ENERGY CONSUMPTION AND MODELING IN HARD MILLING

by

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A THESIS

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ABSTRACT

Manufacturing accounts for approximately 30% of the energy use of the U.S. every year. Machining, including milling, turning, and drilling, accounts for about 80% of the manufacturing energy use. End milling has wide applications in manufacturing of die and mold. However, energy efficiency in end milling process is low and needs to be improved. The low energy efficiency not only leads to high production cost but also causes negative environmental impacts such as intensive CO₂ emission. Therefore, a thorough study on energy consumption during end milling is highly needed.

This research starts with a literature review of energy consumption and other energy related issues in machining processes. A systematic energy measuring method using high resolution power analyzer in end milling of AISI H13 steel has been developed. A feasibility and sensitivity study were conducted to evaluate the capability of power analyzer in data acquisition. Then, power and energy variables in end milling were comprehensively characterized.

Power and specific energy were measured and correlated to process parameters [axial depth of cut, radial depth of cut, cutting speed, feed per tooth, and material removal rate (MRR)] in end milling. The power and specific energy for the same MRR by different combinations of process parameters was also investigated. Finally, the influence of up milling and down milling on power and specific energy was studied.
DEDICATION

This work is dedicated to my family, especially my parents.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$a_p$</td>
<td>Axial depth of cut</td>
</tr>
<tr>
<td>$a_e$</td>
<td>Radial depth of cut</td>
</tr>
<tr>
<td>$f_z$</td>
<td>Feed per tooth</td>
</tr>
<tr>
<td>$v$</td>
<td>Cutting speed</td>
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<tr>
<td>$n$</td>
<td>Number of tooth</td>
</tr>
<tr>
<td>MRR</td>
<td>Material removal rate</td>
</tr>
<tr>
<td>$V$</td>
<td>Approximate chip volume</td>
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<tr>
<td>$L$</td>
<td>Sample length (mm)</td>
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<tr>
<td>$L_c$</td>
<td>Cutting length</td>
</tr>
<tr>
<td>$t_c$</td>
<td>Cutting time</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of cutting tool</td>
</tr>
<tr>
<td>$E_{c}^s$</td>
<td>Spindle energy before cutting</td>
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<tr>
<td>$E_{c}^f$</td>
<td>Spindle energy after cutting</td>
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<tr>
<td>$E_s$</td>
<td>Spindle energy</td>
</tr>
<tr>
<td>$P_{ac}^s$</td>
<td>Starting power at air cutting</td>
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<tr>
<td>$P_{ac}^f$</td>
<td>Final power at air cutting</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Spindle power</td>
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</table>
\( P_{nc}^s \) \hspace{1cm} \text{Starting net cutting power}

\( P_{nc}^f \) \hspace{1cm} \text{Final net cutting power}

\( P_{nc} \) \hspace{1cm} \text{Net cutting power}

\( \eta \) \hspace{1cm} \text{Power efficiency}

\( U_s \) \hspace{1cm} \text{Spindle specific energy}

\( U_{nc} \) \hspace{1cm} \text{Net cutting specific energy}

\( VB \) \hspace{1cm} \text{Tool flank wear}
ACKNOWLEDGMENTS

I am pleased to have this opportunity to express my appreciation to the people who helped me in this research project. I am most indebted to my advisor Dr. Yuebin Guo for providing me the research opportunity, financial aid, and technical guidance to conduct this research. I am deeply grateful to my co-advisor Dr. Michael P. Sealy, who directly guided me throughout this research work. He set an example of excellence as a researcher, mentor, and role model.

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## CONTENTS

ABSTRACT .................................................................................................................. ii  
DEDICATION .............................................................................................................. iii  
LIST OF ABBREVIATIONS AND SYMBOLS ............................................................. iv  
ACKNOWLEDGMENTS ............................................................................................... vi  
LIST OF TABLES ......................................................................................................... xi  
LIST OF FIGURES ..................................................................................................... xii

1. INTRODUCTION ..................................................................................................... 1  
   1.1 Energy resources ............................................................................................... 1  
   1.2 Energy consumption in manufacturing process .............................................. 2  
   1.3 Significance of improving energy efficiency ................................................... 3  
   1.4 Current issues .................................................................................................... 3  
   1.5 Research objectives ........................................................................................... 4  
   1.6 References ......................................................................................................... 4  

2. LITERATURE REVIEW ............................................................................................ 6  
   2.1 Overview of Energy Consumption in Machining .......................................... 6  
   2.2 Energy Measurement Methods and Equipment .......................................... 6  
   2.3 Predictive Models in Machining ...................................................................... 12  
   2.4 Energy Optimization Methods in Machining .............................................. 16
2.4.1 Multi-Objective Optimization ............................................................... 17
2.4.2 Fixed Energy Reduction .......................................................................... 17
2.4.3 Other Energy Reduction Methods .......................................................... 18
2.5 Pressing Issues/ Challenges ........................................................................ 19
2.6 References .................................................................................................... 19

3. EXPERIMENT SETUP .................................................................................. 23
3.1 Experiment Setup ......................................................................................... 23
3.2 Feasibility ..................................................................................................... 27
  3.2.1 Definition ................................................................................................. 27
  3.2.2 Design of Experiment .............................................................................. 27
  3.2.3 Results ..................................................................................................... 30
  3.2.4 Conclusions ............................................................................................. 35
3.3 Sensitivity ..................................................................................................... 36
  3.3.1 Definition ................................................................................................. 36
  3.3.2 Design of Experiment .............................................................................. 36
  3.3.3 Results ..................................................................................................... 39
  3.3.4 Conclusion ............................................................................................... 40
3.4 References .................................................................................................... 40

4. MAIN EXPERIMENT ................................................................................... 41
  4.1 Power & Energy vs. Process Parameters ...................................................... 41
4.1.1 Design of Experiment ................................................................. 41
4.1.2 Results .................................................................................. 42

Spindle Power and Energy ............................................................... 42

Net Cutting Power and Energy ....................................................... 46
4.1.3 Power Efficiency .................................................................. 51
4.1.4 Conclusions ......................................................................... 52

4.2 Power & Energy at Same MRR Condition ................................... 52
4.2.1 Design of Experiment ............................................................. 52
4.2.2 Results .................................................................................. 53

Spindle Power and Energy ............................................................... 53

Net Cutting Power and Energy ....................................................... 57
4.2.3 Power Efficiency .................................................................. 60
4.2.4 Tool Wear Analysis ............................................................... 60
4.2.5 Conclusion ............................................................................ 61

4.3 Power & Energy in Up vs. Down Milling ................................. 62
4.3.1 Design of Experiment ............................................................. 62
4.3.2 Results .................................................................................. 64

Spindle Power and Energy ............................................................... 64

Net Cutting Power and Energy ....................................................... 67
4.3.3 Power Efficiency .................................................................. 70
4.3.4 Tool Wear Analysis ............................................................... 70
4.3.5 Conclusions........................................................................................................72
4.4 References ...........................................................................................................72
4.5 Appendix ..............................................................................................................73

5. SUMMARY & FUTURE WORK...............................................................................78
# LIST OF TABLES

2.1 Specific Energy and Power Models in Machining .........................................13  
3.1 Normal Chemical Composition of AISI H13 Steel (wt%) ..............................23  
3.2 Material Properties of AISI H13 Steel.............................................................23  
3.3 End Milling Test on Average Time at Low MRR (0.27 mm³/s) ..................28  
3.4 End Milling Test on Average Time at High MRR (16.6 mm³/s) ...............28  
3.5 Average Spindle Cutting Energy and Power Data vs. Different Average Times at Low MRR .................................................................32  
3.6 End Milling Conditions in Sensitivity Test .....................................................37  
4.1 End Milling (up) Conditions ...........................................................................41  
4.2 Regression Analysis for Spindle Specific Energy ...........................................42  
4.3 Regression Analysis for Spindle Power ...........................................................45  
4.4 Regression Analysis for Net Cutting Power ...................................................49  
4.5 Regression Analysis for Net Cutting Specific Energy ....................................49  
4.6 Coefficients of Linear Regression Model .......................................................50  
4.7 Process Conditions for Same MRR Condition ..............................................53  
4.8 Experiment Conditions for Up vs. Down Milling .........................................63
LIST OF FIGURES

1.1 Energy consumption by source in the U.S. in 2011 ....................... 1
1.2 Energy consumption distribution in the U.S. in 2011 ....................... 2
2.1 Motion diagrams, torque, and power profiles for (a) spindle and (b) X and Y axes ................................................................. 7
2.2 Machine tool electrical energy consumption estimation model ........ 8
2.3 Specific energy as a function of MRR ........................................ 9
2.4 Experiment setup and an example of power measurement in milling experiment ................................................................. 10
2.5 Architecture of online power monitoring system ......................... 11
2.6 Axes and spindle power consumption in: (a) rapid traverse, and (b) effective machining ................................................................. 12
2.7 Specific energy demand for various manufacturing processes as a function of process rate ......................................................... 14
2.8 Energy comparison of conventional cutting vs. high speed cutting .... 15
2.9 Power demand for steel, aluminum, and polycarbonate working pieces in milling ................................................................. 15
2.10 Power profile of a turning process .............................................. 16
2.11 Average fixed energy breakdown of reviewed machine tools ...... 18
3.1 Experiment setup of power measurement in milling process ............ 24
3.2 Representative curves of spindle energy and power and definition of terminology ................................................................. 25
3.3 Schematic of cutting path ......................................................... 26
3.4 Schematic cutting plan for feasibility study..............................................29
3.5 Power and energy curves in low MRR (0.27 mm$^3$/s) at an average
time of (a) 15 ms, (b) 150 ms, (c) 300 ms, (d) 500 ms, (e) 750 ms,
and (f) 1000 ms .......................................................................................31
3.6 Slopes of spindle energy curve in different milling regions ..................32
3.7 Spindle cutting energy and power at different average times
for low MRR (0.27 mm$^3$/s) .................................................................33
3.8 Spindle cutting power and energy at high MRR 16.6 mm$^3$/s
at average time of a) 15 ms, b) 50 ms, c) 150 ms,
d) 300 ms, and e) of 1000 ms .................................................................34
3.9 Spindle cutting power and energy consumption at different
average times for high MRR ....................................................................35
3.10 Schematic cutting plan for sensitivity study ........................................38
3.11 Spindle cutting power vs. MRR ..............................................................39
3.12 Net cutting power vs. MRR ..................................................................39
3.13 Spindle specific energy vs. MRR ............................................................40
3.14 Net cutting specific energy vs. MRR .......................................................40
4.1 Spindle specific energy and power vs. process parameters for
(a) axial depth of cut ($a_p$), (b) radial depth of cut ($a_e$),
(c) cutting speed ($v$), and (d) feed per tooth ($f_z$) .................................43
4.2 Spindle specific energy vs. MRR .............................................................44
4.3 Spindle specific cutting energy vs. approximate chip volume ............44
4.4 Spindle power vs. MRR ..........................................................................45
4.5 Spindle air cutting power vs. rotation speed ..........................................46
4.6 Net cutting power vs. MRR .................................................................47
4.7 Net cutting power vs. approximate chip volume .......................... 47

