus the volumetric flux of delivered MQL or efficiency to MQL delivery is important in controlling tool performance and reducing wear rate.
- In high speed milling under MQL the selection of the ratio between feed per tooth and cutting edge radius is a major factor that influences surface finish. This condition prevails because HSM finishing operations are done at very low feed per tooth and the so called size effect is important as driven by highly

negative effective rake angles. Thus, for high speed milling finishing operations the ratio between feed per tooth and tool edge radius should be monitored because it sufficiently influences the surface finish.

- Taguchi experimental designs and analysis of variable concluded that in high speed milling of tool steels using carbide tools and MQL coolant, lower cutting speed, higher feed per tooth (minimising size effect impact), moderate depth of cut and a higher MQL volumetric flow rate (better lubrication) are essential for extending the life of the cutting tool.
- The positioning of the nozzle at an appropriate inclination to the tool-entry side and engagement position can massively improve the effectiveness of MQL application. This is a new and novel contribution of this thesis.
- When machining tool steels at rotational speeds up to 10,000 rpm, the nozzle should be directed toward the rake face and located at the closest distance to the end-milled face and tool engagement point (increase wiping angle) to enable effective fluid delivery. Meanwhile for rotational speeds above 10,000 rpm, the position of the nozzle has to be moved away from the engagement point. This allows delivery of high volumes of cutting fluid before the tool engages. This is essential to compensate for the short tool-workpiece interaction time.
- In respect of energy consumption and waste stream, the environmental burden of MQL is significantly lower than that of flood coolant due to use of reduced fluid volume and less power demand for fluid pumping operations.
- In the case of machining single components, the effect of non-productive activities such as setup time and tool change has a dominant effect on the carbon footprint and is more critical than the choice of machining environment.
- The environmental burden of milling is primarily influenced by the electricity demanded by the process, rather than by the volume of solid waste and/ fluid waste. Knowing the electrical energy requirements of a machining process is a good indicator of the environmental burden.

8.2 Recommendations

Based on this research, potential areas are highlighted for improving MQL application as follows;

- Nozzle position has significant contribution in improving tool wear performance. From the study, fluid trapping can help in retarding tool wear progression. The capability of fluid particles to remain on the surface might be affected by fluid particle size, its properties and tool surface material. Therefore, the atomisation of MQL fluid, MQL fluid properties e.g. viscosity and fluid interaction with cutting tool surface morphology and coatings may be areas for further research.
- The work in this thesis is based on the environmental impact of direct electricity demanded by the end milling process; for those interested in extending the boundary beyond the machine tool and company then the impact of the embodied footprints of process inputs can be considered. This can include the energy embodied in cutting tools, cutting fluid, workpiece materials, and chips.
- This work was based on tool steel. Therefore, further work is required to optimise MQL quantity and cutting variables for other workpiece materials. Additionally, the minimum amount of cutting fluid supplied to cutting zones should be theoretically defined thus the terminology of minimum quantity lubrication can be made clear.
- From the study of effect nozzle positions on tool performance, it was found that flank wear growth rate for all observed nozzle positions (i.e. 12.5^o, 45^o and 135^o) was comparable up to certain cutting time. Further increase of cutting time promoted divergence of flank wear progression among the observed nozzle positions. There is need for further research to understand the mechanism responsible for the different wear rates observed at the extended machining times.

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Appendix 1: Cutting Edge Radius

Definition:

Cutting-edge radius can be defined; for sharp edge, as intersection of the tool face (Rake Face) and tool flank. Meanwhile, for rounded edge, it can be represented by a curvature that connects between tool face plane (rake face) and tool flank plane [132].

Many methods have been proposed in respect to cutting-edge measurement. In general, all proposed method use edge profile approach, where it is measured by means of wide variety of optical sensor [132]. Figure App3.1 and Figure App3.2 show the cross section of the insert and profile of cutting edge respectively.

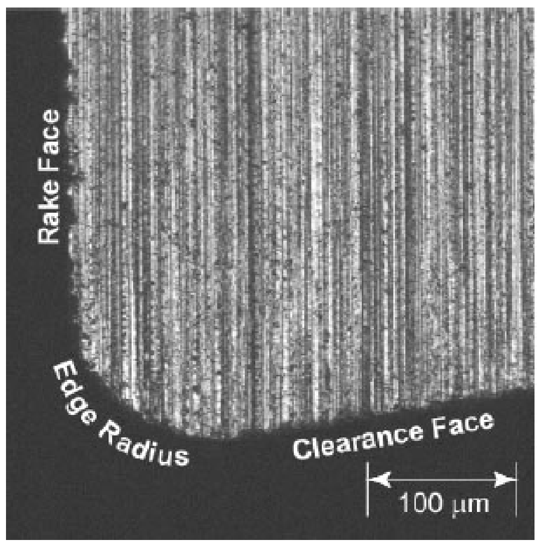


Figure App3. 1 Sample edge cross-section as viewed under optical microscope at 100X [177]

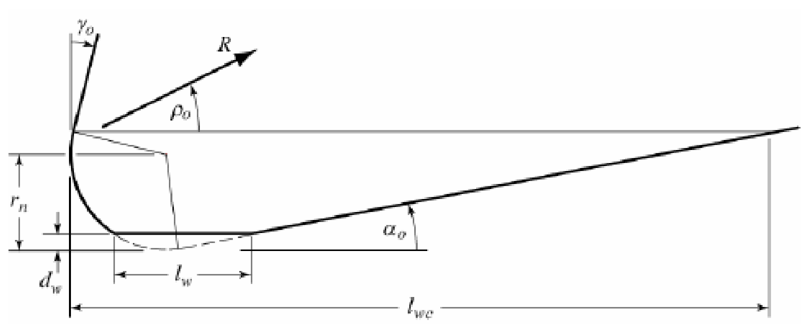


Figure App3. 2 Geometry of and edge-radius tool with a flank wear land [177]

Here, in this section, it is tried to describe two methods that are most likely used to measure the cutting-edge radius. The first method is that was developed by Assai et al [130]. By this method, the edge-radius is measured by marking the profile of insert's cross section (Figure App3.3) along rake face plane and flank face plane using Scanning Electron Microscope (SEM). Thus, a circle and / or a parabolic curve fit intersection between those two planes. The radius created by fitted circle and/ or parabolic curve is defined as cutting-edge radius of the insert.

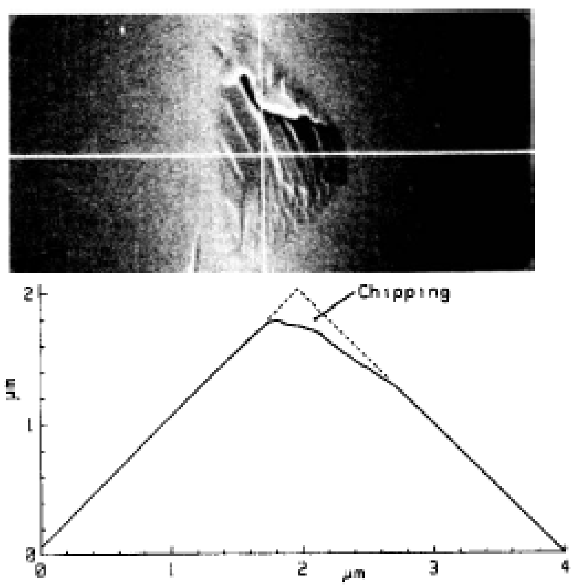


Figure App3. 3 SEM image and sectional curve for chipped cutting edge [130]

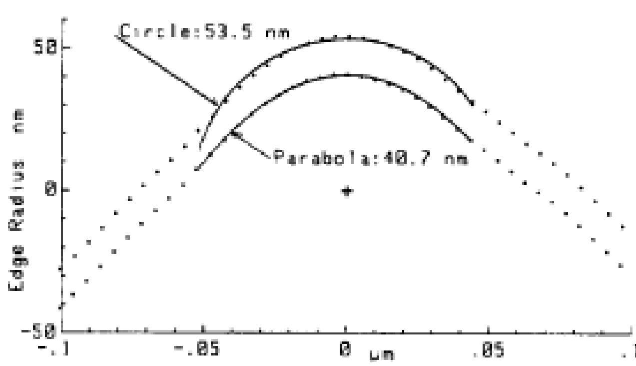


Figure App3. 4 Comparison between circle and parabola, calculated by the least square method [130]

After comparing between the circle and parabolic approximation, Assai et al [130] concluded that parabolic approximation is more suitable in determining edge radius. A parabolic approximation for different edge profile can be seen in Figure App3.5.

