Energy Analysis in Turning and Milling

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Parameter	Description	Units
$\frac{1}{\alpha}$	Cutting velocity exponent in tool-life equation	-
$\frac{1}{\beta}$	Feed exponent in tool-life equation	-
η	Efficiency of energy generation	-
A	Constant in tool life equation	-
a_p	Depth of cut	mm
D_{avg}	Average workpiece diameter	mm
E	Total energy consumption	J
E_1	Machine setup energy (energy consumed by idle machine)	J
E_2	Cutting energy (energy consumed during material removal)	J
E_3	Energy consumed during tool change	J
E_4	Energy to produce cutting tool per cutting edge	J
E_5	Energy to produce workpiece raw material	J
E_6	Energy to dispose the machining process waste	J
F_a	Force in depth of cut direction	N
F_f	Feed force	N
F_r	Resultant force	N
F_v	Tangential force	N
f	Feedrate	mm/rev
I	Current	A
k	Specific energy in cutting operations	Ws/mm^3

l	Length of cut	mm
N	Spindle speed	RPM
P_o	Power consumed by machine modules without the machine cutting	W
P_c	Power consumed to turn on coolant	W
P_s	Power consumed to turn on spindle	W
r_i	Initial workpiece radius	mm
t_1	Machine setup time	S
t_2	Actual cutting time	S
t_3	Tool change time	S
T	Tool-life	S
$T_{opt\text{-}E}$	Optimum tool-life for minimum energy	S
V_c	Cutting speed	m/min
$\dot{v}$	Material removal rate	mm^3/s
x	Machine cost rate	£/min
y_E	Energy footprint per tool cutting edge	J
y_C	Tool cost per cutting edge	£

List of Abbreviations

BAU	Business as usual
CCS	Carbon capture and storage
CES	Carbon emissions signature
CNC	Computer numerical control
DEFRA	Department for Environment, Food and Rural Affairs
ETS	Emissions trading scheme
GA	Genetic algorithm
GDP	Gross domestic product
GHG	Green house gasses
IEA	International Energy Agency
MIT	Massachusetts Institute of Technology
MMC	Metal matrix composite
MQL	Minimum quantity lubrication
MRR	Material removal rate
NAFCAM	National Council for Advance Manufacturing
PVD	Physical vapour deposition
TiN	Titanium nitride
UK	United Kingdom
WC/C	Tungsten carbide with carbon

List of publications

Journals

[1] Rajemi MF and Mativenga PT, Machinability analysis from energy footprint considerations. Journal of Machine Engineering, 2008; 8 (2): 106 - 13.

[2] Rajemi MF, Mativenga PT, and Jaffery SI, Energy and carbon footprint analysis for machining Titanium Ti-6Al-4V Alloy. Journal of Machine Engineering, 2009; 9 (1): 103 - 12.

[3] Rajemi MF, Mativenga PT, and Aramcharoen A, Sustainable machining: selection of optimum turning conditions based on minimum energy considerations. Journal of Cleaner Production, 2010; 18 (10-11): 1059-65.

[4] Mativenga PT, Rajemi MF, Marimuthu S, Li L, Yang S, and Cooke K, Establishing a basis for sustainable re-use of cutting tools through laaser decoating. Journal of Machine Engineering, 2010; 10 (2): 36-47.

Conferences

[5] XIX CIRP Conference on Supervising and Diagnostics of Machining Systems;
17th-20th March, 2008, Karpacz, Poland

[6] XX CIRP Conference on Supervising and Diagnostics of Machining Systems: High Performance Manufacturing;
16th-19th March 2009, Karpacz, Poland

[7] XIX CIRP Conference on Supervising and Diagnostics of Machining Systems: Knowledge Based Manufacturing;
15th-18th March 2010, Karpacz, Poland

Abstract

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Energy generation as driven by consumption demand is a key contributor to carbon dioxide emissions and climate change. Hence reducing energy usage is an essential consideration in sustainable manufacturing. In addition, the world is experiencing a higher demand and cost of energy, hence reducing energy usage is an important factor for cost control and economic sustainability. Energy availability and security is now recognised as a key aspect to the socio-political sustainability of nations. Thus, reducing energy demand can be associated with the three; economic, environmental and social sustainability pillars.

The manufacturing sector is a key industry that relies on the use of energy in driving value adding manufacturing processes. A widely used process is mechanical machining. This PhD was focussed on an investigation of energy consumption in machining processes and the energy footprints of machined products. A literature review had indicated that despite decades of optimising of machining operations based on cost and productivity, optimising energy use had not received significant attention. In the study a current monitoring device was used to evaluate current requirements and hence power and energy needs for machining processes. The study was done for (i) a range of workpiece materials and (ii) the turning and milling process. This enabled the definition of energy distribution for a machining process and identification of key areas of focus in order to reduce the energy used by a machine tool. The study was then focused on an energy intensive material in terms of machining requirements (titanium alloys) and an in-depth characterisation of the impacts of conventional compared to high speed machining was undertaken.

From the study it was clear that a methodology was needed to ensure that energy use can be reduced or optimised. Thus an energy footprint model for a machined component was developed. This model was then used to derive an optimum tool life equation that satisfies the minimum energy criterion. A methodology for selection of optimum cutting conditions was then developed and tested on a component. Thus, the Thesis presents a new and novel model and methodology for selecting optimum cutting conditions for machining, based on minimum energy requirements. The energy savings associated with using such methodologies are quantified and found to be very significant. This work makes a distinct and important contribution to the machining science for reducing the energy and carbon footprints of machined products.

Declaration

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

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Dedication

To my beloved wife, children and my parents

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CHAPTER ONE

INTRODUCTION

1.1 Definition of sustainability

Sustainability has become an important issue in manufacturing sectors. According to the United Nations world commission on environment and development, sustainable development can be defined as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs [1]. Sustainable manufacturing was specifically defined by the United States, Department of Commerce as the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities and consumers [2].

In literature it is generally now accepted that sustainable development should include three pillars which are economical, environmental and social issues [3, 4]. In order to achieve sustainable development, industries should produce sustainable products [5]. One of the methods to achieve environmentally sustainable products is by reducing energy consumption in manufacture and product use. Higher energy consumption increases production cost and carbon dioxide (CO_2) emissions.

1.2 Sustainability of world resources

One of the main drivers for sustainable development arises from the need to balance demand in increasing world population and protection of the environment. The world population in the year 2009 was 6.8 billion and it was projected that it will increase to 7 billion in late 2011 and may exceed 9.1 billion people in the year 2050 [6]. This increase creates further demand for manufactured products. The question that arises is how industries can cope with this demand and at the same time supporting environmental sustainable manufacturing. One of the answers lies on the efficient use of electrical energy in the manufacturing process.

Increase in world population will increase demand on world natural resources for example oil and coal. It is predicted that the world will face a shortage of oil in 40 years, natural gas in 60 years and coal in 185 years [5]. Increase in fuel prices and higher tariff for electrical usage are signs of this shortage. In manufacturing industries increase in population can be perceived as good since it increases product demand. However, this is at the expense of diminishing world non-renewable resources.

Scientific evidence points to increasing risks of serious, irreversible impact from climate change associated with business as usual (BAU) emissions [7]. There is a strong view that the level of greenhouse gases (GHG) in the atmosphere partly resulting from industrial processes is rising. Energy consumption by industries is one of the dominant factors contributing to the increase in the GHG. According to the United Kingdom, Department for Environment, Food and Rural Affairs (DEFRA) [8], in the year 2007 the total UK GHG emissions was 636 $MtCO_2e$ (542 million tonnes came from CO_2 gases). Energy generation and transport are the main contributors with total amount of 225 $MtCO_2e$ and

137 $MtCO_2e$ respectively. Others for example the industrial iron and steel and other combustion processes contributed 96.8 $MtCO_2e$ of GHG. Referring to huge amount of GHG from energy generation, it is clear that reducing energy consumption would save on energy costs and significantly contribute towards reducing GHG emissions.