4.8 Net cutting specific energy and net cutting power vs. process parameters for (a) axial depth of cut \( (a_p) \), (b) radial depth of cut \( (a_e) \), (c) cutting speed \( (v) \), and (d) feed per tooth \( (f_z) \) ........................................ 48

4.9 Net cutting specific energy vs. MRR ........................................ 50

4.10 Spindle specific cutting energy vs. MRR ................................ 51

4.11 Power efficiency vs. approximate chip volume .......................... 51

4.12 Spindle power vs. MRR at two axial depths of cut \( (a_p) \): \( a_p = 0.5 \text{ mm} \), and \( a_p = 2.0 \text{ mm} \) .................................................. 54

4.13 Spindle power vs. process parameters at Same MRR Condition for (a) radial depth of cut \( (a_e) \), (b) cutting speed \( (v) \), and (c) feed per tooth \( (f_z) \) .......................................................... 55

4.14 Spindle specific energy vs. MRR at two axial depths of cut \( (a_p) \): \( a_p = 0.5 \text{ mm} \), and \( a_p = 2.0 \text{ mm} \) .................................................. 56

4.15 Spindle specific energy vs. process parameters at same MRR condition for (a) radial depth of cut \( (a_e) \), (b) cutting speed \( (v) \), and (c) feed per tooth \( (f_z) \) .......................................................... 56

4.16 Net cutting power vs. MRR at two axial depths of cut \( (a_p) \): \( a_p = 0.5 \text{ mm} \), and \( a_p = 2.0 \text{ mm} \) .................................................. 57

4.17 Net cutting power vs. process parameters at same MRR condition for (a) radial depth of cut \( (a_e) \), (b) cutting speed \( (v) \), and (c) feed per tooth \( (f_z) \) .......................................................... 58

4.18 Net Cutting Specific Energy vs. MRR at two axial depths of cut \( (a_p) \): \( a_p = 0.5 \text{ mm} \), and \( a_p = 2.0 \text{ mm} \) .................................................. 59

4.19 Net Cutting Specific Energy vs. Process Parameters at Same MRR Condition for (a) radial depth of cut \( (a_e) \), (b) cutting speed \( (v) \), (c) feed per tooth \( (f_z) \) .......................................................... 59

4.20 Power efficiency with respect to MRR ........................................ 60
4.21 Fresh tool image

4.22 Tool wear images at same MRR condition at axial depth of cut ($a_p$):
(a) $a_p = 0.5$ mm, (b) $a_p = 2.0$ mm

4.23 Schematic of up and down milling

4.24 Spindle power vs. MRR in up and down milling

4.25 Spindle power vs. process parameters in up and down milling
for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and
(c) feed per tooth ($f_z$)

4.26 Spindle specific energy vs. MRR in up and down milling

4.27 Spindle specific energy vs. process parameters in up and down milling
for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and
(c) feed per tooth ($f_z$)

4.28 Net cutting power vs. MRR in up and down milling

4.29 Net cutting power vs. process parameters in up and down milling
for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and
(c) feed per tooth ($f_z$)

4.30 Net cutting specific energy vs. MRR in up and down milling

4.31 Net cutting specific energy vs. process parameters in up and down milling
for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and
(c) feed per tooth ($f_z$)

4.32 Power efficiency vs. MRR in up and down milling

4.33 Fresh tool image

4.34 Tool wear image under same process condition by (a) up milling
and (b) down milling

4.35 Milling of H13 at an axial depth of cut $a_p = 0.5$ mm while varying
other process parameters
4.36 Milling of H13 at an axial depth of cut $a_p = 1.0$ mm while varying other process parameters.................................................................74
4.37 Milling of H13 at an axial depth of cut $a_p = 1.5$ mm while varying other process parameters.................................................................75
4.38 Milling of H13 at an axial depth of cut $a_p = 2.0$ mm while varying other process parameters.................................................................76
4.39 Milling of H13 at an axial depth of cut $a_p = 2.5$ mm while varying other process parameters.................................................................77
CHAPTER 1
INTRODUCTION

1.1 Energy resources

Energy supports the industrial, transportation, residential, and commercial usages in modern society. Energy resources are classified as renewable and non-renewable. In recent years, the development of renewable energy and nuclear power is increasing due to favorable government policies in the U.S. [1]. However, non-renewable energies, including petroleum, coal, and natural gas, still account for the majority of energy consumption as seen in Fig. 1.1 [2]. Extensive usage of these fossil fuels in industry, especially in manufacturing, presents both economic and environmental concerns. Thus, it is necessary to conduct a thorough study on energy consumption in manufacturing to improve the energy efficiency.

Fig. 1.1 Energy consumption by source in the U.S. in 2011 (adapted from [2]).
1.2 Energy consumption in manufacturing process

In 2011, industrial energy accounts for 31% of the total energy consumption in the U.S. Moreover, manufacturing accounts for 90% of industrial energy usage, see Fig. 1.2 [2]. In the U.S., manufacturing is the most energy-intensive operation [3]. However, whether it is traditional metal machining or additive manufacturing, there is great potential for improving energy efficiency of these processes [4].

![Energy consumption distribution in the U.S. in 2011](adapted from [2]).

![Energy consumption distribution in the U.S. in 2011](adapted from [2]).
1.3 Significance of improving energy efficiency

A thorough study of energy efficiency in manufacturing processes conducted by Rahimifard et al. showed that manufacturing energy efficiencies were low and needed to be improved [5]. Gutowski et al. found that the maximum energy requirement for actual machining of materials was only 14.8% of the total energy consumption in an automotive machining line [6]. For hard and brittle materials, such as difficult-to-cut alloys and ceramics, poor machinability leads to lower material removal rates and thus lower energy efficiency [7]. Improving energy efficiency not only reduces the cost of production but also alleviates environmental impact.

1.4 Current issues

Several studies on specific energy and process parameters in machining have been conducted to characterize and reduce the energy consumption [9-11]. However, previous studies focused on spindle specific energy which overestimates the actual energy consumed during cutting. A new terminology to describe the actual energy to remove a unit volume of material has been defined: net cutting specific energy. The relationship between (a) net cutting specific energy and (b) process parameters is still poorly understood. While material removal rate (MRR) is a good process parameter to predict spindle specific energy, the relationship between MRR and net cutting specific energy has not been investigated. The pressing issue is to determine if MRR can predict net cutting specific energy or must independent process parameters (e.g. depth of cut, cutting speed, and feed per tooth) be used.

Also, it is unknown if MRR is a unique identifier of process power and energy. In other words, whether varying process parameters under the same MRR produce a unique power and
energy profile also needs to be studied. In addition, the cutting mechanics between up and down milling are different [12], but the differences in power and energy consumption have not been investigated.

1.5 Research objectives

In order to conduct the studies above, the objectives of this research are four fold. First, develop an advanced energy measuring method with defined terminologies using high resolution power analyzer in end milling of AHSI H13 tool steel, and conduct a feasibility and sensitivity study. Secondly, study the relationship between (a) power and specific energy with (b) process parameters. Thirdly, study power and specific energy at different combinations of process parameters under the same material removal rate. Fourthly, study the influence of up and down milling on power and specific energy.

1.6 References


CHAPTER 2
LITERATURE REVIEW

2.1 Overview of Energy Consumption in Machining

Manufacturing accounts for substantial part of the energy use in the U.S, while machining process accounts for 83% of all the manufacturing energy consumption [1]. Since machining consumes a significant portion of the energy in manufacturing, performing machining with higher energy efficiency will significantly reduce the total energy consumption [2].

Energy related issues in machining processes have gained increasing attention in recent years. Different methods using various equipment were used in power and energy consumption measurement. However, a systematic measuring method with well-defined terminology using advance equipment has not been implemented in the energy measurement in machining process.

A variety of strategies such as developing predictive models for power and energy [3], and using multi-objective optimization [4] were applied to reduce energy consumption and further reduce the cost in machining. Other methods, such as reducing the fixed energy use [5], and optimizing cutting path and workpiece fixture [6] were also investigated to improve energy efficiency and reduce the energy consumption in machining.

2.2 Energy Measurement Methods and Equipment

A variety of equipment, such as the ammeter, dynamometer, and power meter have been used in data acquisition of the current, cutting force, power, and energy in machining.
Avram et al. studied the total energy consumption of a machine tool system in milling. A Kistler dynamometer (type 9255B) was used to measure the cutting force, and a power cell (Load Controls PPC-3) was used to measure the cutting power. Total energy consumption $E_{DE}$ was composed of spindle acceleration energy $E_{aY}$, tool positioning energy $E_{SY}$, material cutting energy $E_{cut}$, spindle steady state energy $E_{run}$, and spindle deceleration energy $E_{dY}$, see Fig. 2.1 and Eq. 2.1 [7].

$$E_{DE} = E_{aY} + E_{SY} + E_{dY} + E_{run} + E_{cut}$$

$$= \int_{t_0}^{t_1} p_{aY} dt + \int_{t_1}^{t_2} p_{SY} dt + \int_{t_2}^{t_3} p_{dY} dt + \int_{t_3}^{t_4} p_{run} dt + \int_{t_4}^{t_5} p_{c} dt \tag{2.1}$$

Balogun et al. developed a mathematical model for total electrical energy consumption in machining and validated by milling, see Eq. 2.2. The current of the machine tool was measured by a Fluke 345 power quality clamp meter, and power was calculated by clamp peter’s in-built

---

**Fig. 2.1 Motion diagrams, torque, and power profiles for (a) spindle and (b) X and Y axes [7].**
function. The total electrical energy for the machine tool included the auxiliary unit energy consumption and cutting unit energy consumption, and was further divided to the energy use in different stages, see Fig. 2.2 [4].