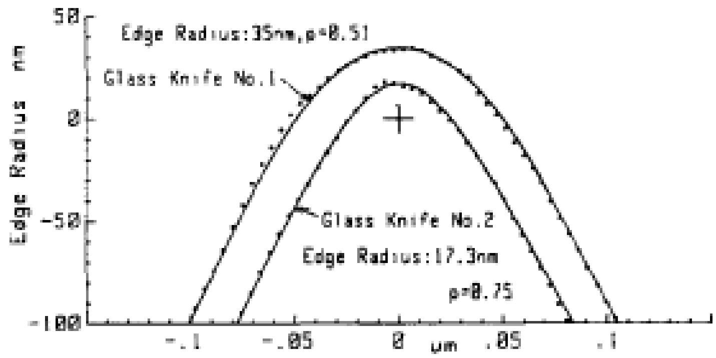


Figure App3. 5 Cutting edge radius of glass knife [130]

The second method was developed by Schimmel et al [131] using white light interferometer to obtain edge profile as shown in Figure App3.6. Thus, the edge radius value is achieved by fitting the intersection curve with circle. The radius of the circle is taken as cutting-edge radius value.

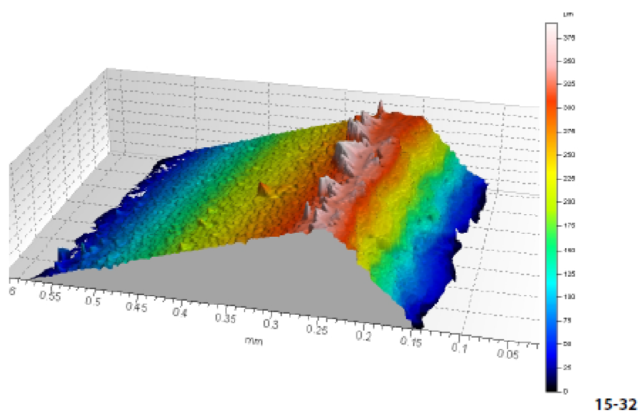


Figure App3. 6 3 Dimensional Cutting edge profile

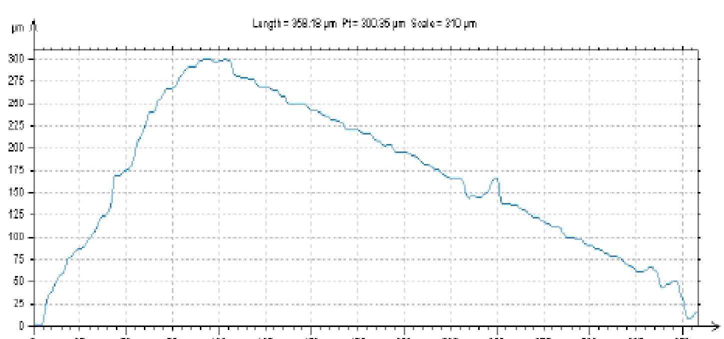


Figure App3. 7 Cutting edge profile detected by using 3D Profilometry [178]

In order to confirm the two methods described above, a geometrical evaluation has been carried out as shown in Figure App3.8 and Figure App3.9. In Figure App3.8, the circle was fitted on the edge of insert's cross section and it must create two points intersection on the imaginary planes that are drawn as projected plane of rake face and flank face. Thus from the centre of fitted circle, the tangent was drawn and it must intersect the imaginary planes. The length of this tangent can represent the radius value. By this approach, the tangent intersects the imaginary plane of rake face at out of circle area.

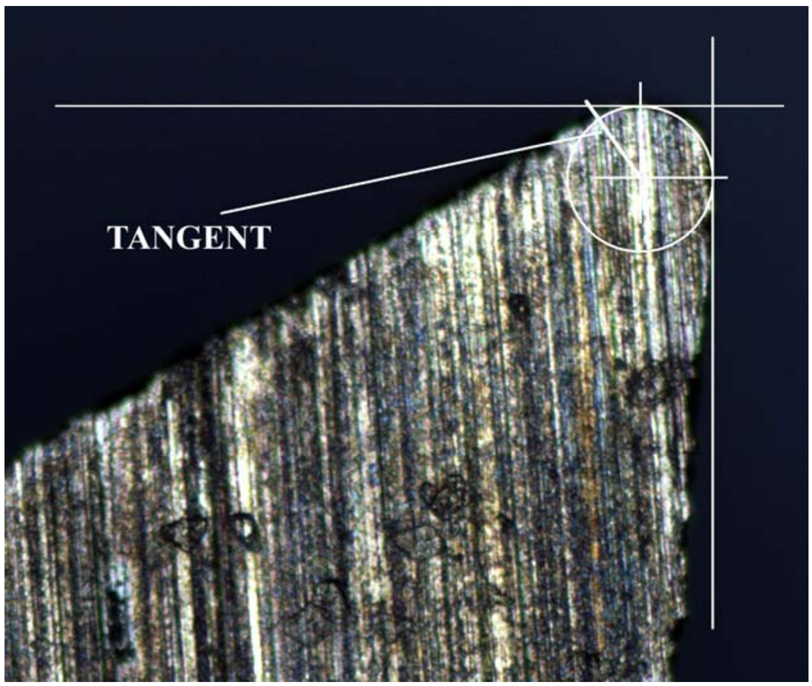


Figure App3. 8 Circle-square approximation

Furthermore, the same principle was also tried to apply but with having different imaginary plane approach as depicted in Figure App3.9. In this approach, both imaginary planes are lying on the rake face and the flank face. Thus, the same procedure for creating the tangent as in Figure App3.8 was also applied. Indeed, with this method, the tangent could intersect the imaginary planes precisely. Therefore, the later approach is most likely preferable in measuring the cutting-edge radius and it affirms that method proposed by two authors at early discussion in this section is an appropriate approach in obtaining cutting edge-radius value.

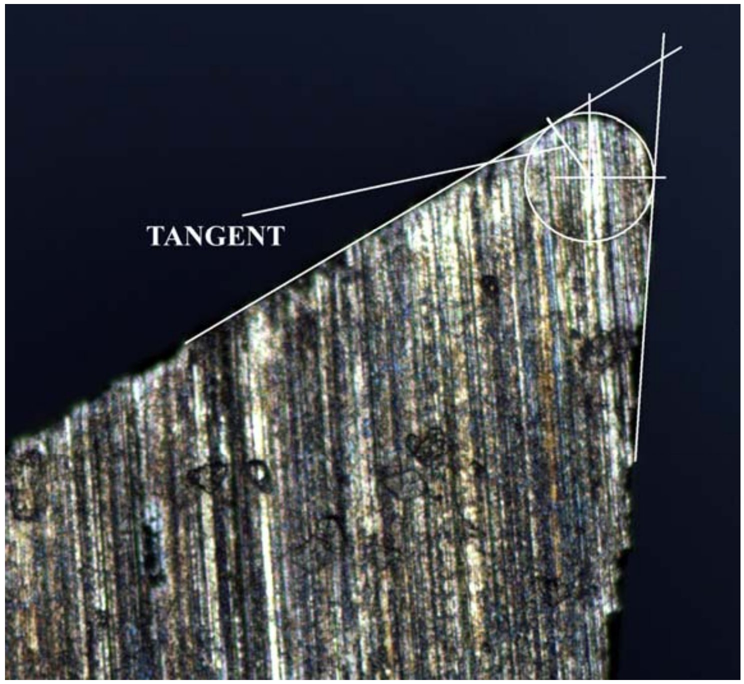


Figure App3. 9 Circle-triangular approximation

<u>Data for edge radius measurement</u>

Measurement No	**r-value (µm)**
1	61
2	60
3	63
4	63
Average r-value	62

Appendix 2: Data and calculation of S/N ratio and ANOVA for tool wear and surface roughness response

A. Tool wear raw data, Signal to Noise Ratio and ANOVA results using manual calculation

No.	Parameters Combination				
	S	F	DoC	Q	AverageT
	rpm	mm/min	mm	click	
1	15924.00	836.25	1.50	40.00	67.920
					67.930
2	11943.00	806.25	1.50	30.00	65.140
					65.070
3	8957.00	806.25	1.50	50.00	58.010
					58.000
4	15924.00	1433.30	1.13	30.00	61.320
					61.040
5	11943.00	604.32	1.13	50.00	62.620
					62.850
6	8957.00	604.50	1.13	40.00	62.840
					62.700
7	15924.00	1074.75	0.85	50.00	59.540
					59.480
8	11943.00	1074.75	0.85	40.00	67.400
					67.480
9	8957.00	453.22	0.85	30.00	63.960
					64.010

No.	Parameters Combination				VB	Ý²	SN	
	Vc	f	DoC	Q				
	rpm	mm/min	mm	click				
1	225.00	0.81	1.37	16.80	63.96	4090.88	4094.08	-36.12
					64.01	4097.28		
2	225.00	1.13	0.02	22.40	62.84	3948.87	3940.08	-35.96
					62.70	3931.29		
3	225.00	1.45	2.42	29.90	58.01	3365.16	3364.58	-35.27
					58.00	3364.00		
4	300.00	0.05	1.82	29.90	62.62	3921.26	3935.69	-35.95
					62.85	3950.12		
5	300.00	0.07	2.42	16.80	65.14	4243.22	4238.66	-36.27
					65.07	4234.10		
6	300.00	0.09	1.37	22.40	67.40	4542.76	4548.16	-36.58
					67.48	4553.55		
7	400.00	0.05	2.42	22.40	67.92	4613.13	4613.81	-36.64
					67.93	4614.48		
8	400.00	0.07	1.37	29.90	59.54	3545.01	3541.44	-35.49
					59.48	3537.87		
9	400.00	0.09	1.82	16.80	61.32	3760.14	3743.01	-35.73
					61.04	3725.88		
					1137.31	72039.02		