1.3 Sustainability in manufacturing

In the UK in the year 2008, electricity consumption was dominated by the residential consumer and industry at 35 % and 33 % respectively [9]. Thus, industries are one of the major consumers for electricity and hence contribute to a large amount of carbon emissions derived from electricity generation. The question that arises is how industries use this huge amount of electricity. One of the answers lies in the amount of machines installed in industries. The higher the number of machines simultaneously used in a particular factory, the higher the electricity consumption will be.

Mechanical machining is widely used in manufacturing industries and represents a major demand for energy. There is an abundant amount of research work done on the machining process, but environmental issues of machining processes have rarely been given much attention. Therefore, one of the motivations for this research was to investigate the environmental issues that relate to energy consumption in machining processes.

As discussed before carbon emissions are a key component of the climate change problem. Therefore, one of the research motivations is to suggest methods for industries to reduce their carbon footprint and hence support the UK’s target of 60% cut in carbon emissions by 2050 (in comparison to 1990 levels) [10]. Most of the steps taken in the UK emphasises reduction of carbon emission by residential consumers but only a limited number of research has been done that tackle the electricity consumption by industry in order to reduce carbon emissions.

1.4 Research aim and objectives

Given the established link between energy consumption in manufacture and the carbon dioxide emitted in generating that energy, the aim of this research is to investigate the impact of machining practice on the energy and carbon footprint of machined products.

The objectives of research are as follows:

1. To study the effect of cutting parameters and the machine tool on energy consumption in turning and milling processes.
2. To study the contribution that can be made by tool coatings and tool re-use in reducing energy consumption and carbon footprint.
3. To explore and develop methodology for the selection of cutting conditions in turning based on minimum energy footprint considerations.
4. To select optimum cutting conditions in turning that satisfies the minimum energy criterion for a given component.

1.5 Organization of thesis

This thesis consists of eight interesting chapters. The first chapter introduces the context for the project and project objectives. The second chapter presents the literature review covering sustainability concepts based on various resources and published papers. The body of work is illustrated in Figure 1.1. This was then focused to two main machining processes, namely milling and turning.

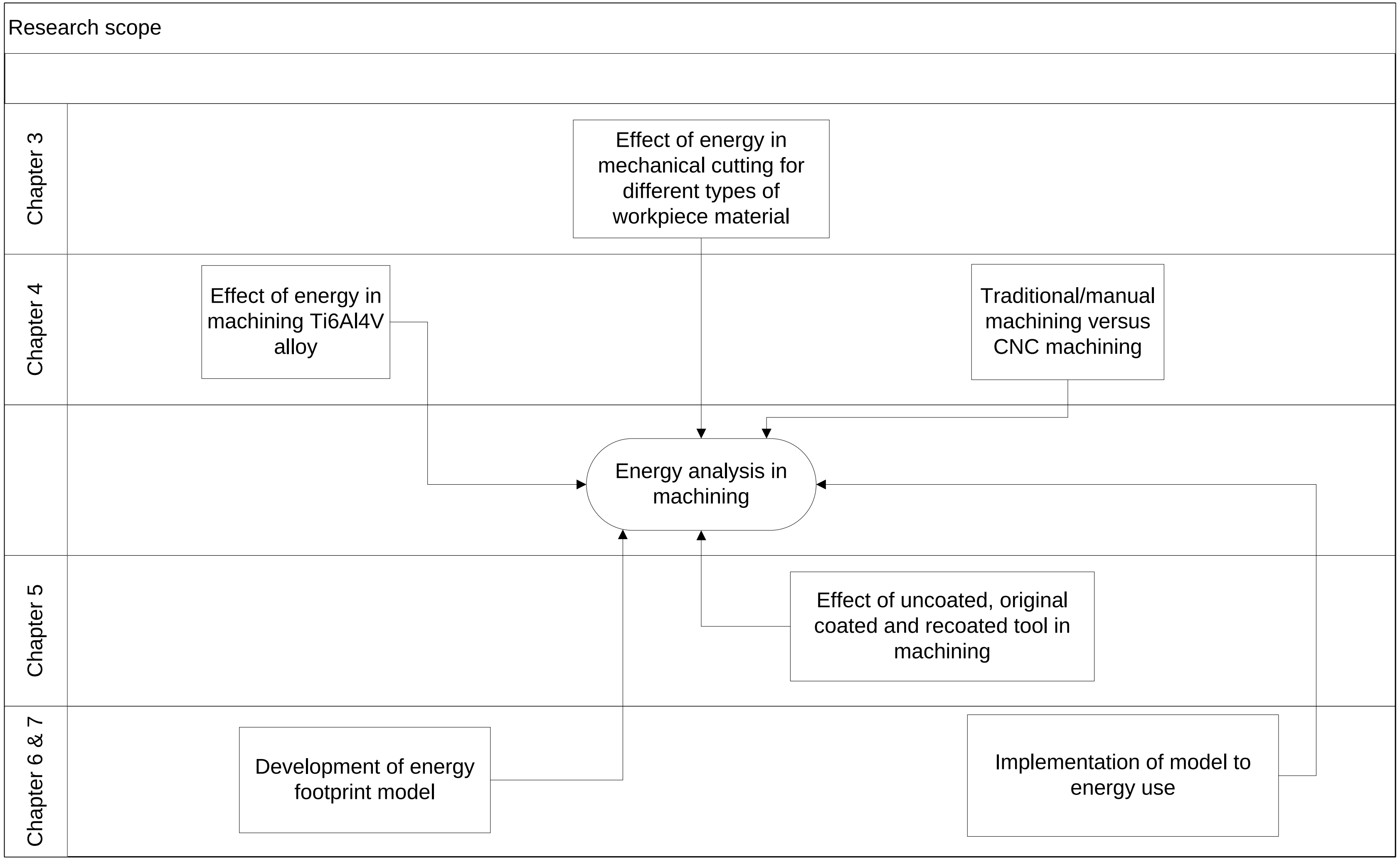


Figure 1.1: Research scope

Chapter three presents results on energy in machining a variety of workpiece materials. This chapter was presented in CIRP XIX Conference on Supervising and Diagnostics of Machining Systems in Poland and also published in the Journal of Machine Engineering.

Chapter four focuses on energy consumption in machining of titanium alloy (i.e Ti-6Al-4V alloy). Titanium was selected for a focused study because, the machining of this alloy was found to be more energy intense compared to other evaluated materials. The cutting tests were done both on a milling and lathe machine. This chapter was presented in the CIRP XX Conference on Supervising and Diagnostics of Machining Systems: High Performance Manufacturing and simultaneously published in the Journal of Machine Engineering.

Chapter five reports on a study to evaluate the energy consumption and footprint associated with the use of first generation coated tooling and re-use of de-coated (chemical compared to laser) and re-coated tooling. The idea was to evaluate the environmental impact of using recoated tooling. This chapter was presented in CIRP XXI Conference on Supervising and Diagnostics of Machining Systems: Knowledge Based Manufacturing and also been published in the Journal of Machine Engineering.

Chapter six develops an energy footprint model for a machined product and proceeds to derive a minimum energy model that can be exploited for selecting optimum tool life. This chapter was published in a high impact journal which is the Journal of Cleaner Production.

Chapter seven implements the minimum cost and minimum energy optimisation philosophy and procedure on a selected component and tooling. This enables quantifying the environmental impact of using the energy minimisation procedures developed in this

PhD thesis. Conclusions and recommendations for further work are presented in chapter eight.

CHAPTER TWO

LITERATURE REVIEW

2.1 Sustainable manufacturing

The United Nations World Commission on Environment and Development [1] define three pillars of sustainability, which are economy, environment and social sustainability. It is desirable to strike a synergy between the sustainability pillars as shown in **Figure 2.1**. With a forecast on environmental sustainability in manufacturing, Alting and Jogensen [11] presented a view that sustainability means that products are designed for their whole life cycle i.e. production, distribution, usage and disposal with minimised (acceptable) influence on the environment.