![Machine tool electrical energy consumption estimation model](image)

Fig. 2.2  Machine tool electrical energy consumption estimation model [4].

\[
E_t = P_b t_b + (P_b + P_r) t_r + P_{air} t_{air} + (P_b + P_r + P_{cool}) t_c
\]  

(2.2)

where \(E_t\) (J) is total energy consumption, \(P_b\) (W) is basic power, \(P_r\) (W) is ready state power, \(P_{air}\) (W) is air cutting power, \(P_{cool}\) (W) coolant pumping power, \(t_b\) (s) is basic time, \(t_r\) (s) is ready time, \(t_{air}\) (s) is non-cutting time, \(t_c\) (s) is cutting time, \(k\) (J/mm\(^3\)) is specific cutting energy and \(v\) (mm\(^3\)/s) is material removal rate [4].

Rajemi et al. investigated the influences of process conditions on energy consumption in turning. The electrical power of the lathe was measured by a DT-266 digital clamp meter. The energy consumed of one turning pass \((E)\) was modeled as Eq. 2.3 [8].
\[ E = P_0 t_1 + (P_0 + k \nu) t_2 + P_0 t_3 \left( \frac{t_2}{T} \right) + y_E \left( \frac{t_2}{T} \right) \]  

(2.3)

where \( P_0 \) is the power consumed by machine modules in W, \( t_1, t_2 \) and \( t_3 \) are machine setup time, cutting time and tool change time in s, \( T \) is tool life in s, \( k \) is specific energy in J/mm\(^3\), \( \nu \) is material removal rate in mm\(^3\)/s and \( y_E \) is energy footprint per cutting edge in J [8].

Diaz et al. investigated the energy consumption reduction strategies for milling machine tool. A Wattnode MODBUS wattmeter was used to measure the total power, see Eq. 2.4. The specific energy was a function of material removal rate (MRR), see Fig. 2.3 [3].

![Fig. 2.3 Specific energy as a function of MRR [3].](image)

\[ e = P_{avg} \times \Delta t = (P_{cut} + P_{air}) \times \Delta t \]  

(2.4)

where \( e \) is total electrical energy consumption in J, \( P_{avg} \) is average power demand in W, \( \Delta t \) is processing time in s, \( P_{cut} \) is cutting power in W and \( P_{air} \) is air cutting power in W [3].
Mori et al. conducted an energy efficiency study for machine tools in end milling and drilling. The total machine power and the spindle power consumption were measured by a clamp-type ammeter. The total power consumption \( P \) was model as Eq. 2.5 [9].

\[
P = P_1 \times (T_1 + T_2) + P_2 \times T_2 + P_3 \times T_3
\]  

(2.5)

where \( P_1 \) (W) is constant power consumption in non-cutting state during the machine operation, \( T_1 \) (h) is the cycle time in non-cutting state, \( T_2 \) (h) is the cycle time in cutting state, \( P_2 \) (W) is the spindle and servo motor power consumption, \( P_3 \) (W) is power consumption to position workpiece and accelerate/decelerate spindle to specified speed, \( T_3 \) (h) is the time required to position the work and accelerate the spindle [9].

Neugebauer et al. studied the influence of cutting tool properties on energy efficiency in drilling and turning process. The total energy consumption of the machine \( E_{\text{machine}} \) was measured by a power meter from the main supply [10].

Kara and Li studied unit process energy consumption for milling and turning process. A NI data acquisition system with a LabVIEW programming interface was used for the power and energy measurement, shown in Fig. 2.4. The sample interval was set at 0.1 s [11].

![Fig. 2.4 Experiment setup and an example of power measurement in milling experiment [11]](image-url)
Behrendt et al. developed a systematic method to assess energy use in machining process and validated it in nine machine centers. The power was measured by a Yokogawa CW240 clamp-on power meter. The maximum sampling frequency of the used device was 10 Hz. The total power consumption included the standby power, component power and machining power [12].

Hu et al. developed an on-line energy monitoring system in turning. The total power and torque were recorded by a power sensor EDA9033A and a torque sensor TQ201 respectively. The sampling period of the power sensor and the torque sensor were set at 50 ms. The total energy including the constant energy and variable energy in turning was assessed by the on-line energy monitoring system, see Fig. 2.5 [13].

Quintana et al. studied and modeled the power consumption in ball end milling process. The X, Y, and Z axis power consumption and spindle power consumption were measured by four ammeters respectively, and data was recorded by a LabVIEW application. The power

![Fig. 2.5 Architecture of online power monitoring system [13].](image)
distribution in the rapid traverse stage and effective machining stage were measured and compared, shown in Fig. 2.6. It showed that spindle power was the main factor to influence the total power consumption [14].

![Image](Image)

(a) Rapid traverses power consumption  
(b) Effective machining

Fig. 2.6 Axes and spindle power consumption in: (a) rapid traverse, and (b) effective machining [14].

### 2.3 Predictive Models in Machining

Developing predictive models in machining process is important to study the relationship between input variables, e.g. process parameters, workpiece properties, and tool geometries, and the outputs, e.g. power and energy consumption. A summary of research work in this area is shown in Table 2.1.

Gutowski et al. summarized the specific energy requirement for a variety of manufacturing processes, see Fig. 2.7. It was concluded that the process rate was the most important factor for the energy requirement. Total power requirement as a function of material processing rate and the specific energy model are shown in Table 2.1 [15].

Shao et al. developed a cutting power model associated with process parameters and average flank wear in face milling. Simulation and experiment results showed that the power model could predict the mean cutting power, see Table. 2.1 [16].
### Table 2.1 Specific Energy and Power Models in Machining

<table>
<thead>
<tr>
<th>Model</th>
<th>Characteristics</th>
<th>References</th>
</tr>
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| $E_{cs} = \frac{P_c}{60\eta Z}$ | $E_{cs}$: specific energy  
$P_c$: cutting power  
$\eta$: energy efficiency  
$Z$: material removal rate | [Draganescu, 2003] |
| $P = ZnD_a_p[kh^{-2}\beta f_z\cos(\varphi_{in})$  
$-\cos(\varphi_{in}) + \psi)]$  
$+ uHV B\psi / 2$ | $P$: average of measured power of spindle motor,  
$Z$: number of cutting teeth on a cutter,  
$D$: diameter of a milling cutter,  
$n$: spindle speed,  
$a_p$: axial depth of cut,  
$K$: cutting force constant,  
$h$: mean chip thickness,  
$c$: chip thickness constant,  
$\varphi_{in}$: entering angle,  
$\psi$: immersion angle,  
$u$: coefficient of friction,  
$H$: Brinell hardness,  
$VB$: average flank wear | [Shao, 2004] |
| $P = P_{idle} + k \times v$ | $P$: total power demand in kW  
$P_{idle}$: idle power in kW  
v: the rate of material processing, in cm$^3$/sec  
k: a constant, in kJ/cm$^3$ | [Gutowski, 2006] |
| $B_{elect} = \frac{P_0}{v} + k$ | $B_{elect}$: specific energy per unit of material processed in kJ/cm$^3$  
P$_0$: idle power in kW  
v: the rate of material processing, in cm$^3$/sec  
k: a constant, in kJ/cm$^3$ | [Gutowski, 2006] |
| $e_{cut} = k \times \frac{1}{M. R. R} + b$ | $e_{cut}$: specific energy  
k: constant  
b: steady-state specific energy. | [Diaz, 2011] |
| $SEC = C_0 + \frac{C_1}{MRR}$ | $SEC$: specific energy  
$C_0, C_1$: machine tool specific coefficients and are different when machine tools are different. | [Kara and Li, 2011] |
| $SEC = SUE + STE + SOE + SFE$ | $SUE$: specific unproductive energy  
$STE$: specific tool tip energy  
$SOE$: specific operational energy  
$SFE$: specific fixed energy | [Li and Kara, 2011] |
Draganescu et al. investigated the specific energy model in milling process, see Table 2.1. The specific energy was a function of cutting power \( P_c \), material removal rate, and machine tool efficiency (\( \eta \)). The machine tool efficiency (\( \eta \)) is shown in Eq. 2.6 [17].

\[
\eta = \frac{P_c}{P_{mc}} = \frac{1}{1 + (P_{m1}/P_c)} \tag{2.6}
\]

where \( P_{mc} \) (W) is the consumed power and \( P_{m1} \) (W) is the power loss in milling.

Diaz et al. investigated the strategies for reducing energy consumption in milling by selection of process parameters. It was concluded that the process time dominated the energy
consumption per unit machined, see Fig. 2.8. The process time decreased with the increase of feed rate [18]. Further study on relationship among specific energy, material removal rate, and power demand in end milling was also conducted by Diaz et al [3]. A specific energy model as a function of process rate was built, see Table. 2.1. Milling of three different materials, low carbon steel, aluminum, and polycarbonate, were taken to study the influence of workpiece property on power consumption, see Fig. 2.9. It can be seen that as the tensile strength of material increased polycarbonate to steel, the ratio of cutting power to total power increased from 1% to 7% [3].

![Energy per unit [KJ]](energy_chart.png)

**Fig. 2.8** Energy comparison of conventional cutting vs. high speed cutting [18].

![Power demand chart](power_demand_chart.png)

**Fig. 2.9** Power demand for steel, aluminum, and polycarbonate working pieces in milling [3].
An empirical specific energy model was built for predicting energy consumption in turning process by Li and Kara. The total specific energy was divided to specific fixed energy, specific operational energy, specific tool tip energy and specific unproductive energy, see Table 2.1 and Fig. 2.10 [5].

![Fig. 2.10 Power profile of a turning process [5].](image)

Kara and Li investigated a unit process energy consumption model as a function of material removal rate in milling and turning process, see Table 2.1. The model was validated on nine machine tools, and predicted the energy consumption at accuracy higher than 90% [19].