Level	Vc	fz	ap	Q
1	-107.35	-108.71	-108.19	-108.13
2	-108.80	-107.72	-107.64	-109.17
3	-107.86	-107.58	-108.18	-106.71
Delta	1.45	1.13	0.54	2.46
Rank	2	3	4	**1**

Analysis of Variances (ANOVA) procedure

1	SSTot	=	179.35		
	CF	=	71859.67		
2	Si				
	A1	=	Y1+Y2+Y3	=	
	A2	=	Y4+Y5+Y6	=	
	A3	=	Y7+Y8+Y9	=	
	B1	=	Y1+Y4+Y7	=	
	B2	=	Y2+Y5+Y8	=	
	B3	=	Y3+Y6+Y9	=	
	C1	=	Y1+Y6+Y8	=	
	C2	=	Y2+Y4+Y9	=	
	C3	=	Y3+Y5+Y7	=	
	D1	=	Y1+Y5+Y9	=	
	D2	=	Y2+Y6+Y7	=	
	D3	=	Y3+Y4+Y8	=	
3	SSe	=	0.084		
4	MSi	=	SSi/Dfi		
	MSA	=	18.8837		
	MSB	=	13.0673		
	MSC	=	4.1106		
	MSD	=	53.5702		
	MSe	=	0.0094		
5	Fi	=	MSi/MSe		
	FA	=	2017.254		
	FB	=	1395.912		
	FC	=	439.110		
	FD	=	5722.633		
	Fe	=	1.000		
6	S'i	=	SSi-(dfixMSe)		
	S'A	=	37.749		
	S'B	=	26.116		

Ai	Ai^2	Ai^2/nk	SSi	
369.52	136545.03	71897.44	37.767478	
390.56	152537.11			
377.23	142302.47			
389.29	151546.70	71885.80	26.134578	
374.77	140452.55			
373.25	139315.56			
381.87	145824.70	71867.89	8.221111	
373.37	139405.16			
382.07	145977.48			
380.54	144810.69	71966.81	107.140411	
396.27	157029.91			
360.50	129960.25		∑	179.263578

	S'C	=	8.202	
	S'D	=	107.122	
	S'e	=	-0.019	
7	Pi	=	S'i/STx100%	
	PA	=	21.058%	
	PB	=	14.572%	
	PC	=	4.584%	
	PD	=	59.739%	
	Pe	=	0%	

9 Anova Table

Source	Df	SS	MS	F	Contribution (%)	P-value
Vc	2	37.77	18.88	2017	20%	0.000000000001
Rf	2	26.13	13.07	1396	15%	0.000000000006
Rap	2	8.22	4.11	439	5%	0.000000001066
Q	2	107.14	53.57	5723	60%	0.000000000000
Error	9	0.08	0.01		0%	1.000000000000
Total	17	179.35	89.64		100.00%	

Predicting the value for optimum setting based on S/N ratio

µopt	=	A1 + B3 + C2 + D3 - 3T			
	=	56.555			
CI	=	0.094			
µopt	=	56.5	-	56.6	
µpresent	=	A2 + B1 + C1 + D2 - 3T			
	=	70			
	=	70.02	-	70.21	
µgain	=	µpresent - µopt			
		13.558			13.558
		19%			19%
		58.000			
		50.000			
		13.8%			

B. Surface roughness raw data, Signal to Noise Ratio and ANOVA results using manual calculation

No.	Parameters Combination				Surface Roughness Data (µm)																					Yi^2		Yitotal	Yave
	S	F	DoC	Q	Vertical										Horizontal										Ra				
	rpm	mm/min	mm	click	1	2	3	4	5	6	AverageV	V^2	SN		1	2	3	4	5	6	7	8	9	AverageH					
1	225.00	0.81	0.85	16.80	0.34	0.30	0.36	0.26	0.36	0.26	0.31	0.098	0.095	10.209		0.14	0.14	0.14		0.12		0.12		0.132	0.223	0.050	0.050	0.463	0.231
					0.28	0.28	0.38	0.30	0.28		0.30	0.092			0.20					0.16	0.16	0.18	0.18	0.176	0.240	0.058	0.058		
2	225.00	1.13	1.13	22.40			0.54	0.52	0.50	0.54	0.53	0.276	0.263	5.804	0.18	0.22	0.16		0.22	0.22	0.22	0.20		0.203	0.364	0.132	0.132	0.725	0.363
					0.46	0.54	0.48			0.52	0.50	0.250			0.28		0.22	0.16	0.20	0.20	0.22	0.28		0.223	0.361	0.131	0.131		
3	225.00	1.45	1.50	29.90		0.82		0.92		0.88	0.87	0.763	0.586	2.320				0.16	0.18		0.16	0.18	0.14	0.164	0.519	0.269	0.269	0.981	0.490
						0.64		0.64		0.64	0.64	0.410			0.28	0.24			0.28	0.36	0.26			0.284	0.462	0.213	0.213		
4	300.00	0.81	1.13	29.90	0.34				0.28	0.34	0.32	0.102	0.084	10.772	0.18	0.16				0.12		0.18	0.16	0.160	0.240	0.058	0.058	0.446	0.223
					0.22	0.28		0.26		0.26	0.26	0.065			0.20	0.16	0.14	0.14		0.14				0.156	0.206	0.042	0.042		
5	300.00	1.13	1.50	16.80	0.60		0.50		0.56		0.55	0.306	0.220	6.570	0.16	0.14	0.16				0.12	0.14		0.144	0.349	0.122	0.122	0.620	0.310
					0.36	0.36	0.38				0.37	0.134			0.18		0.16			0.18		0.18	0.18	0.176	0.271	0.074	0.074		
6	300.00	1.45	0.85	22.40	0.58		0.54	0.58			0.57	0.321	0.221	6.563	0.26	0.14		0.28	0.20	0.26			0.14	0.213	0.390	0.152	0.152	0.657	0.329
						0.34	0.34		0.36		0.35	0.120			0.20			0.20		0.18	0.18		0.18	0.188	0.267	0.071	0.071		
7	400.00	0.81	1.50	22.40	0.66	0.72			0.70		0.69	0.481	0.346	4.607		0.12				0.16	0.18	0.14	0.12	0.144	0.419	0.175	0.175	0.757	0.378
					0.56		0.38			0.44	0.46	0.212			0.20	0.22		0.18			0.26		0.22	0.216	0.338	0.114	0.114		
8	400.00	1.13	0.85	29.90		0.38		0.40		0.38	0.39	0.150	0.207	6.851			0.22		0.24	0.30		0.22	0.22	0.240	0.313	0.098	0.098	0.706	0.353
							0.52	0.52	0.50		0.51	0.264			0.20			0.36	0.16	0.32			0.32	0.272	0.393	0.154	0.154		
9	400.00	1.45	1.13	16.80				0.56	0.54	0.54	0.55	0.299	0.329	4.822		0.34	0.22		0.20	0.20	0.30	0.22	0.22	0.243	0.395	0.156	0.156	0.905	0.452
					0.60		0.60		0.60		0.60	0.360			0.26		0.20	0.52		0.52		0.60		0.420	0.510	0.260	0.260		
											8.76	4.70											∑	3.754	**6.259**	**2.329**	**2.329**		**3.129**

Level	Vc
1	9.23
2	10.88
3	8.07
Delta	2.81
Rank	2

fz
11.37
9.30
7.50
3.87
1

ap
10.41
9.55
8.22
2.18
3

Q
9.88
8.91
9.39
0.97
4

Analysis of Variances (ANOVA) procedure

1	SSTot	=		0.153						
	CF	=		2.176						
2	Si					Ai	Ai^2	Ai^2/nk	SSi	
	A1	=	Y1+Y2+Y3		=	2.169	4.703	2.213	0.0363	
	A2	=	Y4+Y5+Y6		=	1.723	2.968			
	A3	=	Y7+Y8+Y9		=	2.367	5.605			
	B1	=	Y1+Y4+Y7		=	1.665	2.772	2.241	0.0645	
	B2	=	Y2+Y5+Y8		=	2.051	4.208			
	B3	=	Y3+Y6+Y9		=	2.543	6.466			
	C1	=	Y1+Y6+Y8		=	1.826	3.334	2.200	0.0236	
	C2	=	Y2+Y4+Y9		=	2.076	4.308			
	C3	=	Y3+Y5+Y7		=	2.357	5.557			
	D1	=	Y1+Y5+Y9		=	1.987	3.950	2.179	0.00245	
	D2	=	Y2+Y6+Y7		=	2.139	4.577			
	D3	=	Y3+Y4+Y8		=	2.132	4.546		∑	0.127
3	SSe	=		0.0259						
4	MSi	=	SSi/Dfi							
	MSA	=		0.0182						
	MSB	=		0.0323						
	MSC	=		0.0118						
	MSD	=		0.0012						
	MSe	=		0.0029						
5	Fi	=	MSi/MSe							
	FA	=		6.309						
	FB	=		11.209						
	FC	=		4.091						
	FD	=		0.425						
	Fe	=		1.000						
6	S'i	=	SSi-(dfixMSe)							
	S'A	=		0.031						
	S'B	=		0.059						
	S'C	=		0.018						