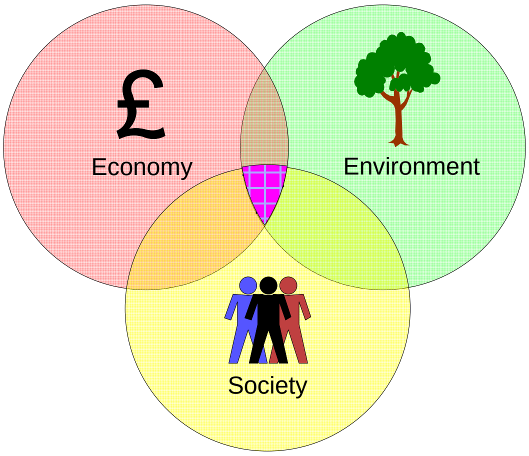


Figure 2.1: Sustainability pillars [1]

Increase in world population (higher demand for resources), economic growth and irreversible environment impact are drivers for the world to adapt a sustainable development.

On 11 December 1997, the Kyoto Protocol [12] which involved 182 parties including 36 developed countries and the European Union agreed on reducing greenhouse gases (GHG) to targets set for each country. Never-the-less the operational strategies needed to reduce the GHG, are still unclear, especially for manufacturing industries. In the UK, the industrial sector is one of the highest amount of electrical energy consumes compared to other users. High demand for energy increases environmental footprints since emissions such as carbon dioxide are traceable to the process of power generation. Thus industrial communities can cut the carbon emission penalty for their electrical energy sources by switching to cleaner power generation sources such as nuclear and hydro-electric. However, the time frame and investment required for setting up an alternative electrical energy generation source is long and expensive respectively. Reducing energy demand by the industrial consumer presents an immediate action that requires urgent attention. This is particularly critical because it takes a long time to de-carbonise already polluted atmosphere. Apart from climate change the escalating cost of energy requires that manufactures reduce energy consumption in order to cut operating costs.

2.2 World population, economy and resources

The world population was 6.8 million in the year 2009 [6] and projected to exceed 9.1 million by the year 2050 subject to fertility rate. An increasing trend for the world gross domestic product (GDP) gives an indication of the growth of the world economy. GDP is a common measure for the economic output of a country. **Table 2.1** shows the historical, current and projected GDP output for the world, European Union and UK [13]. UK GDP shrunk from the year 2007 until 2009 mainly due to the world economic recession. Nevertheless, the GDP in the UK inline with the world and European Union data is projected by International Monetary Fund to increase from the year 2010 as illustrated in **Table 2.1**.

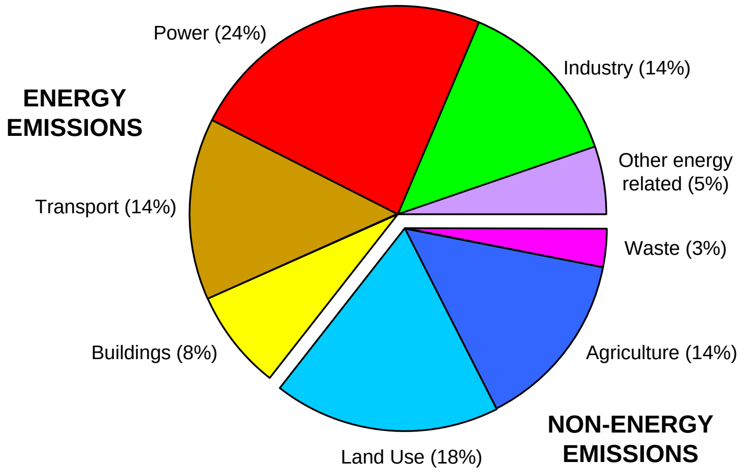
Table 2.1: Gross domestic product (GDP) [US billion dollars] of the World, European Union and UK [13]

	2007	2008	2009	2010	2011	2012	2013	2014	2015
World GDP	55,392	61,220	57,937	61,781	65,003	68,701	72,740	77,132	81,789
European Union GDP	16,942	18,387	16,447	16,543	16,925	17,507	18,139	18,806	19,482
UK GDP	2,800	2,684	2,183	2,222	2,297	2,416	2,553	2,695	2,836

An increase in GDP is indicated by the increase in output of product and this will associate increase in demand for electrical energy to support material, procurement, production processes, product delivery/transportation etc. To address environmental sustainability it is essential to reduce energy intensity of products or use of more renewable energy resources. The depletion of fossil fuels strengthen the case for the use an increase share of renewable energy [14]. Nevertheless, there are barriers to the wide spreads use of renewable energies. Some of these barriers relate to cost-effectiveness and the technological barriers which depend on the country or region [15]. There is a need to compliment the use of renewable energy with a strategy for reducing energy consumption (managing demand).

2.3 Environmental sustainability

Scientific evidence points to increasing risks of serious, irreversible impact from climate change associated with business as usual paths for emissions [16]. There is a strong view that the level of GHG in the atmosphere such as carbon dioxide, methane, nitrous oxide and a number of gases that arise from industrial processes is rising, pursuant to human activity. Among these gases, carbon dioxide (CO_2) is the major GHG that affects global warming [17]. In the year 2000, sources of GHG (calculated as the CO_2 equivalent emissions) were evaluated as shown in **Figure 2.2**.



Total emissions in 2000: 42 GtCO2e

Energy emissions are mostly CO_2 (some non-CO_2 in industry and other energy related). Non-energy emissions are CO_2 (land use) and non-CO_2 (agriculture and waste)

Fig. 2.2: World carbon dioxide equivalent emissions in the year 2000 [7]

The data presented in **Figure 2.2**, show that energy derived emissions contributed 65% of the world CO_2e emissions. More specifically, 24% and 14% of the world CO_2e emissions by then were attributable to power generation and industrial activity respectively. It is thus clear that technologies are required to develop cleaner energy sources as well as sustainable low energy and carbon footprint industries. It was projected by [7], that if the GHG emissions remain at 42 $GtCO_2e$, by the end of this century the global mean temperatures will increase by at least 3° Celsius from its pre-industrial level (i.e. before 18th century), which can in turn result in catastrophic impact to the world.

2.3.1 Carbon emission and energy consumption attributable to industries

There are several factors that contribute to carbon emissions. One of the factors is generation and usage of electrical energy. According to the International Energy Agency (IEA), for the UK in the year 2008, the total domestic supply of electricity was 400388 GWh [9] in which 389366 GWh was from generation of electricity, 12294 GWh was from energy imports and 1272 GWh for energy exports. **Figure 2.3** shows all the sources for electricity generation in UK. Gas and coal are the major sources for generating electricity in UK. Thus a reasonable assumption can be made that the carbon dioxide penalty of electrical energy in the UK is broadly emanating from the carbon footprint of gas and coal power stations.

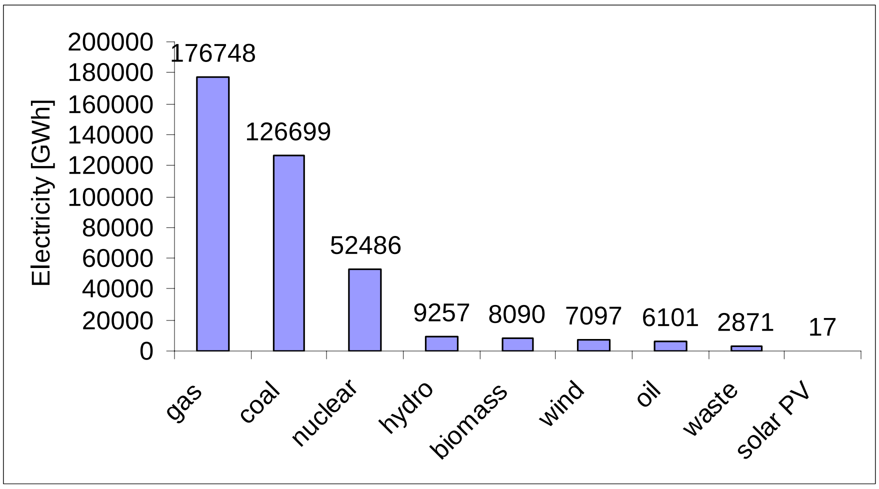


Figure 2.3: The generation of electricity according to sources for the UK in the year 2008 [9]

From **Figure 2.3**, the use of renewable energy sources (i.e. hydro, biomass, wind, and solar) in the UK for generating electricity was less than 10 % in the year 2008. Hence there is a need to promote electricity generation from renewable energies in order to lead to more sustainable energy sources and reduction in carbon emissions. Unfortunately, the use of renewable energy in power generation is a long term investment and is considered as an ongoing improvement; therefore, the objective of finding “DO NOW” methods to reduce energy consumption remains a key strategy towards environmental sustainability.