### 2.4 Energy Optimization Methods in Machining

The low energy efficiency and the associated environmental impacts have received increasing attention [20]. Reducing energy consumption and relieving industrial pollution have become important topics in sustainable manufacturing.
Experiments with statistical methods such as grey relationship analysis and response surface methodology were used to reduce energy consumption, prolong tool life and optimize surface quality in machining process. Reducing fixed energy consumption helps reduce the total energy consumption. Other methods such as choosing optimal process plan and process simulation were also applied to reduce the energy consumption in machining process.

2.4.1 Multi-Objective Optimization

In machining process, the inputs can be process parameters, cutting tool geometry and workpiece property, while the outputs can be power and energy consumption, tool life and machined surface integrity. The objectives can be reducing energy consumption, prolonging tool life and improving machined surface integrity.

Energy consumption and machining cost were reduced simultaneously by selecting optimum process parameters in milling and turning [4, 21, 22]. The optimal tool life and minimum energy consumption were achieved by selecting process parameters and selecting cutting tool geometry in turning process [8, 10, 22]. The surface roughness and energy consumption were optimized by choosing process parameters via grey relational analysis in milling [23] and turning [24].

2.4.2 Fixed Energy Reduction

The energy consumption in machining can be divided into variable part and constant part. The constant part is called fixed energy which ensures the machine readiness [15]. The average fixed energy breakdown of several milling, turning, and drilling machine tools is shown in Fig. 2.11 [5]. It can be seen that coolant and hydraulic systems consume about 58% of the
fixed energy. Oda et al. found out that by reducing number of coolant pumps, optimizing coolant pressure and modifying hydraulic control method, the total energy consumption was reduced approximately by 42% [25].

Fig. 2.11 Average fixed energy breakdown of reviewed machine tools [5].

2.4.3 Other Energy Reduction Methods

The workpiece fixture condition and the cutting path process plan significantly influence the energy consumption in machining process. Optimum fixture conditions of workpiece were achieved by innovative planning method to reduce to total energy consumption in milling [6]. Computer aided process planning was applied to choose the optimal cutting path in machining. The energy consumption was reduced due to the shortened processing time of the optimal cutting path [26, 27]. The energy oriented process modeling and simulation were also applied for the optimization of the energy consumption in machining [28-30].
2.5 Pressing Issues/ Challenges

Previous studies on relationship between specific energy and process parameters focused on spindle specific energy which includes both the air cutting and the actual cutting energy consumed during machining. Net cutting specific energy has been defined to describe the actual energy to remove a unit volume of material as a new terminology. The relationship between (a) net cutting specific energy and (b) process parameters is still poorly understood. While material removal rate (MRR) is a good process parameter to predict spindle specific energy, the relationship between MRR and net cutting specific energy has not been studied. The current issue is to determine if net cutting specific energy can be predicted by MRR or needs to be correlated to independent process parameters (e.g. depth of cut, cutting speed, and feed per tooth).

Also, it is unknown if MRR is a unique identifier of process power and energy. In other words, whether varying process parameters under the same MRR produce a unique power and energy profile needs to be studied. In addition, the cutting mechanics differ between up and down milling, the differences in power and energy consumption between up and down milling needs to be investigated.

2.6 References


3.1 Experiment Setup

Dry end milling of AISI H13 tool steel was carried out on a CNC machine center using one cutting insert. The chemical composition of AISI H13 and its material properties are shown in Table 3.1 and Table 3.2, respectively. A CINCINNATI Arrow 500 CNC machine was used for end milling. The speed of the spindle motor can range from 60 to 6000 RPM. It can provide constant torque from 60 to 750 N·m, and continuous power from 751 to 4500 W. The cutting insert was a SECO XOMX120408TR-D14, 30M.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ni</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32-0.45</td>
<td>0.20-0.50</td>
<td>0.80-1.20</td>
<td>4.75-5.50</td>
<td>1.10-1.75</td>
<td>0.80-1.20</td>
<td>0-0.30</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 3.1 Normal Chemical Composition of AISI H13 Steel (wt%) [1]

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Young’s Modulus (GPa)</th>
<th>Hardness (HRc)</th>
<th>Yield Strength (MPa)</th>
<th>Thermal conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7800</td>
<td>210</td>
<td>52</td>
<td>1520</td>
<td>25.1</td>
</tr>
</tbody>
</table>

Table 3.2 Material Properties of AISI H13 Steel [2]
Power and energy consumption of total machine and spindle motor were measured by a Fluke Norma power analyzer. The net cutting power and net cutting energy were calculated based on measured spindle data. The power analyzer was connected to three phase AC systems of the total machine and spindle motor separately via shunts. The function of shunts was to prevent damaging the power analyzer from high current flow. A laptop operating in Window XP environment was connected to the power analyzer through a digital adaptor to record and display. The experimental setup is shown in Fig. 3.1. In order to eliminate surface defects by heat treatment and reduce errors in machining, both bottom and top surfaces of the samples were ground. The sample geometry was a cuboid measuring approximately $19 \times 15 \times 12 \text{ mm}^3$.

![Fig. 3.1 Experiment setup of power measurement in milling process.](image)

Representative power and energy curves from milling and related terminology are shown in Fig. 3.2. Terminology is defined below for (1) spindle power and energy data and (2) net cutting power and energy data.
Spindle energy before cutting \((E^s_c)\) is the energy consumption of the spindle before the cutting insert removes material. Spindle energy after cutting \((E^f_c)\) is energy consumption of spindle when cutting insert finishes removing material in one path. Spindle energy \((E_s)\) is the energy consumption of the spindle used for material removal, and it can be calculated by subtracting \(E^s_c\) from \(E^f_c\). The spindle air cutting power is assumed constant during material removal and non-material removal stages. Starting power at air cutting \((P^s_{ac})\) is the spindle air cutting power before material removal. Final power at air cutting \((P^f_{ac})\) is the spindle air cutting power after material removal. Spindle power \((P_s)\) is power consumption of the spindle during material removal.

Net cutting power was defined in order to more accurately determine the energy and power consumed during cutting. Starting net cutting power \((P^s_{nc})\) is the difference between the spindle power \((P_s)\) and the start power at air cutting \((P^s_{ac})\). Final net cutting power \((P^f_{nc})\) is the difference between \(P_s\) and the final power at air cutting \((P^f_{ac})\). Net cutting power \((P_{nc})\) was defined as the average of the starting net cutting power \((P^s_{nc})\) and final net cutting power \((P^f_{nc})\).

![Fig. 3.2 Representative curves of spindle energy and power and definition of terminology.](image)

- \(t_c\): Cutting time
- \(E^s_c\): Spindle energy before cutting
- \(E^f_c\): Spindle energy after cutting
- \(E_s\): Spindle energy
- \(P^s_{ac}\): Starting power at air cutting
- \(P^f_{ac}\): Final power at air cutting
- \(P_s\): Spindle power
- \(P^s_{nc}\): Starting net cutting power
- \(P^f_{nc}\): Final net cutting power
- \(P_{nc}\): Net cutting power
Cutting time \((t_c)\) was defined as the time in which the insert contacts the surface while removing material. The cutting time is determined based on workpiece length, feed rate, and radial depth of cut, see Fig. 3.3 and Eq. 3.1.

![Diagram of cutting path](image)

Fig. 3.3 Schematic of cutting path.

\[
t_c = L_c \times 60/v_f = (L + \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - a_e\right)^2}) \times 60/v_f
\]  

(3.1)

where  
- \(L\) : sample length (mm)  
- \(L_c\) : cutting length (mm)  
- \(v_f\) : feed rate (mm/min)  
- \(D\) : diameter of cutting tool (mm)  
- \(a_e\) : radial depth of cut (mm)

Two pre-tests were conducted to study the function and capability of the power analyzer on data acquisition during end milling. One test was to evaluate the feasibility (average time) of the power analyzer, and the other test was to evaluate the sensitivity of the power analyzer.
3.2 Feasibility

3.2.1 Definition

A feasibility study was conducted to evaluate if the power analyzer was capable of measuring a variation in power and energy between air cutting and actual cutting. End milling was used as the cutting process under evaluation. The feasibility of detecting a measurable power and energy change is dependent on the average time.

Average time is the time duration in which all the data points are averaged into one data point by the power analyzer. It is different from the sampling rate. The sampling rate of the power analyzer was fixed at 341 kHz. This meant 341,000 data points could be sampled in one second without averaging. However, the huge data size led to difficulty in data transportation, storage, and even post-processing. Therefore, data needs to be averaged to reduce the data size using an embedded function of the power analyzer. Choosing a reasonable average time is important in data acquisition since the shape of the power curve varies due to signal processing. As a result, accumulative energy could be affected by different average times. Therefore, the effect of average time on being able to feasibly measure a power and energy change during cutting under fixed process condition needs to be studied.

3.2.2 Design of Experiment

Two extreme process conditions were selected to investigate the effect of average time on measuring power and energy consumption in milling process: (1) milling of AISI H13 at low material removal rate (MRR), and (2) milling of AISI H13 at high MRR. The low MRR was 0.27 mm³/s and the high MRR was 16.6 mm³/s. In the power analyzer, the minimum average time was 15 ms. A reasonable range to evaluate the effect of average time was from 15 ms to
1000 ms. Above 1000 ms, there are too few data points to capture any changes in power and energy. At high MRR condition the average time was distributed to six levels, shown in Table 3.3, and at low MRR condition it was distributed to five levels, shown in Table 3.4. The schematic cutting paths are shown in Fig. 3.4.

<table>
<thead>
<tr>
<th>Exp. #</th>
<th>Average time (ms)</th>
<th>Axial depth of cut $a_p$ (mm)</th>
<th>Radial depth of cut $a_e$ (mm)</th>
<th>Feed per tooth $f_z$ (mm/tooth)</th>
<th>Cutting speed $v$ (m/min)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>750</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3.3 End Milling Test of Average Time at Low MRR (0.27 mm$^3$/s)

<table>
<thead>
<tr>
<th>Exp. #</th>
<th>Average time (ms)</th>
<th>Axial depth of cut $a_p$ (mm)</th>
<th>Radial depth of cut $a_e$ (mm)</th>
<th>Feed per tooth $f_z$ (mm/tooth)</th>
<th>Cutting speed $v$ (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>2.5</td>
<td>0.5</td>
<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>2.5</td>
<td>0.5</td>
<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>2.5</td>
<td>0.5</td>
<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>2.5</td>
<td>0.5</td>
<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>2.5</td>
<td>0.5</td>
<td>0.2</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 3.4 End Milling Test of Average Time at High MRR (16.6 mm$^3$/s)
Fig. 3.4 Schematic cutting plan for feasibility study.