	S'D	=	-0.003	
	S'e	=	0.000	
7	Pi	=	S'i/STx100%	
	PA	=	24%	
	PB	=	42%	
	PC	=	15%	
	PD	=	2%	
	Pe	=	17%	

9 Anova Table

Source	Df	SS	MS	F	Contribution (%)	P-value
Vc	2	0.036	0.018	6.309	24%	0.0194
fz	2	0.065	0.032	11.209	42%	0.0036
ap	2	0.024	0.012	4.091	15%	0.0545
Q	2	0.002	0.001	0.425	2%	0.666
Error	9	0.026	0.003		17%	
Total	17	0.153	0.066		100.00%	
		0.127				

Predicting the value for optimum setting based on S/N ratio

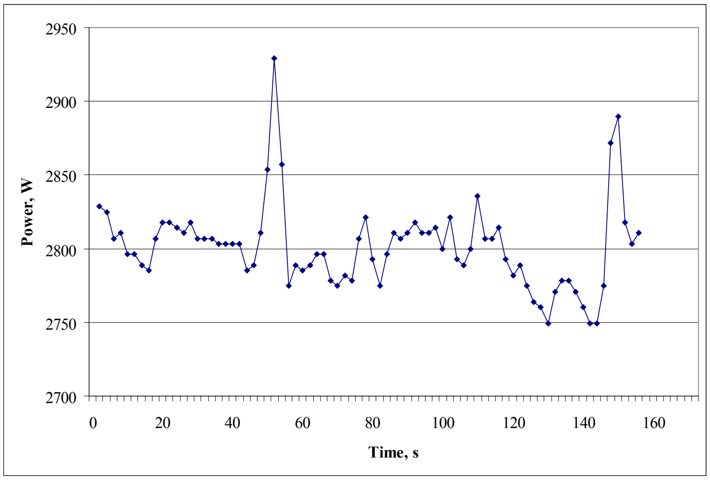
µopt	=	A2 + B1 + C1 + D2 - 3T			
	=	0.157		0.15	
CI	=	0.0521			
µopt	=	0.105	-	0.209	
µpresent	=	A1 + B3 + C3 + D3 - 3T			
	=	0.490		0.223	
	=	0.438	-	0.542	
µgain	=	µpresent - µopt			
		0.073		0.333	
		33%		61%	