From the total UK domestic electrical supply in the year 2008, only 341562 GWh (85 %) was considered as total final consumption. The other 30632 GWh was used by the energy sector to run the plant and electricity for pumped storage and also accounts for power loss during transmissions (i.e. 28194 GWh). **Figure 2.4** shows that from the total final consumption of electricity, in the year 2008, the IEA reported that UK residential and industries are the highest consumers for the electricity with the percentage of approximately 35 % and 33 % respectively. From **Figure 2.4**, based on Pareto analysis it can be concluded that in the year 2008 residential and industries sectors were main consumers for electricity.

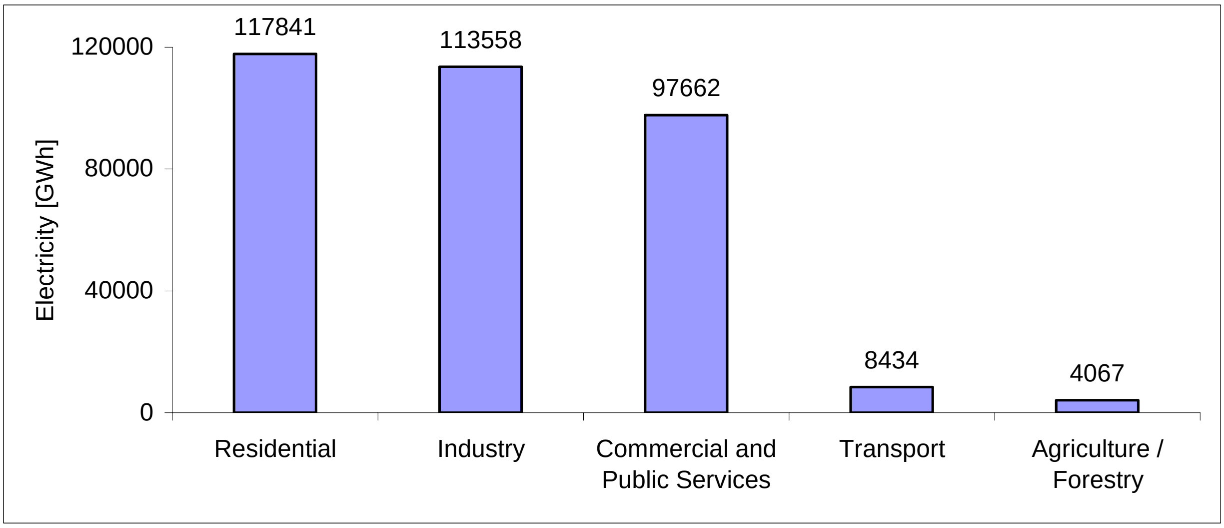


Figure 2.4 : The UK electricity consumers in the year 2008 [9]

In order to achieve the reduction of carbon emissions, special attention must be given to these two main electricity consumers. Most of the steps taken in the UK, emphasise reduction of carbon emission by residential consumers. There are limited research contribution forecast on electricity consumption and reduction of carbon emissions attributable to industry.

One of main international contribution to the environmental analysis of manufacturing processes is undertaken by Professor Gutowski group at Massachusetts Institute of Technology (MIT). Gutowski [18] studied the electrical energy requirements in milling process. Their approach can be used to evaluate energy consumption in machining processes.

2.3.2 Evaluation of carbon emission

Gutowski [19] disaggregated the carbon emissions in terms of four components as shown in **equation 2.1**

$$Carbon = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{Carbon}{Energy} \tag{2.1}$$

According to equation 2.1, the carbon footprint can be seen in terms of three factors the population factor (GDP), energy intensity of output (Energy/GDP) and emissions penalty (Carbon/energy). It is generally agreed that reducing the world population to cut carbon emissions is an unlikely strategy to satisfy socio-political sustainability. However, in terms of production engineering promoting a higher GDP while reducing energy consumption or energy footprint of product and reducing the carbon intensity of energy are more viable and preferable options.

Despite the world attention on the urgent and growing problems of climate change, very little research has been undertaken on the technological solutions for reducing energy and ultimately carbon footprints. In industry the amount of energy consumed is an indirect source of carbon footprints, since CO_2 emissions originate from the generation of that energy. CO_2 emissions per energy use depend on the balance between renewable and non renewable energy sources supplying the electrical grid. Manufactures may not have the freedom to control the energy mix. Thus environmental sustainability in manufacturing can be partly addressed by a goal to reduce the energy footprint of the manufacturing processes. Among industrial processes, mechanical machining is one of the most widely used technologies for the fabrication of discrete components. The technology enables closer dimensional accuracies, a wider product size range and can be economic for both small and large sizes.

Moreover, recent trends in high speed machining have largely promoted dry cutting, which helps mitigate the effects of cutting fluids on the environment [20, 21]. Elimination of the use of cutting fluids can help create a cleaner environment and also reduce process cost [22]. In addition when dry machining is in use, the power that would otherwise be needed to pump the coolant is eliminated and hence reducing energy consumption in the machining process.

Carbon emissions can be an indicator on how much carbon was produced in manufacturing the product so that environmentally conscious consumers can choose when purchasing their goods. Jeswiet and Kara [23] formulated the calculation of carbon emissions as in **equation 2.2**. In this equation, the "Carbon Emission Signature" (CES^{TM}) is used to determine the carbon emissions depending on which type of source for the power generation.

$$\text{Carbon emission } [\text{ kgCO}_2] = \text{EC}_{\text{part}}\ [\text{GJ}] \text{ x } \text{CES}^{\text{TM}}\ [\text{kgCO}_2/\text{GJ}] \qquad (2.2)$$

where EC_{part} is the energy consumed to produce part and CES^{TM} is the carbon emission signature as calculated for the energy mix.

The carbon emission signature for known energy source can be evaluated from a summation of the carbon emission per energy output of each source multiplied by the share of the source to the total energy mix and divided by efficiency of generation as shown in **equation 2.3**.

$$CES = \frac{\sum\left(P_E \times F_e\right)}{\eta} \qquad (2.3)$$

where P_E is the percentage of the electricity supplied to the factory according to its source of generation, F_e is the emission factor [$kgCO_2/GJ$] according to its source and η is the efficiency of generation.

Figure 2.5 shows the carbon emission factor for different types of energy generation sources for the year 2008 [24]. In reality, it is very difficult for industries to determine the source of power from the electrical power grid supplied for their daily operations. The electricity carbon emission factor is updated every year. Hence the carbon emissions may differ year to year. To ease this problem, the climate Change Levy Negotiated Agreements and the UK Emissions Trading Scheme (ETS) use an "average carbon intensity factor for electricity fixed at 0.43 $kgCO_2/kWh$" [25]. Alternatively depending on units of current assessment the UK average carbon intensity factor equates to 0.000119 $kgCO_2/kWs$ or 119 $kgCO_2/GJ$.

In conventional power plants, turbines have a fuel conversion efficiency of 33 % [26]. In literature an efficiency of 0.34 was reported as commonly used in evaluating carbon emission signature for Ontario, Canada and New South Wales ,Australia [23].