Note: ● Represents the position of cutter according to origin. The (X,Y) represents displacements programmed in to the G-code.
3.2.3 Results

Power and energy curves with respect to different average times at low MRR condition are shown in Fig. 3.5. The cutting time at the low MRR condition was 57.3 seconds. Detailed data of cutting energy consumption and cutting power at low MRR condition is shown in Table 3.5.

In each graph of Fig. 3.5, the air cutting and cutting regions were divided by two red vertical dashed lines, where the cutting region is between the two vertical dashed lines. It can be seen that the spindle cutting power was higher than spindle air cutting power due to the mechanical load of removing the material. The noise of the spindle power decreased significantly with an increase of average time. At an average time of 15 ms in Fig. 3.5(a), it was difficult to distinguish the cutting and air cutting regions by spindle power curve since there was no obvious difference in power. While in Fig. 3.5(c) to 3.5(f), the different cutting and air cutting regions were clearly distinguishable since there was a 5 W difference between cutting power and air cutting power.

From Fig. 3.5, it was also noticed that the spindle energy increased linearly as time increased. Also, since the spindle energy is the integral of the spindle power, there was a slight slope variation (typically less than 0.5%) of spindle energy between cutting and air cutting regions. The total spindle energy curve can be divided into three regions: AB, BC, and CD, see Fig 3.6. The slope of region AB and CD are 0.2158 while slope of region BC is 0.2163. The higher slope in region BC was due to a higher cutting power in region BC compared with the lower air cutting power in region AB and CD.
Fig. 3.5 Power and energy curves in low MRR (0.27 mm$^3$/s) at an average time of (a) 15ms, (b) 150 ms, (c) 300 ms, (d) 500 ms, (e) 750 ms, and (f) 1000 ms.
Table 3.5 Average Spindle Cutting Energy and Power Data vs. Different Average Times at Low MRR

<table>
<thead>
<tr>
<th>Average time (ms)</th>
<th>Cutting time (s)</th>
<th>$E_c^c$ (J)</th>
<th>$E_c^f$ (J)</th>
<th>$E_s$ (J)</th>
<th>$P_s$ (W)</th>
<th>$P_{nc}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>57.3</td>
<td>7.05</td>
<td>19.47</td>
<td>12.42</td>
<td>780.04</td>
<td>4.17</td>
</tr>
<tr>
<td>150</td>
<td>57.3</td>
<td>7.29</td>
<td>19.70</td>
<td>12.41</td>
<td>781.18</td>
<td>5.19</td>
</tr>
<tr>
<td>300</td>
<td>57.3</td>
<td>7.01</td>
<td>19.46</td>
<td>12.45</td>
<td>778.71</td>
<td>5.68</td>
</tr>
<tr>
<td>500</td>
<td>57.3</td>
<td>7.31</td>
<td>19.70</td>
<td>12.39</td>
<td>780.31</td>
<td>4.87</td>
</tr>
<tr>
<td>750</td>
<td>57.3</td>
<td>6.46</td>
<td>18.97</td>
<td>12.51</td>
<td>779.67</td>
<td>5.24</td>
</tr>
<tr>
<td>1000</td>
<td>57.3</td>
<td>7.37</td>
<td>19.81</td>
<td>12.44</td>
<td>780.31</td>
<td>5.18</td>
</tr>
<tr>
<td>AVG</td>
<td></td>
<td>7.08</td>
<td>19.52</td>
<td>12.44</td>
<td>780.04</td>
<td>5.05</td>
</tr>
<tr>
<td>STD</td>
<td></td>
<td>0.34</td>
<td>0.30</td>
<td>0.04</td>
<td>0.82</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Fig. 3.6 Slopes of spindle energy curve in different milling regions.

However, the data in Table 3.5 showed that the differences between spindle cutting energy consumption ($E_s$) under different average times was approximately 1%, and the differences between spindle cutting power ($P_{cut}$) was approximately 0.3%. The spindle cutting energy consumption and spindle cutting power were not affected by average time when the process condition was fixed, see Fig. 3.7. Even though the effect average time on spindle cutting
energy and power was negligible, the cutting region was not clearly discernible using an average
time less than 300 ms for these cutting conditions.

Fig. 3.7 Spindle cutting energy and power at different average times for low MRR (0.27 mm\(^3\)/s).

At the high material removal rate condition (16.6 mm\(^3\)/s), the cutting time for one path was 1.4 seconds. The results also validated that the average time could affect the spindle cutting power curve graphically, i.e. changes the appearance of the power curves. From Figs. 3.8(a) to 3.8(e), it is shown that as the average time decreased, the noise in the data tended to increase.
Fig. 3.8 Spindle cutting power and energy at high MRR 16.6 mm$^3$/s at average time of a) 15 ms, b) 50 ms, c) 150 ms, d) 300 ms, and e) of 1000ms.
While in high MRR condition, the spindle cutting energy consumption and power varied with respect to different average times, shown in Fig. 3.9. The spindle energy consumption tended to decrease as the average time increased to 1000 ms. Also, the spindle power was lower at higher averages times. This may be due to the fact that higher average times produced less data leading to inaccurate power and energy measurements. Therefore, at high MRR condition, a low average time needs to be selected for the measurement. Based on the experiment results, criteria of selecting the average time was that at least 10 data point needs to be recorded in the material removal region to accurately capture the spindle power and energy consumption.

Fig. 3.9 Spindle cutting power and energy consumption at different average times for high MRR.

3.2.4 Conclusions

In conclusion, it is important to determine an appropriate average time based on the process condition for accurate power and energy data acquisition. For a fixed process condition at a low material removal rate (0.27 mm³/s in this study), the spindle power and spindle energy
consumption are independent of average time. The difference in spindle power was approximately 0.3% and the difference in spindle energy consumption was approximately 1% at different average times. As the average time increased, the noise in the data of the spindle power curve significantly decreased; hence, it was easier to distinguish the cutting and air cutting regions.

For a fixed process condition at a high material removal rate (16.6 mm$^3$/s in this study), the average time affected the spindle power and energy measurement. The spindle power and energy consumption tended to decrease when the average time increased. Also, as the average time increased, the noise in the spindle power curve significantly decreased. Therefore, a low average time should be used in power and energy measurements at high MRR conditions. Criteria of selecting the average time was that at least 10 data point need to be recorded in the material removal region to accurately capture the spindle power and energy consumption.

3.3 Sensitivity

3.3.1 Definition

The sensitivity of a system is the minimum magnitude of input required to produce a specified output. The purpose of a sensitivity analysis was to determine if the power analyzer can detect a change in outputs (e.g. power and energy consumption) corresponding to a change in inputs (e.g. material removal rate, depth of cut, feed rate, cutting speed).

3.3.2 Design of Experiment

In end milling, the spindle cutting power and energy consumption are strongly dependent on the material removal rate (MRR). This sensitivity test was to determine if the power analyzer
can detect changes in power and energy when MRR slightly changes. The design of experiment is shown in Table 3.6. The range of MRR is from 0.20 mm$^3$/s to 0.40 mm$^3$/s. This range for MRR was used since it represented some of the lower extremes to be used in the main experiment. A schematic of the cutting paths is shown in Fig. 3.10.

### Table 3.6 End Milling Conditions in Sensitivity Test

<table>
<thead>
<tr>
<th>Exp. #</th>
<th>Axial depth of cut ($a_p$) (mm)</th>
<th>Radial depth of cut ($a_e$) (mm)</th>
<th>Feed per tooth ($f_z$) (mm/min)</th>
<th>Cutting speed ($v$) (m/min)</th>
<th>Material removal rate (MRR) (mm$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>0.3</td>
<td>0.025</td>
<td>50</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>0.4</td>
<td>0.025</td>
<td>50</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>0.5</td>
<td>0.025</td>
<td>50</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>0.6</td>
<td>0.025</td>
<td>50</td>
<td>0.40</td>
</tr>
</tbody>
</table>

In end milling, $\text{MRR} = a_p \cdot a_e \cdot v_f$, where $a_p$ is axial depth of cut (mm), $a_e$ is radial depth of cut (mm), and $v_f$ is feed rate (mm/min). The feed rate ($v_f$) is proportional to the cutting speed ($v$) and feed per tooth ($f_z$) and is given by $v_f = (v \cdot f_z \cdot n) / (\pi \cdot D)$, where $n$ is the number of teeth (1 tooth) and $D$ is the diameter of the cutting tool (20 mm). Both the depth of cut and feed rate affect the cutting force and consequently affect the power and energy consumption during cutting. In order to minimize the influence of different process parameters on power and energy consumption, only one process parameter was varied while others remained constant. In this sensitivity test, the radial depth of cut ($a_e$) varied and was divided into four levels. Axial depth of cut ($a_p$), feed per tooth ($f_z$) and cutting speed ($v$) were kept constant. At each process condition, measurements were repeated three times in order to obtain more reliable data and reduce error.
Fig. 3.10 Schematic cutting plan for sensitivity study.
3.3.3 Results

The results in Fig. 3.11 show that the spindle cutting power increased as MRR increased. Also, the net cutting power increased with an increase of MRR, shown in Fig. 3.12. The increase of MRR was due to the increase of radial depth of cut. As radial depth of cut increased, the cross sectional area of contact between cutting insert and workpiece increased. This leads to a higher mechanical load which will increase both the net cutting power and spindle power.

![Spindle cutting power vs. MRR.](image1)

![Net cutting power vs. MRR.](image2)

Fig. 3.11 Spindle cutting power vs. MRR.  
Fig. 3.12 Net cutting power vs. MRR.

The spindle specific energy and net cutting specific energy are presented in Figs. 3.13 and 3.14, respectively. The spindle specific energy exhibited the typical exponential decay pattern; As MRR increased, the spindle specific energy decreased. The net cutting specific energy also decreased as MRR increased.
3.3.4 Conclusion

The results above show that the power analyzer is sensitive enough to detect the difference in cutting power and specific energy both at the spindle level and net cutting level as the material removal rate changed from 0.20 mm$^3$/s to 0.40 mm$^3$/s.