Appendix 3: Energy profile and calculation for direct energy model

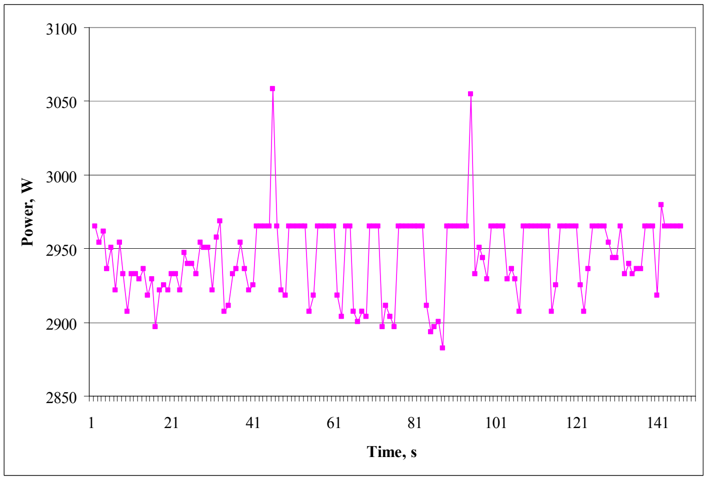
Appendix 3.1 Basic Power

Appendix 3.1.1 Idle Power

Appendix 3.1.1.1 Idle power without tool holder

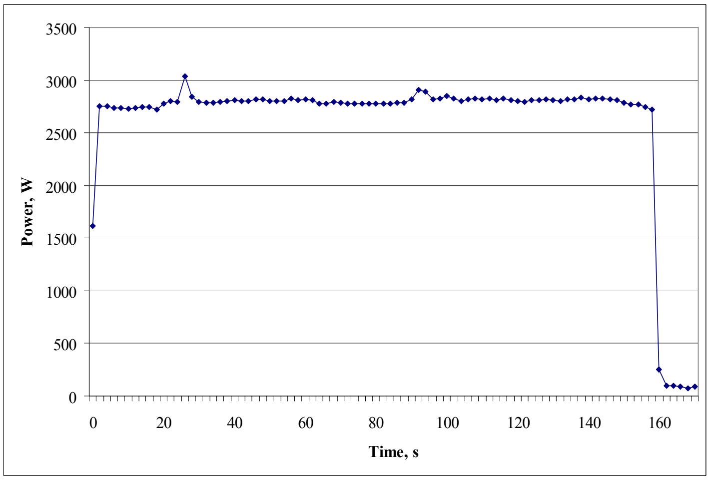


Appendix 3.1.1.2 Idle power with tool holder

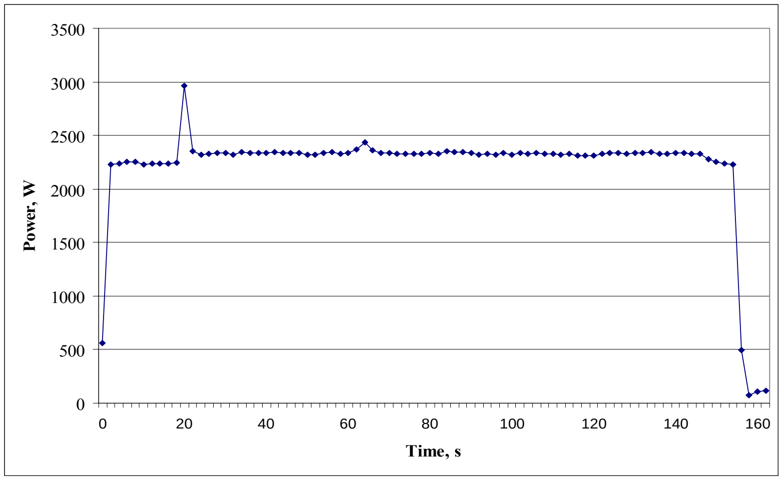


Appendix 3.1.2 Ready power

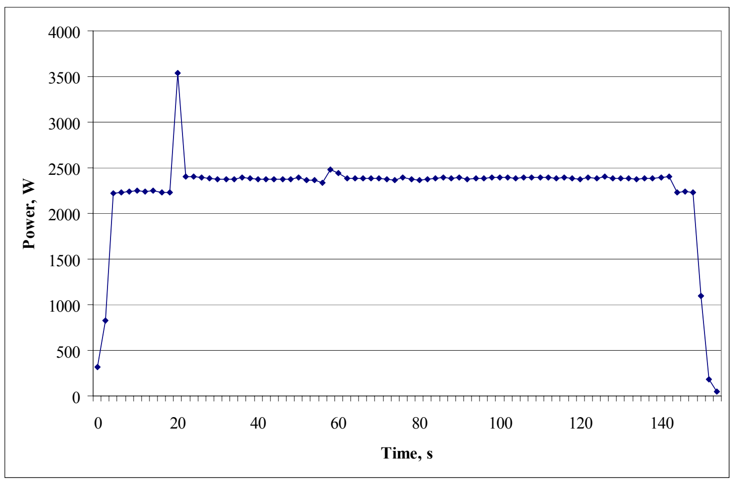
Vc=100 m/min



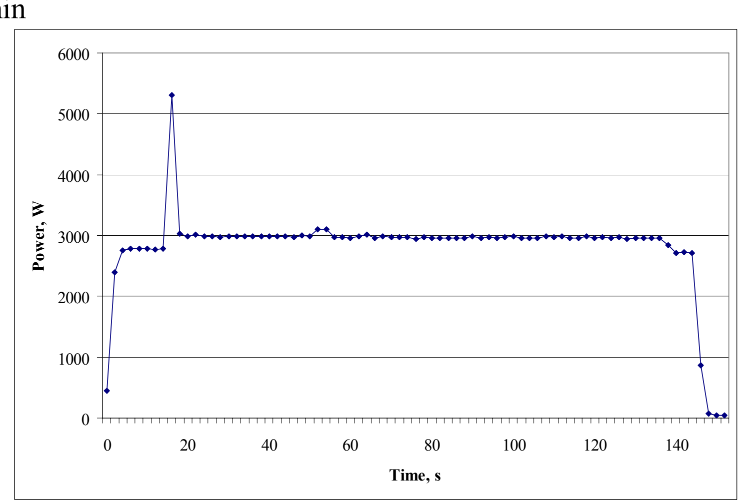
Vc=200 m/min



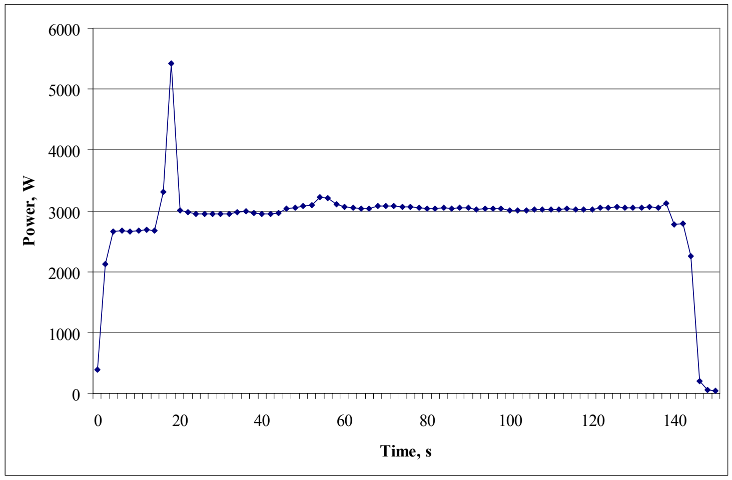
Vc=300 m/min



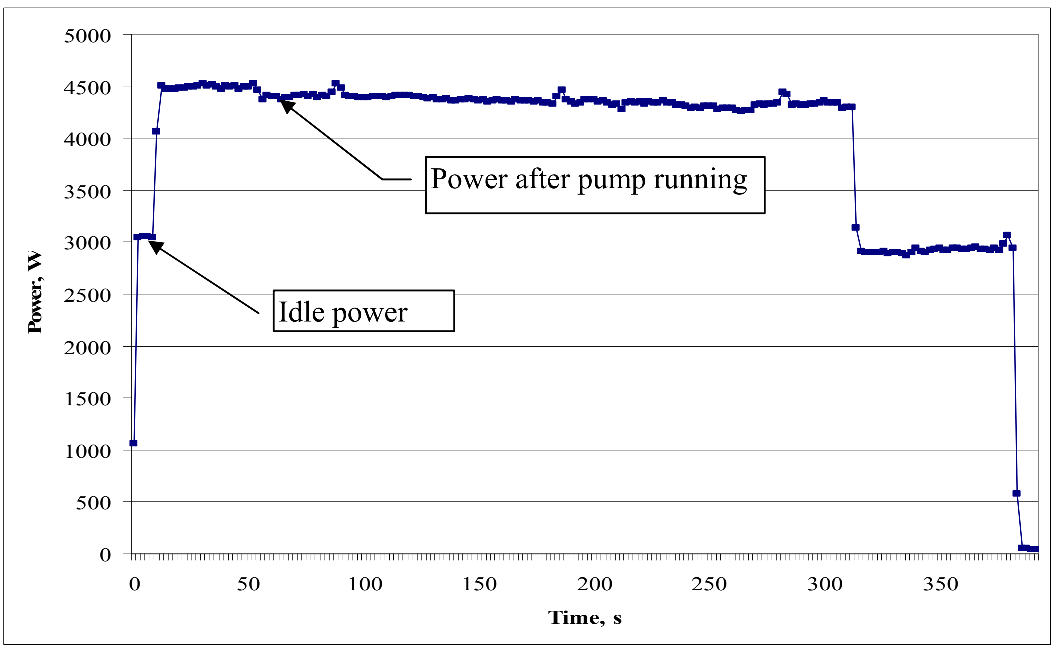
Vc=400 m/min



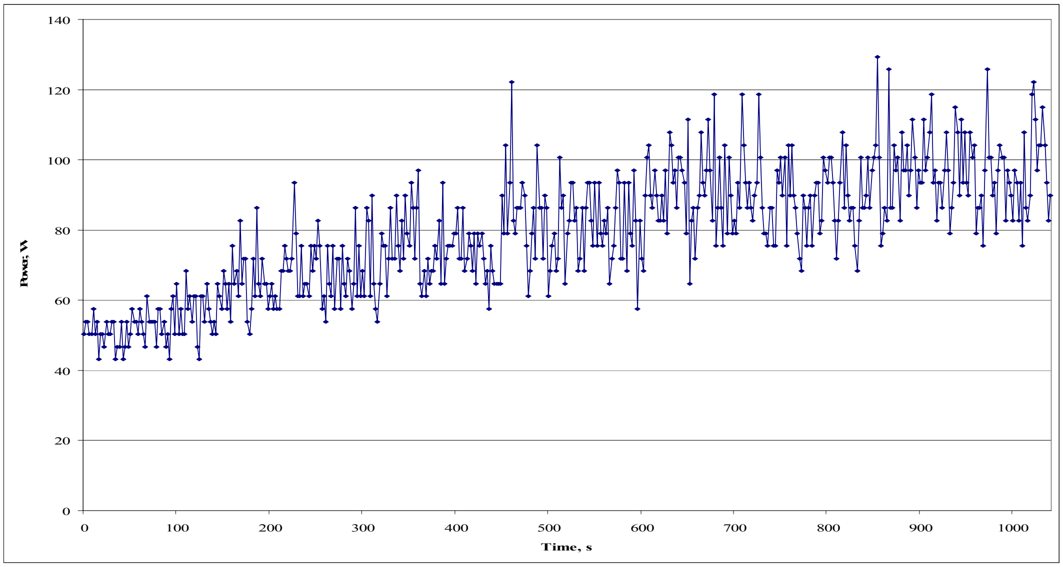
Vc=500 m/min



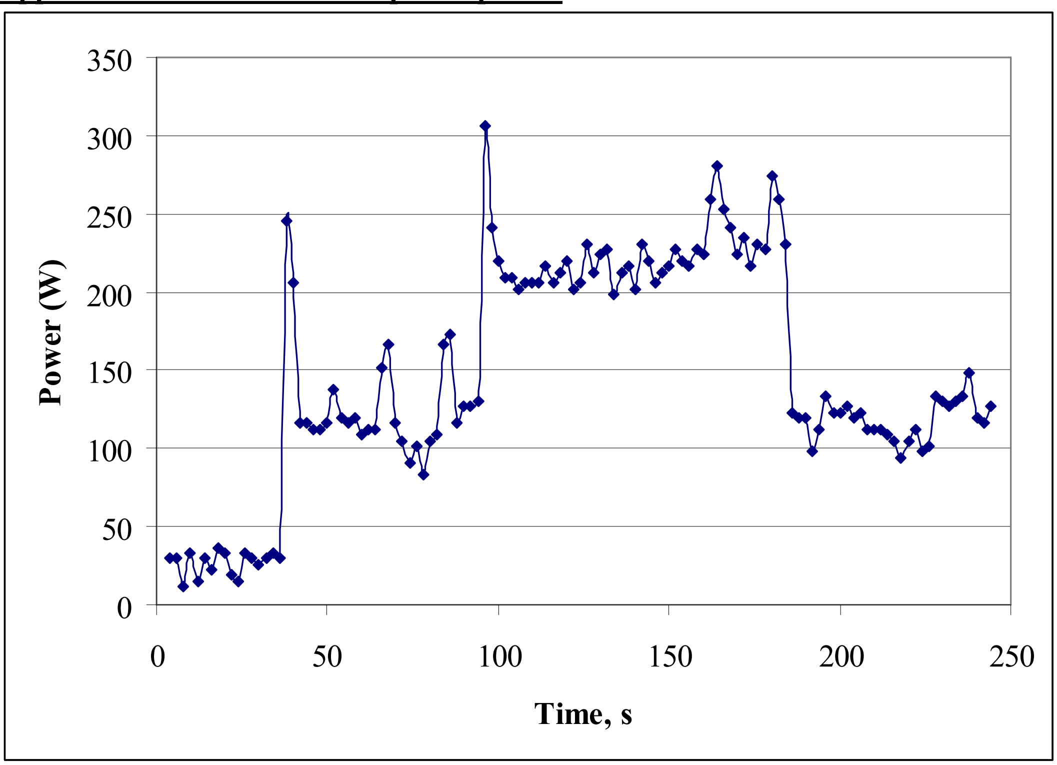