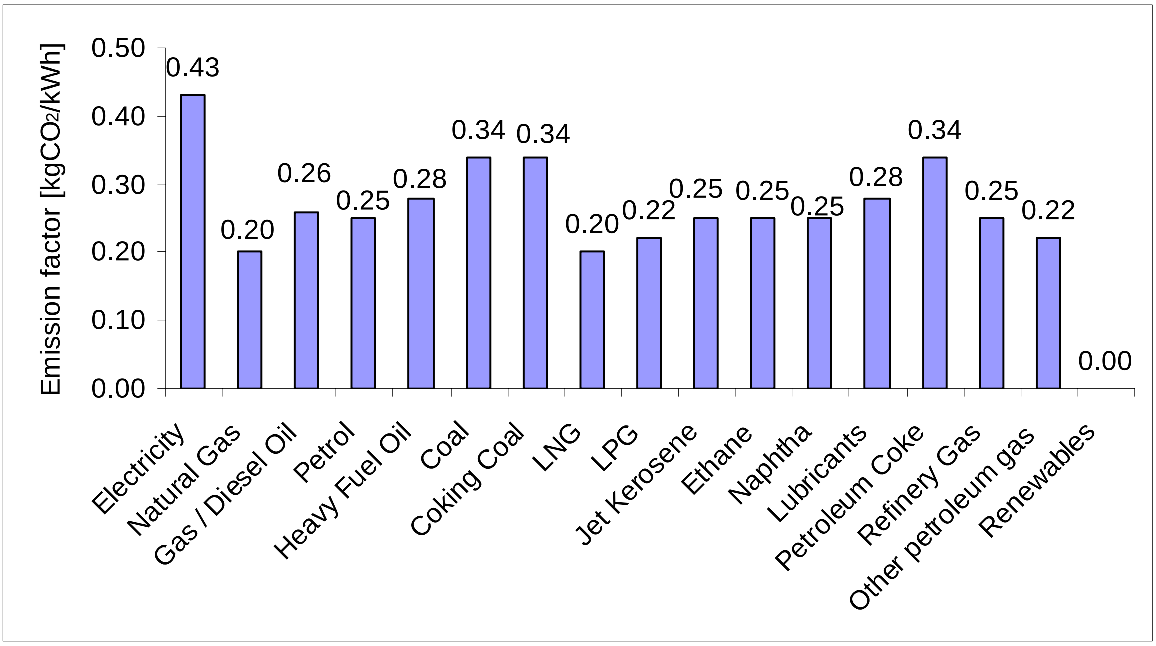


Figure 2.5: Carbon emission factor for different types of energy generation sources in the UK for the year 2008 [24].

2.4 Energy in manufacturing

Mechanical machining is widely used in most manufacturing industries hence represents a major demand for energy. There is an abundant amount of research work done on the machining process but environmental issues of machining processes have rarely been given much attention except for the work done by Gutowski's group at the Massachusetts Institute of Technology (MIT). Dahmus and Gutowski [27] presented a flow diagram of materials for environmental analysis of the machining process as shown in **Figure 2.6**. The green shaded area indicates the research area for this project. The main contributor to the energy budget and CO_2 emissions is the energy used in the machining process and the energy embodied in the workpiece materials. The energy required for the machining process is drawn from the electrical grid. In generating the energy (electricity) from different power station sources, CO_2 was emitted by the processes.

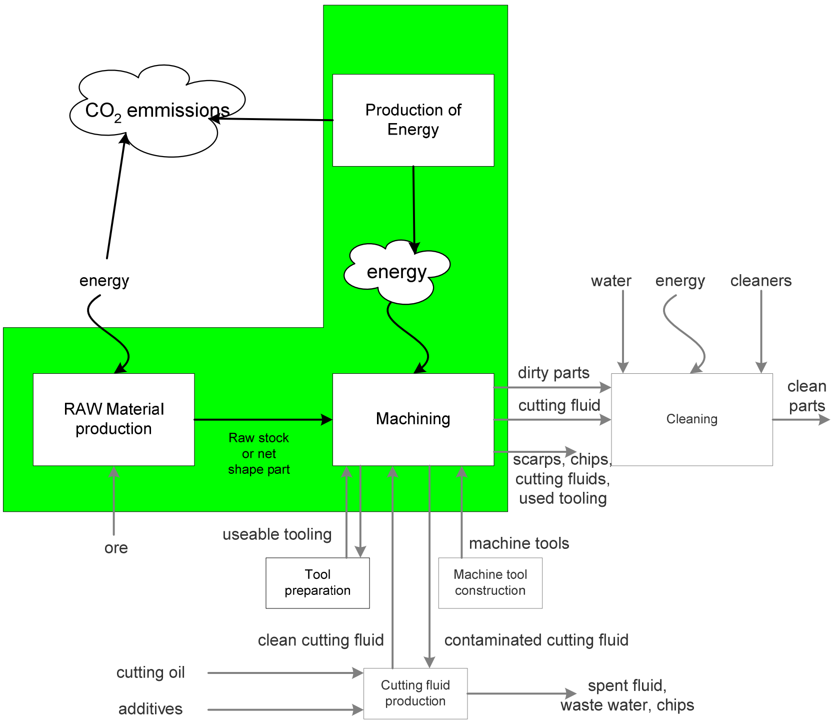


Figure 2.6: Energy in manufacturing adapted from Gutowski [27]

The production of raw materials also contributes to the total energy consumption for a given manufactured product. Different types of raw materials (mainly metals) have different techniques of extraction and purification from ore and hence this influences the carbon footprint of the material. Manufacturing companies can influence energy consumption in machining but may not have a choice on material extraction. Even so, the information regarding how much energy is needed to produce the raw material is useful to the manufacturing company to calculate the carbon footprint of the machined product. The carbon footprint includes the footprint associated with machining process and the indirect footprint embodied in the inputs to the process.

2.4.1 Power and energy footprints

Gutowski et al reported that the energy required for the material removal processes can be quite small compared with the total energy for the machine tool operation [18]. It was further suggested that the energy footprint for primary processes involved in material fabrication is usually higher than that for secondary shaping processes [19]. This emphasises the need for life cycle analysis in the evaluating energy footprint of products. Notwithstanding this factor, for manufacturing companies the raw material inputs are usually defined by the customer and sustainable innovations thus relate to improvements in the secondary production processes.

Following on earlier work by Gutowski [18], the electrical power requirement, *P*, for machining can be calculated from **equation 2.4**.

$$P = P_0 + k\dot{v} \tag{2.4}$$

where, P is the power [W] consumed by the machining process, P_0 is the power [W] consumed by all machine modules for a machine operating at zero load (powered machined which is not cutting), k is the specific energy requirement $[\mathrm{Ws/mm^3}]$ in cutting operations, *and* $\dot{v}$ is the material removal rate (MRR), in $[\mathrm{mm^3/s}]$.

As shown in **equation 2.4**, the energy requirement for the machining process is dependent on the power consumed and specific energy in the cutting operations. Representative specific energy for machining different materials were published by Kalpakjian & Schmid [28]. The values to adapt depend on the combination of tooling and workpiece material/grades used.

Thus, from **equation 2.4** the total power for machining can be divided into two, namely the idle power (P_0) and the machining power $(k\dot{v})$. The idle power is the power needed or required for equipment features that support the machine. For example, power to start up the computer and fans, motor, coolant pump etc. The power drawn by a machine tool using a three phase motor, *P*, is calculated using **equation 2.5**:

$$P = V \cdot I \cdot \sqrt{3} \tag{2.5}$$

where *V*, is the voltage and *I* is the current [A].

The energy required for machining process, ***E***, can be deduced from converting the power **equation 2.4** into an energy **equation 2.6**.

$$E = (P_0 + k\dot{v})t \tag{2.6}$$

where t is the time taken for machining, in *seconds*.