3.4 References


CHAPTER 4
MAIN EXPERIMENT

4.1 Power & Energy vs. Process Parameters

4.1.1 Design of Experiment

A four factor, five level design of experiment was carried out to investigate the relationship among power, energy consumption, and process parameters in end milling. Every process parameter was distributed to five levels within their ranges, shown in Table 4.1. In order to reduce error, each process condition was repeated three times. The average time ranged from 150 ms to 1000 ms depending on the cutting conditions. Power and energy for the total machine tool, spindle motor, and net cutting were recorded. The cutting insert was regarded as a sharp tool since tool flank wear (VB) did not exceed 0.1 mm after its usage. A schematic of the cutting paths similar to the ones from Chapter 3 are provided in Figs. 4.35 to 4.39 in the Appendix.

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Axial depth of cut $a_p$ (mm)</th>
<th>Radial depth of cut $a_r$ (mm)</th>
<th>Cutting speed $v$ (m/min)</th>
<th>Feed per tooth $f_z$ (mm/tooth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levels</td>
<td>0.5, 1.0, 1.5, 2.0, 2.5</td>
<td>0.2, 0.3, 0.4, 0.5, 0.6</td>
<td>50, 100, 150, 200, 250</td>
<td>0.025, 0.05, 0.10, 0.15, 0.20</td>
</tr>
</tbody>
</table>
4.1.2 Results

The relationships among power, specific energy, and process parameters were investigated to improve the power efficiency during milling. The specific energy is defined as the energy used to remove a unit volume of material in machining [1]. The power and specific energy of the total machine, spindle motor, and net cutting were recorded during milling. In the results, since spindle motor power accounted for 35% to 45% of the total machine tool, the trends for spindle specific energy and spindle power are similar to the trends for total specific energy and total power.

Spindle Power and Energy

The relationships between spindle specific energy ($U_s$) and spindle power ($P_s$) versus independent process parameters [axial depth of cut ($a_p$), radial depth of cut ($a_e$), cutting speed ($v$), and feed per tooth ($f_z$)] are shown in Fig. 4.1. It can be seen that as each process parameter increased the general trend of spindle specific energy was decreasing. The regression analysis showed that the radial depth of cut ($a_e$) was the most important factor to influence the spindle specific energy ($p$ value of 0.043), see Table 4.2.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>4567.8829</td>
<td>757.7670</td>
<td>6.0281</td>
<td>3.18E-06</td>
</tr>
<tr>
<td>$a_p$</td>
<td>-542.8759</td>
<td>300.6088</td>
<td>-1.8059</td>
<td>0.0835</td>
</tr>
<tr>
<td>$a_e$</td>
<td>-5086.3453</td>
<td>1610.6213</td>
<td>-3.1580</td>
<td>0.0043</td>
</tr>
<tr>
<td>$v$</td>
<td>-1.9751</td>
<td>3.6632</td>
<td>-0.5392</td>
<td>0.5947</td>
</tr>
<tr>
<td>$f_z$</td>
<td>-3048.3702</td>
<td>3483.0393</td>
<td>-0.8752</td>
<td>0.3901</td>
</tr>
</tbody>
</table>
Fig. 4.1 Spindle specific energy and spindle power vs. process parameters for (a) axial depth of cut \((a_p)\), (b) radial depth of cut \((a_e)\), (c) cutting speed \((v)\), and (d) feed per tooth \((f_z)\).

The material removal rate (MRR) as a combination of process parameters influences the specific energy significantly. The result shows that as MRR increased the spindle specific energy decreased. The regression model can predict the spindle specific energy with an \(R^2\) of 99.36%, shown in Fig. 4.2. This means spindle energy consumption can be reduced at a higher material removal rate. However, other critical issues arise at higher material removal rates, e.g. poor machined surface integrity and rapid tool wear.
Also, the spindle specific energy decreased as the approximate chip volume increased as shown in Fig. 4.3. The approximate chip volume is the volume of chip removed per revolution of the spindle. The approximate chip volume was determined by dividing the total volume removed by the number of revolutions in one cutting path. This indicates that as chip volume increased, the cutting load increased, and spindle energy was used more efficiently.

Fig. 4.2 Spindle specific energy vs. MRR.

![Fig. 4.2 Spindle specific energy vs. MRR.](image)

\[ U_s = 535.62 \cdot \text{MRR}^{-0.983} \]
\[ R^2 = 0.9936 \]

Fig. 4.3 Spindle specific energy vs. approximate chip volume.

![Fig. 4.3 Spindle specific energy vs. approximate chip volume.](image)

\[ y = 7.8573 \cdot V^{-1.12} \]
\[ R^2 = 0.9065 \]
For spindle power, a regression analysis showed that cutting speed \((v)\) was the most important factor to influence the spindle power \((p\) value of 0.0712), see Table 4.3.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>648.7892</td>
<td>50.8748</td>
<td>12.7527</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a_p)</td>
<td>8.4828</td>
<td>20.1822</td>
<td>0.4203</td>
<td>0.6780</td>
</tr>
<tr>
<td>(a_e)</td>
<td>-123.8119</td>
<td>108.1336</td>
<td>-1.1450</td>
<td>0.2635</td>
</tr>
<tr>
<td>(v)</td>
<td>-0.4643</td>
<td>0.2459</td>
<td>-1.8878</td>
<td>0.0712</td>
</tr>
<tr>
<td>(f_z)</td>
<td>252.3553</td>
<td>233.8437</td>
<td>1.0792</td>
<td>0.2912</td>
</tr>
</tbody>
</table>

The material removal rate (MRR) also influences the spindle power \((P_s)\), see Fig. 4.4. The results showed that the spindle power increased as MRR increased. However, the \(R^2\) of the linear regression model between the spindle power and MRR was only 12.35%. This infers that spindle power does not highly correlate linearly with MRR.

![Fig. 4.4 Spindle power vs. MRR.](image-url)
Since spindle power is composed of spindle air cutting power \( (P_{ac}) \) and net cutting power \( (P_{nc}) \), it is necessary to see the relationship between each of the two components and process parameters, i.e. rotation speed and MRR. There is a second order polynomial relationship between spindle air cutting power and rotation speed \( (N) \) as shown in Fig. 4.5. The \( R^2 \) was 91.78\% which meant the model was able to predict the spindle air cutting power. This can be explained by the fact that the spindle air cutting power is machine tool dependent.

![Spindle air cutting power vs. rotation speed.](image)

**Fig. 4.5** Spindle air cutting power vs. rotation speed.

**Net Cutting Power and Energy**

The net cutting power \( (P_{nc}) \) increased linearly with an increase of MRR, see Fig. 4.6. The \( R^2 \) was 95.45\% which indicates net cutting power significantly depends on the MRR. The relationship between net cutting power and approximate chip volume \( (V) \) is shown in Fig. 4.7. Although not as linear \( (R^2 = 83.53\%) \), net cutting power was also linearly proportional to
approximate chip volume. As the approximate chip volume increased, there was more cutting load which caused the net cutting power to increase.

![Fig. 4.6 Net cutting power vs. MRR.](image1)

![Fig. 4.7 Net cutting power vs. approximate chip volume.](image2)
The relationship between net cutting power ($P_{nc}$) and process parameters is shown in Fig. 4.8. Net cutting power was generally increasing as each process parameter increased. A regression analysis showed that axial depth of cut ($a_p$) was the most important factor influencing net cutting power ($p$ value of 0.0005), see Table 4.4.

![Fig 4.8](image-url)  
Fig 4.8 Net cutting specific energy and net cutting power vs. process parameters for (a) axial depth of cut ($a_p$), (b) radial depth of cut ($a_e$), (c) cutting speed ($v$), and (d) feed per tooth ($f_z$).
Table 4.4 Regression Analysis for Net Cutting Power

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-54.1166</td>
<td>18.9153</td>
<td>-2.8610</td>
<td>0.0086</td>
</tr>
<tr>
<td>$a_p$</td>
<td>30.3214</td>
<td>7.5038</td>
<td>4.0408</td>
<td>0.0005</td>
</tr>
<tr>
<td>$a_e$</td>
<td>73.7532</td>
<td>40.2041</td>
<td>1.8345</td>
<td>0.0790</td>
</tr>
<tr>
<td>$v$</td>
<td>0.0005</td>
<td>0.0914</td>
<td>0.0056</td>
<td>0.9956</td>
</tr>
<tr>
<td>$f_z$</td>
<td>116.1693</td>
<td>86.9431</td>
<td>1.3362</td>
<td>0.1940</td>
</tr>
</tbody>
</table>

It can be seen that as radial depth of cut ($a_e$), cutting speed ($v$), and feed per tooth ($f_z$) increased the net cutting specific energy ($U_{nc}$) generally decreased, see Fig. 4.8. As axial depth of cut ($a_p$) increased, $U_{nc}$ generally increased. The regression analysis showed that the cutting speed ($v$) was the most important factor to influence the net cutting specific energy ($p$ value of 0.0686), see Table 4.5.

Table 4.5 Regression Analysis for Net Cutting Specific Energy

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>102.5535</td>
<td>43.4683</td>
<td>2.3593</td>
<td>0.0268</td>
</tr>
<tr>
<td>$a_p$</td>
<td>24.3081</td>
<td>17.2440</td>
<td>1.4097</td>
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</tr>
<tr>
<td>$a_e$</td>
<td>-101.2996</td>
<td>92.3912</td>
<td>-1.0964</td>
<td>0.2838</td>
</tr>
<tr>
<td>$v$</td>
<td>-0.4006</td>
<td>0.2101</td>
<td>-1.9064</td>
<td>0.0686</td>
</tr>
<tr>
<td>$f_z$</td>
<td>-90.7306</td>
<td>199.8000</td>
<td>-0.4541</td>
<td>0.6538</td>
</tr>
</tbody>
</table>

The general trend of net cutting specific energy ($U_{nc}$) was decreasing with the increase of MRR, see Fig. 4.9. However, the model by Li and Kara [2] poorly predicted net cutting specific energy ($R^2$ of 25.51%). Therefore, a new regression model is needed to accurately capture the true energy from cutting, i.e. the net cutting specific energy.
A model based on the four process parameters and their interactions was used to better predict the net cutting specific energy, see Equation 4.1. There were 16 terms in the full regression model, including 1 constant, 4 independent variables, 6 second order interactions, 4 third order interactions, and 1 fourth order interaction. The values of coefficients of each term are shown in Table 4.6. The $R^2$ drastically increased to 99%. This infers the net cutting specific energy is more related to the independent process parameters and their interactions rather than the MRR as their combination.

\[
U_{nc} = \frac{1}{MRR} \left( \beta_0 + \beta_1 a_p + \beta_2 a_e + \beta_3 v + \beta_4 f_z + \beta_5 a_p a_e + \beta_6 a_p v \\
+ \beta_7 a_p f_z + \beta_8 a_e v + \beta_9 a_e f_z + \beta_{10} v f_z + \beta_{11} a_p a_e v \\
+ \beta_{12} a_p a_e f_z + \beta_{13} a_p v f_z + \beta_{14} a_e v f_z + \beta_{15} a_p a_e v f_z \right)
\]  

(4.1)

Fig. 4.9 Net cutting specific energy vs. MRR.