Appendix 3.1.3 Pump idle power



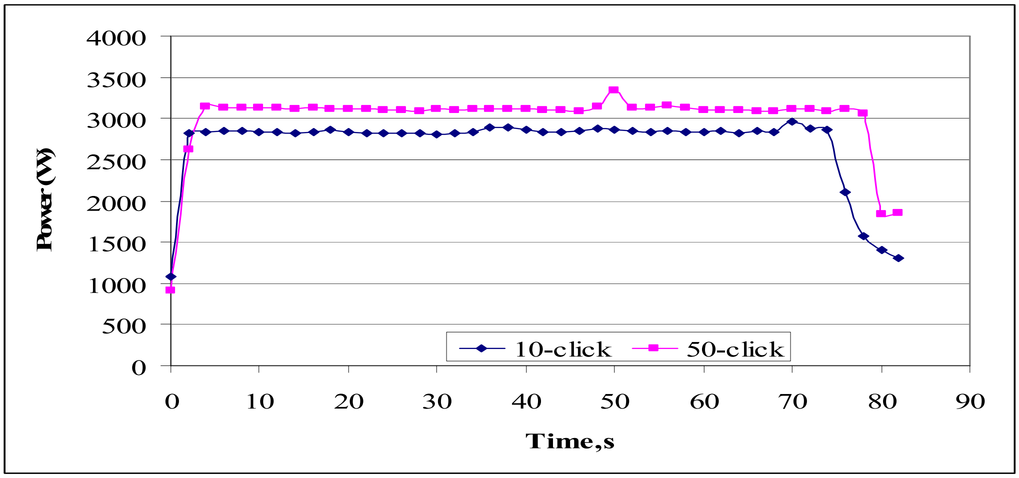
Appendix 3.1.4 Compressor idle power



Appendix 3.1.5 Mist extractor power profile

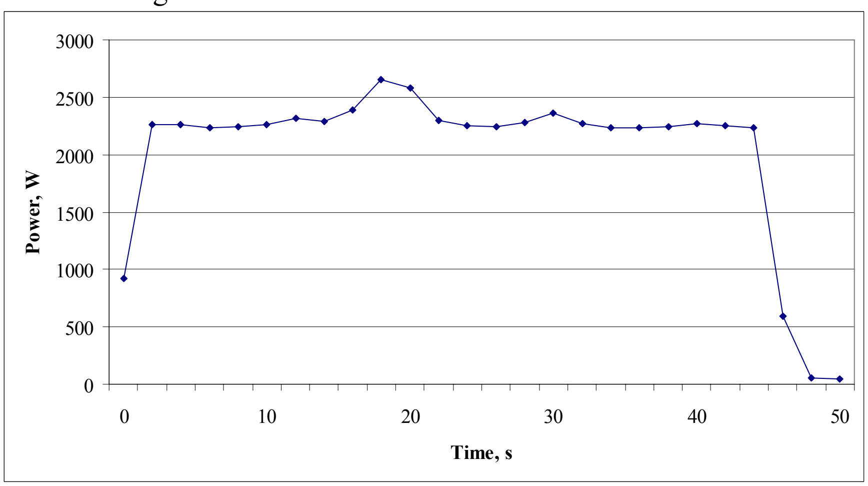


Appendix 3.1.6 UNILUB MQL system power profile

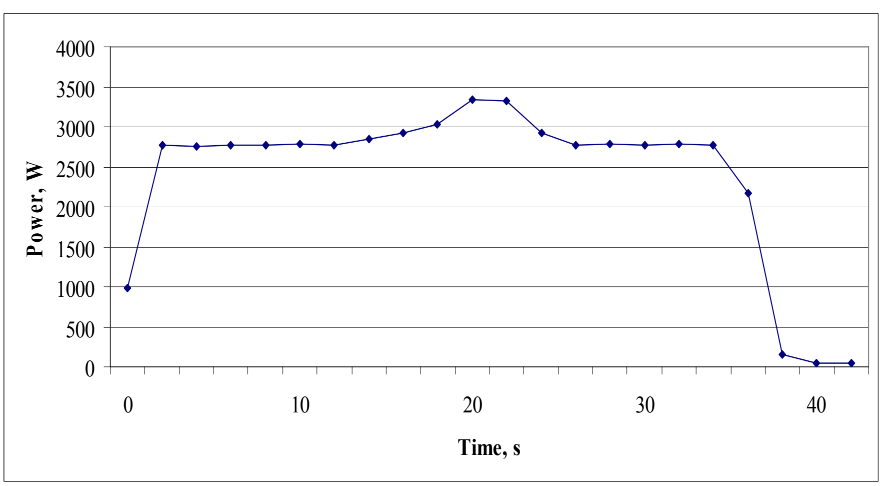


Appendix 3.2 Effect of tool and tool holder weight on energy consumption

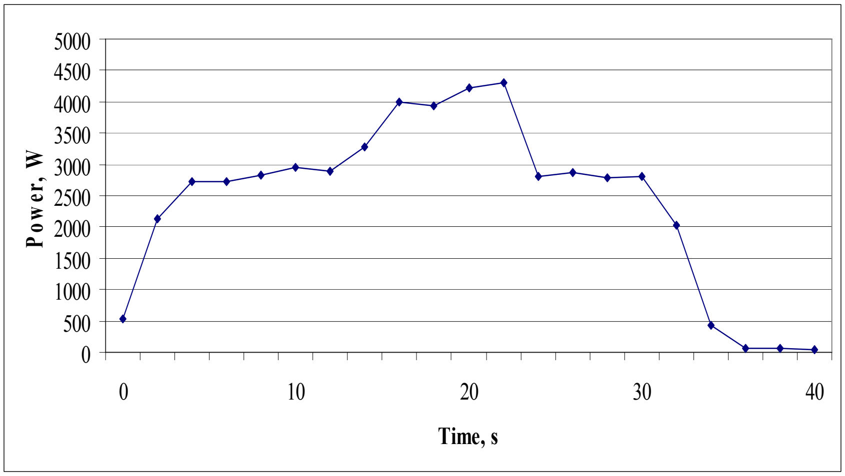
From blank to drilling tool



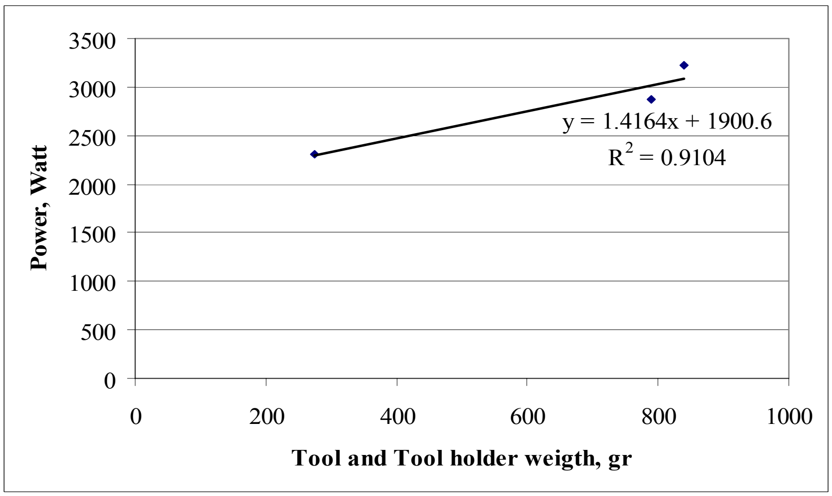
Blank to insert-endmill tool



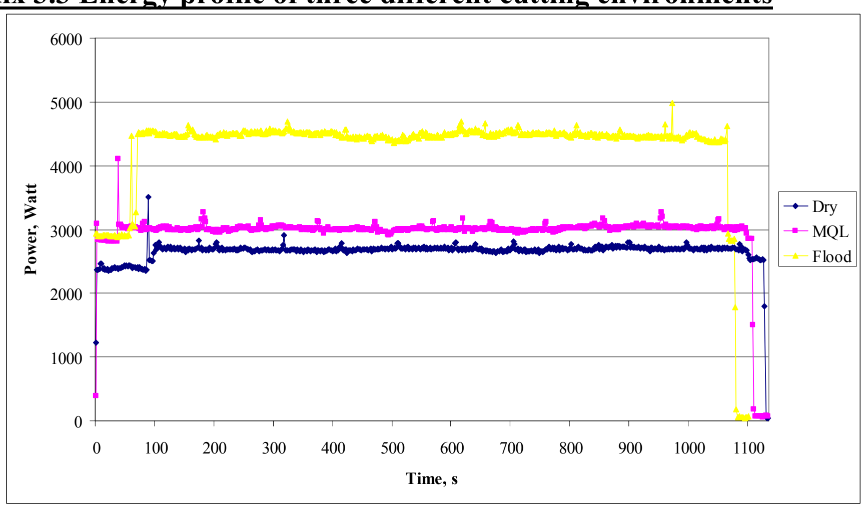
Blank to solid_endmill tool



Tool clasification	Tool weight (g)	Power (W)
Drilling tool	275	2302.941
Insert endmill	790	2874.57
Solid endmill	840	3222.539