Trends in high speed machining have largely promoted dry or near dry cutting, which helps mitigate the effects of cutting fluids on the environment. The use of cutting fluids in machining was reported to endanger the environment and machine operator [29, 30]. Key et al [31] reported that exposure to soluble oils and synthetic coolant can cause skin diseases such as eczematous contact dermatitis which harm the machine operator. Hence, elimination of cutting fluids can help create a cleaner environment and also reduce process cost. Research shows that by using dry cutting, energy consumption for machining process can be reduced from 16% to 4% [32, 33].

2.4.2 Energy footprint and material selection

The carbon footprint for extracting a range of workpiece materials from their natural ore is shown in **Figure 2.7**. These data derived from the Cambridge Engineering Selector [34] software shows that relative to steel, aluminium, cast iron or brass, the extraction of titanium alloys is associated with the highest carbon footprint. In extracting one kg of titanium alloy, 55 kg of carbon are emitted. Such considerations are seldom taken into account when selecting a material for a particular application. This emphasises the need for a holistic view, of the life cycle carbon footprint of materials if the greatest strides in cutting carbon emissions are to be realised.

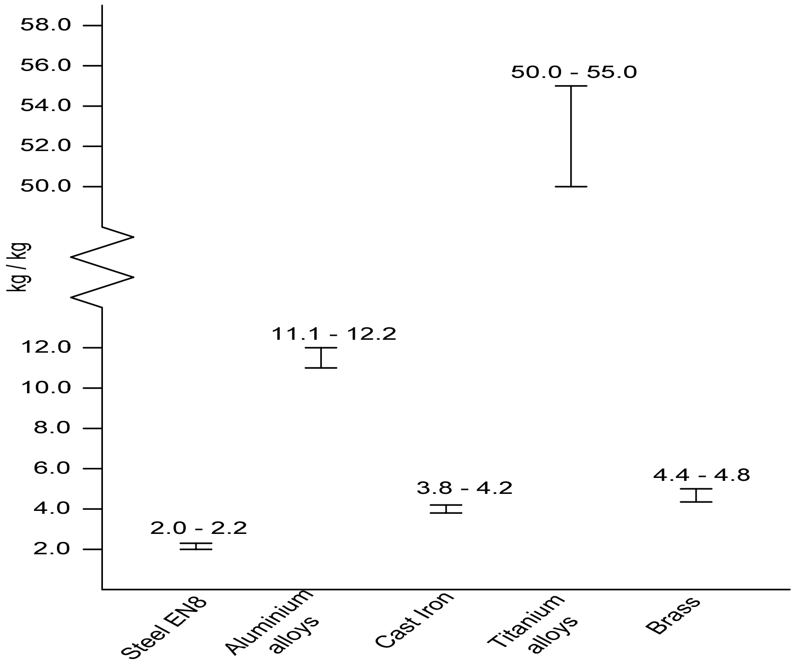


Figure 2.7: Carbon emissions per kg of raw material produced [34].

2.5 The global machine tool market

As discussed before in section 2.3 industry was one of major consumer for electricity and contributes a large amount of carbon emissions in terms of electricity consumption. The question that arises is how industries use this huge amount of electricity. One of the answer lies on the amount of machines and facilities installed in industries. The higher number of machines used simultaneously in a particular factory, the higher electricity consumption it will be. It is difficult to get the exact amount of machines in the world because no combined data could be located in literature. In order to get a crude estimate the number of machine tools in the world based on **2009** World Machine Tool Output and Consumption Survey [35] were used. The 2009 survey was based on machine data in the year 2008. **Figure 2.8** shows world main machine tool producers in **2008** [35]. In this survey, a machine tool is defined as a power driven machine, powered by an external source of energy and not portable by hand. These can be divided into two groups namely metalcutting and metalforming machine tools.

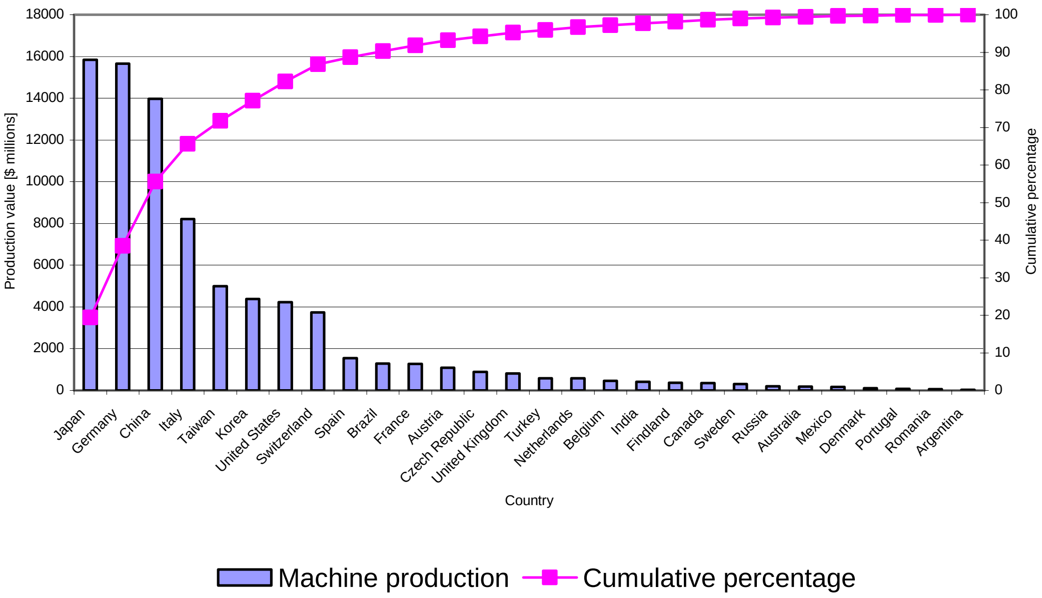


Figure 2.8: World production of machine tools produces in the year 2008 (adapted from [35])

According to Pareto analysis (80-20 rule) there are eight countries that can be considered as the world's main machine producers. The countries in descending order are Japan, Germany, China, Italy, Taiwan, Korea and United States. UK only contributed 1% of world machine tools and is in 14th place of the producer countries for machine tools. One of the reasons for UK to be in the 14th place is due to structural changes in the industry whereby the country is concentrating more of work on service sector rather than manufacturing sector.

Japan was the global leader in producing machine tools. They produced one-fifth of the world machine tools [35]. According to Japan Machine Tool Builders' Association, machine tool production in the year 2008 was USD14 billion (¥1249 billion) [36]. German as the second largest producer showed a 15% increase in Euros for machine tool production in the year 2007 [35]. Unlike in Japan, a significant amount of machine tools produced in Germany are for large, custom made machine (engineering-intensive special-purpose machine). The fact that machines are custom made makes the analysis for energy consumption more complex and difficult. According to a press released in May 2010 by German Machine Tool Builders' Association, the orders for machine tools rose sharply in the first quarter of the year 2010 [37]. Hence this can be one of the early signs for economic recovery after the year 2009. China as the third world machine tool producers increased it production by 43 % in the year 2007 [35].

Considering consumers for machine tools produced in 2008, China is the number one consumer for machine tools. The consumption grew from USD16 billion in the year 2007 to astonishingly USD19 billion in the year 2008 (18 percent increase). **Figure 2.9** shows, Germany and Japan were the second and third largest consumers for machine tools. Obviously, these countries should pay an even higher attention to energy footprints in their machining processes.