<table>
<thead>
<tr>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
<th>$\beta_5$</th>
<th>$\beta_6$</th>
<th>$\beta_7$</th>
<th>$\beta_8$</th>
<th>$\beta_9$</th>
<th>$\beta_{10}$</th>
<th>$\beta_{11}$</th>
<th>$\beta_{12}$</th>
<th>$\beta_{13}$</th>
<th>$\beta_{14}$</th>
<th>$\beta_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-47.7</td>
<td>22.6</td>
<td>195</td>
<td>0.386</td>
<td>123</td>
<td>-99.8</td>
<td>-0.179</td>
<td>-9.48</td>
<td>123</td>
<td>-607</td>
<td>-1.81</td>
<td>0.930</td>
<td>54.8</td>
<td>0.76</td>
<td>7.23</td>
<td>-1.43</td>
</tr>
</tbody>
</table>

Table 4.6 Coefficients of Linear Regression Model
4.1.3 Power Efficiency

Power efficiency is important because machining consumes the majority of energy used in manufacturing goods. The power efficiency ($\eta$) was defined by the ratio of net cutting power ($P_{nc}$) to spindle power ($P_s$). The results show that the power efficiency increased with the increase of MRR, see Fig. 4.10. This means that power and energy can be used more efficiently at high material removal rate in milling process. The power efficiency also increased with the increase of approximate chip volume, see Fig. 4.11.

\[
\eta = 1.114 \cdot \text{MRR} + 1.7023 \\
R^2 = 0.9345
\]

Fig. 4.10 Spindle specific cutting energy vs. MRR.

\[
\eta = 76.189 \cdot V + 0.684 \\
R^2 = 0.8549
\]

Fig. 4.11 Power efficiency vs. approximate chip volume.
4.1.4 Conclusions

There is no obvious relationship between (a) spindle specific energy or spindle power and (b) individual independent process parameter. The regression analysis shows radial depth of cut \( (a_e) \) mostly affects the spindle specific energy, and cutting speed \( (v) \) mostly affects the spindle power.

The spindle specific energy decreased with an increase of MRR. The spindle specific energy also decreases with the increase of approximate chip volume, which means energy is used more efficiently at higher cutting loads. The spindle power can be decomposed to spindle air cutting power and net cutting power, and the net cutting power is highly proportional to MRR.

There is no obvious relationship between either (a) net cutting specific energy or net cutting power and (b) individual independent process parameter. The regression analysis shows cutting speed \( (v) \) mostly affects the net cutting specific energy, and axial depth of cut \( (a_p) \) mostly affects the net cutting power.

The net cutting specific energy and MRR could not be correlated by previous empirical model by Li and Kara \cite{2}. It turns out a comprehensive regression model with the four independent process parameters and their interactions can accurately predict the net cutting specific energy with an \( R^2 \) of 99%. The net cutting power was linearly proportional to MRR and approximate chip volume.

4.2 Power & Energy at Same MRR Condition

4.2.1 Design of Experiment

The material removal rate (MRR) is a significant factor to power and energy consumption in machining processes. Several power and energy models have been built
associated with MRR. However, it is unknown whether cutting power, specific energy, energy efficiency, or tool wear are unique for the same MRR in milling and needs to be investigated. Up milling experiments were conducted by changing process parameters while keeping MRR the same. The design of experiment is shown in Table 4.7. The aim was to investigate if MRR alone can determine the power and energy consumption.

<table>
<thead>
<tr>
<th>MRR (mm³/s)</th>
<th>(a_p) (mm)</th>
<th>(a_e) (mm)</th>
<th>(f_z) (mm/tooth)</th>
<th>(v) (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>0.5</td>
<td>0.20</td>
<td>0.025</td>
<td>100</td>
</tr>
<tr>
<td>0.30</td>
<td>0.5</td>
<td>0.30</td>
<td>0.150</td>
<td>50</td>
</tr>
<tr>
<td>1.06</td>
<td>0.5</td>
<td>0.40</td>
<td>0.100</td>
<td>200</td>
</tr>
<tr>
<td>0.50</td>
<td>0.5</td>
<td>0.50</td>
<td>0.050</td>
<td>150</td>
</tr>
<tr>
<td>0.07</td>
<td>2.0</td>
<td>0.10</td>
<td>0.0125</td>
<td>100</td>
</tr>
<tr>
<td>0.30</td>
<td>2.0</td>
<td>0.15</td>
<td>0.075</td>
<td>50</td>
</tr>
<tr>
<td>1.06</td>
<td>2.0</td>
<td>0.20</td>
<td>0.050</td>
<td>200</td>
</tr>
<tr>
<td>0.50</td>
<td>2.0</td>
<td>0.25</td>
<td>0.025</td>
<td>150</td>
</tr>
</tbody>
</table>

4.2.2 Results

Spindle power \(P_s\), spindle specific energy \(U_s\), net cutting power \(P_{nc}\), and net cutting specific energy \(U_{nc}\) were recorded and compared at two different axial depths of cut \(a_p\) under the same MRR condition: \(a_p = 0.5\) mm and \(a_p = 2.0\) mm. Results from the power/energy analysis are presented below.

Spindle Power and Energy

The results show that at the same MRR, the spindle power \(P_s\) was not affected, see Fig. 4.12. The difference of spindle power for the same MRR at two different axial depths of cut was a negligible 0.65%. There was no observable trend for spindle power as MRR increased. A
spike in $P_s$ was observed at 0.3 mm$^3$/s. The relationship between spindle power ($P_s$) and process parameters is shown in Fig. 4.13.

Fig. 4.12  Spindle power vs. MRR at two axial depths of cut ($a_p$):
$a_p = 0.5$ mm, and $a_p = 2.0$ mm.
Fig. 4.13 Spindle power vs. process parameters at same MRR condition for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$).

The spindle specific energy ($U_s$) was also not affected when cutting at the same MRR, see Fig. 4.14. Since the spindle specific energy was the spindle power divided by MRR, the difference of spindle specific energy for the same MRR in two axial depths of cut was also a negligible 0.65%. The spindle specific energy of the two conditions both decreased as MRR increased. The relationship between spindle specific energy and process parameters is shown in Fig. 4.15.
Fig. 4.14 Spindle specific energy vs. MRR at two axial depths of cut ($a_p$): $a_p = 0.5$ mm, and $a_p = 2.0$ mm.

Fig. 4.15 Spindle specific energy vs. process parameters at same MRR condition for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$)
**Net Cutting Power and Energy**

The results show that net cutting power \((P_{nc})\) was on average 3.5 times higher for the same MRR at a higher axial depth of cut \((a_p = 2.0\, \text{mm})\) than a lower axial depth of cut \((a_p = 0.5\, \text{mm})\), see Fig. 4.16. Hence, MRR was not able to determine the net cutting power alone. The net cutting power increased with an increase of MRR for both axial depths of cut. The relationships between net cutting power \((P_{nc})\) and process parameters are shown in Fig. 4.17.

![Graph showing net cutting power vs. MRR at two axial depths of cut \((a_p)\): \(a_p = 0.5\, \text{mm}\), and \(a_p = 2.0\, \text{mm}\).](image)

**Fig. 4.16** Net cutting power vs. MRR at two axial depths of cut \((a_p)\): \(a_p = 0.5\, \text{mm}\), and \(a_p = 2.0\, \text{mm}\).
Fig. 4.17 Net cutting power vs. process parameters at same MRR condition for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$).

Also, the net cutting specific energy ($U_{nc}$) was on average 3.5 times higher for the same MRR at a higher axial depth of cut ($a_p = 2.0$ mm) than a lower axial depth of cut ($a_p = 0.5$ mm). As MRR increased, net cutting specific energy for both axial depths of cut was generally decreasing despite a sudden drop at 0.3 mm$^3$/s, see Fig. 4.18. The relationship between net cutting specific energy ($U_{nc}$) and process parameters is shown in Fig. 4.19.
Fig. 4.18 Net cutting specific energy vs. MRR at two axial depths of cut ($a_p$): $a_p = 0.5$ mm, and $a_p = 2.0$ mm.

Fig. 4.19 Net cutting specific energy vs. process parameters at same MRR condition for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), (c) feed per tooth ($f_z$).
4.2.3 Power Efficiency

The power efficiency ($\eta$) under two different MRR conditions was analyzed. The results show that power efficiency was on average 3.5 times higher for the same MRR at the higher axial depth of cut ($a_p = 2.0$ mm) than the lower axial depth of cut ($a_p = 0.5$ mm), see Fig. 4.20. Also power efficiency increased as MRR increased for both two conditions.

![Power efficiency with respect to MRR.](image)

4.2.4 Tool Wear Analysis

Tool wear during milling is significantly affected by the material removal rate (MRR). Tool wear propagates faster at a higher MRR. However, little research has been done to investigate the tool wear condition under the same MRR using a different combination of process parameters.

In this experiment, two cutting inserts were used with the same MRR condition at two different combinations of process parameters. In one condition, the axial depth of cut was 2.0 mm. In the second condition, the axial depth of cut was 0.5 mm. Tool wear images were taken by a KEYENCE VHX-1000E digital microscope.
A fresh insert is shown in Fig. 4.21 and compared with worn tools in Fig. 4.22. The optical images show that there was more flank wear ($VB$) after milling for the same MRR with an $a_p$ of 2.0 mm than an $a_p$ of 0.5 mm, see Fig. 4.22. This may infer that axial depth of cut has a larger influence than radial depth of cut and feed per tooth on tool flank wear propagation.