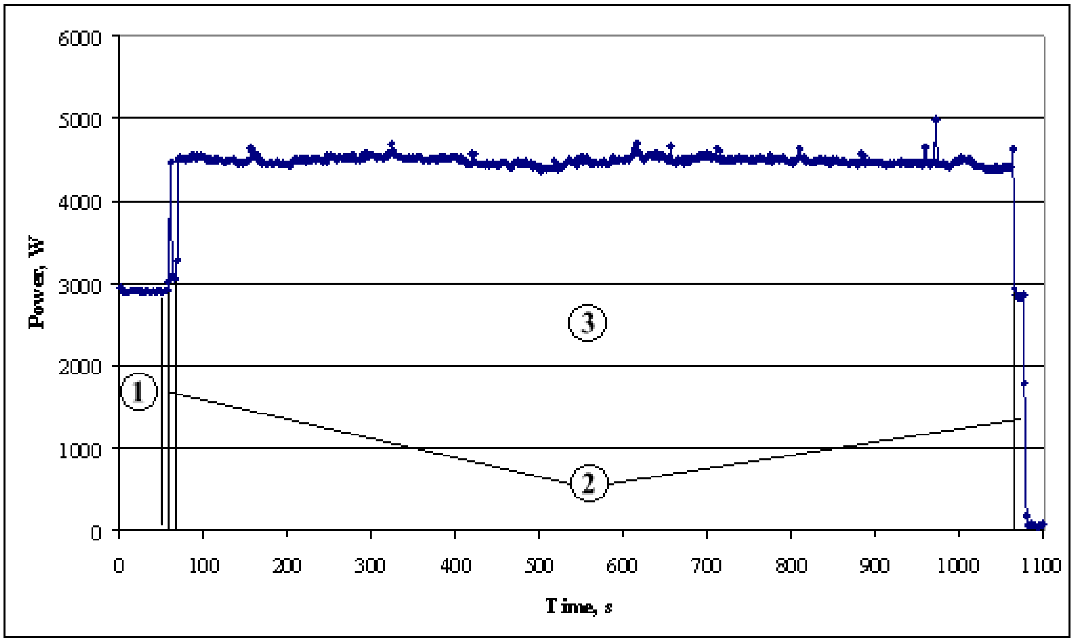


Appendix 3.3 Energy profile of three different cutting environments



Appendix 3.4 Validation

To validate the direct energy model proposed in this study, the flood-cooling environment was taken into account. This is due to higher energy consumption shown in direct energy demand calculation for this cutting environment. Besides, the higher the magnitude of the real current measurement compared to that results in calculation is the better possibility of the model to show its error.



No.	Energy parts	Real		Model		Error	
		Energy demand (J)	Time (second)	Energy demand (J)	Time (second)	Energy	Time
1	Idle	191.70	66	172	60	10 %	9 %
2	Ready	56.30	18	10	4.2	80 %	77 %
3	Cutting	4,450.07	994	2,357	922	11 %	7%
4	Tool change	0		0			
5	Cooling	-(included in cutting energy)		1,566	922		
Accumulative		4,698		4,105		12.6 %	8.5 %

Appendix 3.5 Calculation for determining energy demand and environmental burden based on direct energy model

Appendix 3.5.1 Energy consumption

Appendix 3.5.1.1 Data for machining single components

P_o	2,864	W	(obtained from idle power profile of machine tool)
P_{comp_o}	52	W	(obtained from idle power profile of compressor used in this study)
P_{pump_o}	1516	W	(obtained from idle power of pump used in this study)
$P_{MQL\text{-}o}$	2	W	
$P_{extractor}$	217	W	(obtained from extractor power consumption during the switched on mode)

V_c	350	m/min	
a_p	1.5	mm	
a_e	0.6	mm	
f	0.05	mm/rev	
t_1	60	s	(based on assumption)
t_r	4.2	s	(based on assumption)
t_2	154.8	s	(based on predicted cutting time obtained from simulation)
t_3	18	s	(based on measured time for tool change)
T_{dry}	918	s	(based on tool wear experiment using the same cutting parameter stated above and only for annealed H13 tool steel)
T_{MQL}	1,278	s	(based on tool wear experiment using the same cutting parameter stated above and only for annealed H13 tool steel)
T_{Flood}	1,782	s	(based on tool wear experiment using the same cutting parameter stated above and only for annealed H13 tool steel)
k_{dry}	7.143	Ws/mm^3	(based on results depicted in Figure 6.8)
k_{MQL}	7.104	Ws/mm^3	(based on results depicted in Figure 6.8)
k_{flood}	7.003	Ws/mm^3	(based on results depicted in Figure 6.8)
$\dot{v}$	10.455	mm^3/s	
$Pump_{eff}$		80%	
Q_{pump}	1800	ml/h	
ΔP_{pump_o}	3	bar	
g	9.81	m/s^2	
ρ	1	kg/cm^3	

Appendix 3.5.1.2 Calculations

Here the calculation example was carried out for single component and flood-cooling environment.

1. Calculation of setup energy demand (E_{setup})

$$E_{setup} = P_o t_1$$
$$E_{setup} = 2{,}864x60$$
$$E_{setup} = 172 \text{ kJ}$$

2. Calculation of ready energy demand (E_{ready})

$$P_{ready} = 4{,}662 - 26.7V_c + 0.09V_c^{\,2} - 9x10^{-5}V_c^3$$
$$P_{ready} = 4{,}662 - 26.7x350 + 0.09x350^2 - 9x10^{-5}x350^3$$
$$P_{ready} = 4{,}662 - 9{,}450 + 12{,}250 - 3{,}858.75$$
$$P_{ready} = 2{,}644.65 \text{ W}$$

$$E_{ready} = P_{ready} t_{ready}$$

$$E_{ready} = 2{,}644.65x4.2$$
$$E_{ready} = 11\,\text{kJ}$$

3. Calculation of cutting energy demand (E_{cut})

$$E_{cut} = (P_{ready} + k\dot{v})t_2$$
$$E_{cut} = (2{,}644.65 + 7.003x10.445)x154.8$$
$$E_{cut} = 421\ \text{kJ}$$

4. Calculation of tool change energy demand ($E_{tool\text{-}change}$)

$$E_{tool-change} = P_o t_3 \left[INT\left(\frac{t_2}{T}\right) + 1 \right]$$

For this case, due to $t_2 < T_{flood}$ then there is no tool change activity taken place in the process, thus $E_{tool\text{-}change}$ would be equal to zero

5. Calculation of cooling energy demand ($E_{cooling}$)

$$P_{cool} = P_{pump\_o} + Q\Delta p\eta$$
$$P_{cool} = 1{,}520 + (1{,}800x4.745x0.8)$$
$$P_{cool} = 1{,}647.5\ \text{W}$$

$$E_{cool} = P_{cool}t_2$$
$$E_{cool} = 1{,}647.5x154.8$$
$$E_{cool} = 255\ \text{kJ}$$

Appendix 3.5.1.3 Results

Single component

No	Energy parts	Dry	MQL	Flood
1	Setup Energy	172	172	172
2	Ready Energy	11	11	11
3	Cutting Energy	421	421	421
4	Tool Change Energy	0	0	0
5	Cooling Energy	0	42	255
Total Energy, kJ		604	645	858

A dozen components in on setup

No	Energy parts	Dry	MQL	Flood
1	Setup Energy	0.172	0.17	0.17
2	Ready Energy	0.133	0.13	0.13
2	Cutting Energy	5.051	5.051	5.049
3	Tool Change Energy	0.154	0.103	0.103
4	Cooling Energy	0.00	0.500	3.060
Total Energy, MJ		5.511	5.959	8.517

Appendix 3.3.2 Environmental burden

Appendix 3.5.2.1 Data

Acidification	0.42	g-SO_2/kwh
Human toxicity	0.379	g-1.4-$C_6H_4Cl_2$/kwh
Global warming	430	g-CO_2/kwh

Appendix 3.5.2.2 Calculations

Calculation for environmental burden caused by utilising direct energy model is carried out for a dozen components in on setup and flood cooling based on only some impact categories. In general, for calculating environmental burden caused by utilising direct electrical energy, the electrical energy value depicted in Appendix 6.5.1.3 can be used and it is converted to environmental burden by using the general formula as expressed in equation below;

$$B_n = \frac{E}{3600} x \, impact \, categories$$

1. Acidification

No	Energy parts	Calculation	Results
1	Setup Energy	(172/3600) x 0.42	0.020
2	Ready Energy	(133/3600) x 0.42	0.016
3	Cutting Energy	(5049/3600) x 0.42	0.589
4	Tool Change Energy	(103/3600) x 0.42	0.012
5	Cooling Energy	(3060/3600) x 0.42	0.357
Environmental burden, g-SO_2/kWh			0.994