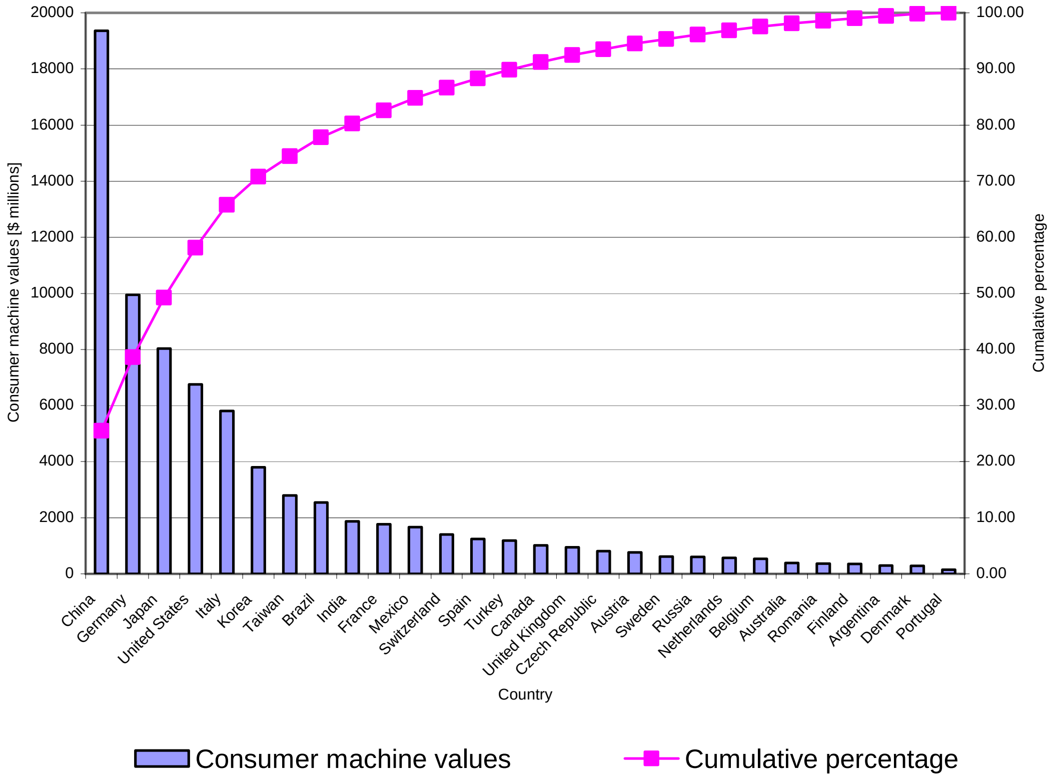


Figure 2.9: World consumers for machine tools in the year 2008 adapted from [35]

Figure 2.9 shows another 6 major consumers for machine tools. The countries in descending order are United States, Italy, Korea, Taiwan, Brazil and lastly India. UK only consumed 1% of the total machine tools produced in 2008 and is in the 16th place for the consumers of the machine tools.

According to World machine Tool Output and Consumption Survey [35], in 2008, UK has spent around 945.1 million US dollar on buying new machines. Taking average price of machining centres produced in Japan for the year 2008 [38] that is around USD160,000 (¥13 000 000) per machine (currency conversion of USD1 equals to ¥82), the total number of machine bought in UK for the year 2008 is approximately 5907 units. Even though the number of machines is just an approximate; the shear value of money to buy the machines and the number of machine bought shows that the industry is investing a lot in it. Hence higher energy is needed to operate these machines. For example if a MHP lathe machine being turn on without any operation for 8 hours a day for 365 days, the total electricity consumption is 10.5 MWh (Idle current at 5 A). If this value is multiplied with the total number of machine bought in 2008, the total electricity consumption is 62 GWh or 0.05 % from total electricity used by the industry in the year 2008 (refer to **Figure 2.4**). This action will definitely increase the carbon emission in the UK as a result of increase in energy consumption. Some examples of the major designers for machine tools are Mikron, Mori Seiki, Bridgeport, Denford, Matsura , Mazak and Cincinati.

UK is neither the highest producers nor the significant consumers for machine tools in the world. It used to be one of the leading industrial countries during the year 1800s. Nevertheless, with the current interest in sustainable manufacturing, UK should be one of the leading countries to promote sustainable manufacturing. It should be also noted that, data on the number of machine tools does not reveal the size of the industrial base or the country's geographical area. Thus the UK may have a relatively small number of machines but over a small ecological footprint. Furthermore, UK electricity data shows that industry was one of major consumers for electricity and hence should be a target for investigations.

2.6 Current strategies towards environmental sustainable manufacturing

Steeneveldt et al [39] presented three main actions that can be used to reduce CO_2 emissions. The steps are improving the energy efficiency, changing the fuel source (for example, from coal to gas) and carbon capture and storage (CCS). The authors concluded that CCS requires additional energy for the combustion and separation process. Hence improving the energy efficiency and changing the fuel source may have additional advantages over CCS. The CO_2 emission by changing fuel mix was discussed by

Hamilton [40]. Nevertheless improving the energy efficiency will be discussed in this thesis.

The technology developed in CCS stores the CO_2 emission from fossil fuels in a safe geological storage instead of emitting it to the atmosphere [41]. A good example of the implementation of CCS in Norway was discussed in [42]. The impact of CCS may need some time to be realised. According to Viebahn et al, in Germany for the next 15 years some of the fossil power plants might need to be substituted whereas the CCS technology might not be fully developed yet [43]. Hence using renewable energy sources might be a timely (short term) solutions compared to CCS. However, the generation of energy from renewable resources is still low and need some time to be developed. As was shown in **Figure 2.3,** the amount of energy generated in the UK for the year 2008 from renewable energy sources was less than 10 percent of the total needed. Other than energy sustainability and clean energy generation, resource efficiency is another aspect that is needed to support sustainable manufacturing.

2.6.1 Material selection

In designing a certain part (eg. shaft), the mechanical properties (eg. density, strength, elasticity, etc.) plays an important role in determining the functional requirements of the components. Unfortunately the machinability of materials is challenged by high strength workpiece materials. The workpiece properties affect the specific energy required for material removal. Selecting tougher material, for example, titanium alloy gives certain advantages to the component such as high specific strength and excellent corrosion resistance [44]. Unfortunately, this difficult-to-cut material requires higher specific energy and needs copious amounts of coolant for the machining processes. This increases the environmental burden associated with machining components from titanium alloys.

Mechanical machining is one of the widely used processes in industry for manufacturing of discrete parts. Titanium alloys are being increasingly used in aerospace manufacturing as well as medical devices. This research focuses on the electrical power and hence energy requirements for machining titanium alloy. It was suggested that the energy required for the material removal processes can be quite small compared with the total energy for the machine tool operation [18]. Additionally, the energy footprint for primary processes in material fabrication is usually higher than that for secondary shaping processes [19]. The carbon footprint for extracting a range of workpiece materials from their natural ore are shown in **Figure 2.10 and Figure 2.11**. It showed that titanium alloy has the highest carbon footprints. Such considerations are seldom taken into account when selecting a material for a particular application. This, emphasises the need for a holistic view of the life cycle of a product if the greatest strides in cutting carbon emissions are to be realised.

Holloway [45] introduced material selection in design incorporating the environmental effect. In the paper, the extended material selection in mechanical design by Ashby [46] which include environmental analysis helps designers, design products that is sustainable throughout their life cycle. It was suggested in literature that the properties of material that are required for selection may not be defined to sufficient detail or greater accuracy in material databases [47]. An example software for material selection is the Cambridge Engineering Selector [34]. Some useful information in this software includes the amount of energy and carbon associated with material extraction from ore in producing raw materials as shown in **Figure 2.10 and 2.11** for ferrous and non-ferrous materials respectively.

Specific to machining, Kalpakjian & Schmid [48] published specific cutting energy for different materials.