![Fig. 4.21 Fresh tool image.](image1)

![Fig. 4.22 Tool wear images at same MRR condition at axial depth of cut ($a_p$): (a) $a_p = 0.5$ mm, (b) $a_p = 2.0$ mm.](image2)
4.2.5 Conclusion

In summary, MRR is not the unique factor to determine net cutting power ($P_{nc}$), net cutting specific energy ($U_{nc}$), power efficiency ($\eta$), and tool flank wear (VB). The spindle power ($P_s$) and spindle specific energy ($U_s$) are unique for the same MRR. The spindle specific energy decreased as MRR increased. However, the spindle power did not necessarily increase with the increase of MRR in the range from 0.07 mm$^3$/s to 1.06 mm$^3$/s.

The net cutting power ($P_{nc}$) and net cutting specific energy ($U_{nc}$) were not unique for the same MRR. Both the net cutting energy and net cutting specific energy were on average 3.5 times higher for the same MRR at a higher axial depth of cut ($a_p = 2.0$ mm) over the lower axial depth of cut ($a_p = 0.5$ mm). This was probably caused by the higher cutting load from having a higher axial depth of cut.

For the same MRR, power efficiency was on average 3.5 times higher at a higher axial depth of cut ($a_p = 2.0$ mm) over a lower axial depth of cut ($a_p = 0.5$ mm). This implies power efficiency is not solely dependent on MRR. Other process parameters must be considered when evaluating the efficiency during cutting.

The tool wear was not unique for the same MRR. Tool flank wear propagated faster at the higher axial depth of cut condition. Therefore, tool wear propagation could be minimized by optimizing process parameters for a given MRR.

4.3 Power & Energy in Up vs. Down Milling

4.3.1 Design of Experiment

Up milling and down milling operations are shown in Fig. 4.18 [3]. In up milling, the workpiece is fed against the rotation of the cutter. In down milling, the workpiece moves in the
same direction as the rotating cutter. The chip formation and cutting dynamics differ significantly between up and down milling [4, 5]. This could lead to differences in power, specific energy, and tool wear when process conditions are the same. Thus, experiments on up and down milling were conducted under the same process parameters to investigate if different milling operations can affect the power, specific energy, and tool wear. The design of experiment is shown in Table 4.8.

![Fig. 4.23 Schematic of up and down milling [3].](image)

Table 4.8 Experiment Conditions for Up vs. Down Milling

<table>
<thead>
<tr>
<th>Milling Operation</th>
<th>$a_p$ (mm)</th>
<th>$a_e$ (mm)</th>
<th>$v$ (m/min)</th>
<th>$f_z$ (mm/tooth)</th>
<th>MRR (mm³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>1.5</td>
<td>0.4</td>
<td>250</td>
<td>0.05</td>
<td>1.99</td>
</tr>
<tr>
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<tr>
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<td>4.77</td>
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<tr>
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<td>0.6</td>
<td>150</td>
<td>0.15</td>
<td>5.37</td>
</tr>
</tbody>
</table>
4.3.2 Results

Spindle power ($P_s$), spindle specific energy ($U_s$), net cutting power ($P_{nc}$), and net cutting specific energy ($U_{nc}$) were recorded and compared in up and down milling under the same process parameters. Results from the power/energy analysis are presented below.

Spindle Power and Energy

Results show that the spindle power during up milling was on average 2.3% higher than that of down milling, see Fig. 4.24. The higher spindle power of up milling over down milling was due to the longer tool/chip contact length which resulted in a higher cutting force [1]. Spindle powers for both up and down milling decreased as MRR increased.

![Spindle Power vs. MRR in up and down milling.](image)

The relationship between spindle power ($P_s$) and independent process parameter is shown in Fig. 4.25. It can be seen the spindle power is always higher in up milling than in down milling as each process parameter increases.
Fig. 4.25 Spindle power vs. process parameters in up and down milling for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$).

The spindle specific energy ($U_s$) was not affected by up versus down milling. Spindle specific energy in up milling was on average 0.86% higher over down milling. As MRR increased, the spindle specific energy from both up and down milling decreased, see Fig. 4.26. The relationship between $U_s$ and independent process parameters for up and down milling is shown in Fig. 4.27.
Fig. 4.26 Spindle specific energy vs. MRR in up and down milling.

Fig. 4.27 Spindle specific energy vs. process parameters in up and down milling for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$).
Net Cutting Power and Energy

The net cutting power \( (P_{nc}) \) during up milling was on average 18\% higher than in down milling. The net cutting power of both up and down milling are generally increasing with an increase of MRR, see Fig. 4.28. The relationship between net cutting power \( (P_{nc}) \) and independent process parameters is shown in Fig. 4.29. It can be seen the net cutting power is always higher in up milling than in down milling.

![Fig. 4.28 Net cutting power vs. MRR in up and down milling.](image)

```latex
Fig. 4.28  Net cutting power vs. MRR in up and down milling.
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Fig. 4.29 Net cutting power vs. process parameters in up and down milling for (a) radial depth of cut \(a_e\), (b) cutting speed \(v\), and (c) feed per tooth \(f_z\).

The net cutting specific energy \(U_{nc}\) of up milling condition was on average 18% higher than that of down milling. As MRR increased, net cutting specific energy of both up and down milling decreased, see Fig. 4.30. The relationship between \(U_{nc}\) and independent process parameters is shown in Fig. 4.31. It can be seen that net cutting specific energy is always higher in up milling than down milling as each process parameter increases.
Fig. 4.30  Net cutting specific energy vs. MRR in up and down milling.

Fig. 4.31  Net cutting specific energy vs. process parameters up and down milling for (a) radial depth of cut ($a_e$), (b) cutting speed ($v$), and (c) feed per tooth ($f_z$).
4.3.3 Power Efficiency

The power efficiency in up and down milling are measured and compared under the same process conditions. The results showed that power efficiency in up milling was on average 15% higher than that in down milling. This indicates that power can be used more efficiently with up milling. As MRR increased, power efficiency in both up and down milling increased, see Fig. 4.32.

![Power efficiency vs. MRR in up and down milling.](image)

4.3.4 Tool Wear Analysis

Tool wear in milling is not only affected by the process parameters, but also by different milling operations, e.g. up and down milling. In this experiment, two cutting inserts were used under the same process conditions for up and down milling. The amount of workpiece removed was the same for each milling experiment. Optical images were used to investigate the effects of up and down milling on tool wear.

A fresh insert and worn inserts from up and down milling are shown in Fig. 4.33 and Fig. 4.34, respectively. The optical images show that flank wear is higher after up milling than
down milling. This can be explained by the fact that a longer tool/chip contact length in up milling led to higher cutting forces and consequentially larger tool wear [1].

Fig. 4.33  Fresh tool image.

Fig. 4.34  Tool wear image under same process condition by (a) up milling and (b) down milling.
4.3.5 Conclusions

In summary, up and down milling operations affect the spindle power ($P_s$), net cutting power ($P_{nc}$), net cutting specific energy ($U_{nc}$), power efficiency ($\eta$), and tool flank wear ($VB$). Spindle power was on average 2% higher in up milling than down milling. However, the spindle specific energy was not significantly affected by up and down milling operations. For net cutting power and net cutting specific energy, up milling consumed on average 18% more than in down milling. Power efficiency in up milling was on average 15% higher than that in down milling. Tool wear was affected by up and down milling. Although the two cutting inserts experienced the same cutting time and removed the same amount of volume, tool flank wear propagated faster in up milling than in down milling.

4.4 References


Fig. 4.35 Milling of H13 at an axial depth of cut $a_p = 0.5$ mm while varying other process parameters.

Note: Represents the position of cutter according to origin. The (X,Y) represents displacements programmed into the G-code.
Fig. 4.36 Milling of H13 at an axial depth of cut $a_p = 1.0$ mm while varying other process parameters.

Note: Represents the position of cutter according to origin. The $(X,Y)$ represents displacements programmed in to the G-code.
Fig. 4.37 Milling of H13 at an axial depth of cut $a_p = 1.5$ mm while varying other process parameters.
Fig. 4.38 Milling of H13 at an axial depth of cut $a_p = 2.0$ mm while varying other process parameters.
Fig. 4.39  Milling of H13 at an axial depth of cut $a_p = 2.5$ mm while varying other process parameters.

Note: ● Represents the position of cutter according to origin. The (X,Y) represents displacements programmed in to the G-code.
CHAPTER 5
SUMMARY & FUTURE WORK

A summary of this research is as follows:

(1) Energy measurement in end milling of AISI H13 tool steel was conducted using the high resolution power analyzer. A feasibility and sensitivity study shows that the power analyzer is capable of measuring power and energy consumption accurately in end milling.

(2) The relationship between specific energy, power, and process parameters has been investigated at both spindle level and net cutting levels. It was found out that spindle specific energy can be correlated to material removal rate (MRR) by an empirical decay model, while net cutting specific energy can be accurately predicted by a multi regression model of process parameters (axial depth of cut, radial depth of cut, cutting speed, and feed per tooth) and their interactions.

(3) Net cutting power, net cutting specific energy, and power efficiency are not solely determined by material removal rate (MRR). They are different for the same MRR at different combinations of process parameters. The spindle power and spindle specific energy are unique for the same MRR.

(4) The effects of up and down milling operations on power and specific energy were studied. For the same process parameters, net cutting power and net cutting specific
energy are 18% higher in up milling than that in down milling. Power efficiency is 15% higher in up milling compared to down milling. This can be explained by the fact that tool flank wear develops faster in up milling than in down milling.

The future work of this research is planned as follows,

1. The relationship between power, specific energy, and process parameters for a worn tool needs to be studied. The influence of tool wear on spindle power, spindle specific energy, net cutting power, and net cutting specific energy needs to be evaluated.

2. Tool wear model as function of power, specific energy, and process parameters may be developed in order to achieve the on-line real time tool wear monitoring.

3. The spindle power and net cutting power in a single cutting revolution needs to be studied to catch the transient phenomena in end milling. A drastic increase in spindle power or net cutting power may be correlated to other process phenomena such as chatter in end milling.

4. The relationship between power, specific energy, and surface integrity can be investigated both in fresh tool condition and worn tool condition.