2. Human toxicity

No	Energy parts	Calculation	Results
1	Setup Energy	(172/3600) x 0.379	0.018
2	Ready Energy	(133/3600) x 0.379	0.014
3	Cutting Energy	(5049/3600) x 0.379	0.532
4	Tool Change Energy	(103/3600) x 0.379	0.011
5	Cooling Energy	(3060/3600) x 0.379	0.322
Environmental burden, g-1.4-$C_6H_4Cl_2$/kwh			0.897

3. Global warming

No	Energy parts	Calculation	Results
1	Setup Energy	(172/3600) x 0.43	0.021
2	Ready Energy	(133/3600) x 0.43	0.016
3	Cutting Energy	(5049/3600) x 0.43	0.603
4	Tool Change Energy	(103/3600) x 0.43	0.012
5	Cooling Energy	(3060/3600) x 0.43	0.366
Environmental burden, kg-CO_2/kwh			1.018

Appendix 3.5.2.3 Results

1. Acidification

No	Energy parts	Dry	MQL	Flood
1	Setup Energy	0.020	0.020	0.020
2	Ready Energy	0.016	0.016	0.016

3	Cutting Energy	0.589	0.589	0.589
4	Tool Change Energy	0.018	0.012	0.012
5	Cooling Energy	0.000	0.058	0.357
Environmental burden, g-SO2/kWh		0.643	0.695	0.994

2. Human toxicity

No	**Energy parts**	**Dry**	**MQL**	**Flood**
1	Setup Energy	0.018	0.018	0.018
2	Ready Energy	0.014	0.014	0.014
3	Cutting Energy	0.532	0.532	0.532
4	Tool Change Energy	0.016	0.011	0.011
5	Cooling Energy	0.000	0.053	0.322
Environmental burden, g-1.4-$C_6H_4Cl_2$/kwh		0.580	0.627	0.897

3. Global warming

No	**Cooling**	**Dry**	**MQL**	**Flood**
1	Setup Energy	0.021	0.021	0.021
2	Ready Energy	0.016	0.016	0.016
3	Cutting Energy	0.603	0.603	0.603
4	Tool Change Energy	0.018	0.012	0.012
5	Cooling Energy	0.000	0.060	0.366
Environmental burden, kg-CO_2/kwh		0.658	0.712	1.018

Appendix 4 Example calculation of environmental impact based on environmental burden model

Appendix 4.1 Environmental burden of different cutting environments

Appendix 4.1.1 Data

Acidification

GESTM = impact categories intensity	=	1.16667E-07	kg-SO2/kWh
CDE = environmental burden of cutting fluid disposal	=		
Water miscible cutting fluid	=	0.06503	kg-SO2/L
Soluble cutting fluid	=	0.06308	kg-SO2/L
TDE = environmental burden of cutting tool disposal	=	0	kg-SO2/kg
TTH = environmental burden of tool holder disposal		0	kg-SO2/kg
WDE = environmental burden of metal chips	=	0.00007	kg-SO2/kg

Human Toxicity

GESTM = impact categories intensity	=	1.05278E-07	kg-1.4-C6H4Cl2/kWh
CDE = environmental burden of cutting fluid disposal	=		
Water miscible cutting fluid	=	0.37992	kg-1.4-C6H4Cl2/L
Soluble cutting fluid	=	0.3787	kg-1.4-C6H4Cl2/L
TDE = environmental burden of cutting tool disposal	=	0	kg-1.4-C6H4Cl2/kg
TTH = environmental burden of tool holder disposal		0	kg-1.4-C6H4Cl2/kg
WDE = environmental burden of metal chips	=	0.000066	kg-1.4-C6H4Cl2/kg

Photochemical

GESTM = impact categories intensity	=	2.7778E-09	kg-C2H4/kWh
CDE = environmental burden of cutting fluid disposal	=		
Water miscible cutting fluid	=	0.004964	kg-C2H4/L
Soluble cutting fluid	=	0.00492707	kg-C2H4/L
TDE = environmental burden of cutting tool disposal	=	0	kg-C2H4/kg
TTH = environmental burden of tool holder disposal		0	kg-C2H4/kg
WDE = environmental burden of metal chips	=	0.000002	kg-C2H4/kg

Global Warming

GESTM = impact categories intensity	=	0.43	kg-CO2/kWh
CDE = environmental burden of cutting fluid disposal	=		
Water miscible cutting fluid	=	3.779	kg-CO2/L
Soluble cutting fluid	=	2.555	kg-CO2/L
TDE = environmental burden of cutting tool disposal	=	0.013	kg-CO2/kg
TTH = environmental burden of tool holder disposal		0.013	kg-CO2/kg
WDE = environmental burden of metal chips	=	0.195	kg-CO2/kg

		Eutrophication	
GESTM = impact categories intensity	=	1.08E-08	kg-PO4/kWh
CDE = environmental burden of cutting fluid disposal	=		
Water miscible cutting fluid	=	0.003988	kg-PO4/L
Soluble cutting fluid	=	0.003988	kg-PO4/L
TDE = environmental burden of cutting tool disposal	=	0	kg-PO4/kg
TTH = environmental burden of tool holder disposal		0	kg-PO4/kg
WDE = environmental burden of metal chips	=	0	kg-PO4/kg

Meanwhile, the machining data used to estimate the environmental burden in this study is the same with the data provided in Appendix 4.5.1.1

Appendix 4.1.2 Calculation

Here, the calculation is conducted for 12-nested components in one setup and flood-cooling environment and based on only global warming.

1. Environmental burden estimation of electrical energy consumption (B_E)

$$B_E = ES^{TM}\left[\left(P_o t_1 + P_{ready} t_{ready} + \left(P_{ready} + k\dot{v}\right)t_2 + P_o t_3\left[INT\left(\frac{t_2}{T}\right)+1\right] + P_{cool} t_2\right)/3600\right]$$

$$B_E = 0.43x\left[8517/3600\right]$$

$$B_E = 1.017 \text{ kg-CO}_2$$

2. Environmental burden estimation of cutting fluid disposal (B_{CF_disp})

$$B_{CF\_disp} = \frac{\sum_{i=1}^{N} t_{2i}}{t_{CF}}\left[\sum_{i=1}^{N}\left(Q_i t_{2i}\right)\right]C_{DE}$$

$$B_{CF\_disp} = \frac{1857.6}{10{,}800{,}000}\left[0.5x1857.6\right]x3.779$$

$$B_{CF\_disp} = 0.60 \text{ kg-CO}_2$$

3. Environmental burden estimation of cutting tool disposal (B_{Tool_disp})

$$B_{Tool\_disp} = \left(W_{Tool}\ INT\left[\left(\frac{t_2}{Tz}\right)+1\right]C_T\right) + \left(W_{TH}\left[\frac{\sum_{i=1}^{N} t_{2i}}{nTz}\right]C_H\right)$$

$$B_{Tool\_disp} = \left(0.0045\left[\left(\frac{1857.6_2}{1782x2}\right)+1\right]x0.013\right) + \left(0.79\left[\frac{1857.6}{400x1782x2}\right]x0.013\right)$$

$$B_{Tool\_disp} = 7.19x10^{-5} \text{ kg-CO}_2$$

4. Environmental burden estimation of chip disposal (B_{chip})

$$B_{Chip} = \left[\dot{v}t_2\rho\right]C_{ch}$$

$$B_{Chip} = [10.455x1857.6x0.00000775]0.195$$

$$B_{Chip} = 0.03 \text{ kg-CO}_2$$

Appendix 4.1.3 Results

Global Warming

No	Environmental burden	Dry	MQL	Flood
1	Electric Emission	0.658000	0.712000	1.017000
2	Cutting Fluid disposal	0	0	0.603709
3	Cutting tool disposal	0.000143	7.44E-05	7.19E-05
4	Chips disposal	0.02935	0.02935	0.02935
	Total	0.688000	0.741000	1.650000

Acidification

No	Environmental burden	Dry	MQL	Flood
1	Electric Emission	1.7337E-07	1.87137E-07	2.73843E-07
2	Cutting Fluid disposal	0	0	0.010388777
3	Cutting tool disposal	0	0	0
4	Chips disposal	1.0536E-05	1.0536E-05	1.0536E-05
	Total	1.07094E-05	1.07231E-05	0.010399586

Human toxicity

No	Environmental burden	Dry	MQL	Flood
1	Electric Emission	1.56446E-07	1.6887E-07	2.4711E-07
2	Cutting Fluid disposal	0	0	0.060693588
3	Cutting tool disposal	0	0	0
4	Chips disposal	9.93395E-06	9.9339E-06	9.93395E-06
	Total	1.00904E-05	1.0103E-05	0.060703769

Photochemical

No	Environmental burden	Dry	MQL	Flood
1	Electric Emission	4.12785E-09	4.45563E-09	6.52E-09
2	Cutting Fluid disposal	0	0	0.000793
3	Cutting tool disposal	0	0	0
4	Chips disposal	3.01029E-07	3.01029E-07	3.01E-07
	Total	3.05157E-07	3.05484E-07	0.000793