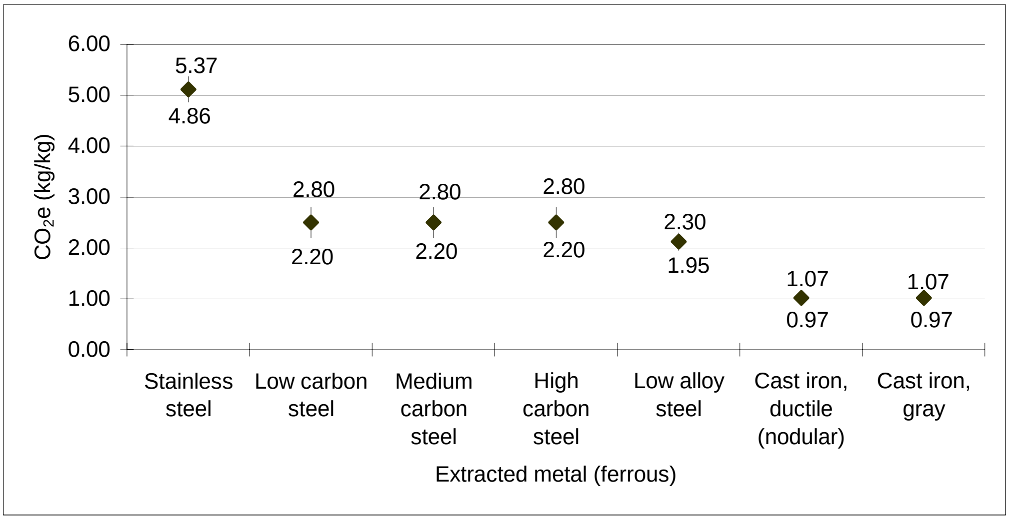


Figure 2.10: Carbon emissions for ferrous metal extraction [34]

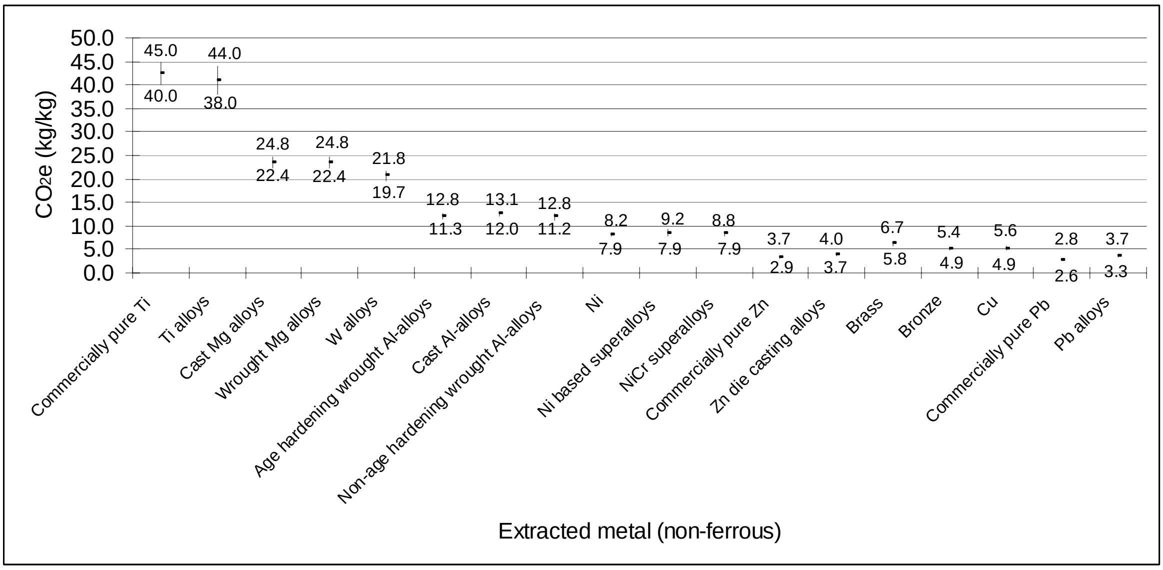


Figure 2.11: Carbon emission for non-ferrous metal extraction [34]

In related research, Davim [49] studied the effect of cutting conditions on metal matrix composite (MMC). MMC has a metal base alloy (e.g. titanium alloy) with reinforcing ceramics (e.g. Al_2O_3). The paper concluded that cutting velocity had the highest effect on power consumed in the turning process. The feedrate was the second highest contributor. The study suggests that the selection of cutting parameters can influence the energy consumed in machining. It is noted here that the study by Davim does not consider the energy footprint for all machining sequences or the energy embodies in tooling.

2.6.2 Dry and minimum quantity lubricant machining

Dry or near dry machining has gained a lot of interest in machining process research. This is because it eliminates or significantly reduces the use of cutting fluids. This reduces the cost of fluid acquisition, the associated cost with pumping cutting fluids and the environmental burden associated with fluid disposal. However, eliminating coolant and lubricant from the machining process is difficult given the advantages of machining using cutting fluids. Cutting fluid reduces the tool-workpiece friction hence prolonging tool life. Additionally it’s flushing and cooling effect enables heat transfer from the machining process [50].

One of the disadvantages in dry machining is that it reduces tool life due to the high thermal load and friction between tool and workpiece material. Near dry machining is often referred to as minimum quantity lubrication (MQL). In MQL small quantity (10-50 ml MQL medium per machine hour) is usually supplied in the form of an aerosol [51].

Another near dry lubrication system that has gained interest is cryogenic cooling. Cryogenic cooling uses liquid nitrogen supplied through a specially design micro-nozzle. This method has potential to substitute conventional cooling, especially for difficult-to-machine materials, for example, titanium alloy and metal matrix composite (MMC). The cooling medium (i.e. liquid nitrogen) is ejected to the tool-workpiece area which has a high temperature during machining. As the liquid nitrogen evaporates, it lowers the coefficient of friction between the chip and tool hence prolonging tool life [52]. Nevertheless, this reported work did not discuss energy consumed in pumping the liquid nitrogen which increases the energy consumed for machining process.

2.6.3 Cutting tool selection

There are several types of cutting tools such as polycrystalline diamond (PCD), Cubic Boron Nitride (CBN), ceramics and carbide tools which can be used in turning operations. PCD tools are used extensively in automotive and aerospace industries. They are ideal for high speed machining and suitable to cut aluminium alloys and ceramics. CBN is the second hardest known substance and because of its physical properties, many advantages appear when using CBN tooling as an alternative to tungsten carbide or to grinding operations. Both PCD and CBN tools are relatively very expensive and hence not selected for present research. Ceramic are good materials for high-speed finishing and can be used to machine materials such as superalloys, hard-chill cast iron and high strength steels [53]. Ceramic cutting tools have a lower fracture toughness compared to carbide tools and hence they are less widely used especially where machine vibration may compromise performance. Given all of the factors for the tool materials mentioned previously, tungsten carbide tools are the most common tools for machining steels. Hence carbide tools are selected for this research. Additionally, carbide tools have a wider process window compared to the CBN alternative and hence selection of optimum cutting conditions is likely to yield greater benefits.

The type of tool used in machining can influence the energy consumption for machining processes [54]. Coated tools are preferred in many machining operations since it is shown that coating generally produce lower friction at the tool-chip interface, which will result in lower cutting energy, contact temperature and tool wear [54]. For example, TiN coating reduces crater wear, while TiC coating enables high resistance to flank wear [55] and this reduces energy consumption during machining processes, owing to the cutting tool retaining it's sharpness for a longer time. Derflinger et al [50] discussed the use of a hard coated TiAlN with lubricant layer (WC/C) coating in dry machining processes. The coated and lubricated insert tool prolongs tool life and promotes dry machining processes. In their work, dry drilling experiment was implemented with assisted compressed air to remove the chips. Unfortunately, the energy consumed during machining with auxiliary compressed air equipment was not presented. Hence it is difficult to make a comparison on the amount of energy saved using dry machining as compared to wet machining process. Another area of interest is the re-use of tooling and it's impact on environmental footprint.

2.6.4 Selection of machining processes

Selection of optimum machining parameters may save cost and energy consumption in producing a particular product. Another factor that affects the energy consumed in machining is the size of the part. It is sometimes unsuitable to machine a small part using a conventional machining centre. Microfactory which use smaller machines reduce the space occupied by the machine as well as energy consumed in the actual cutting process [56]. Liow [57], for example, in his study showed that the conventional milling machine consumed 800 times more energy in comparison to a micro milling machine. It can be concluded that selecting a suitable machine and machining process can reduce energy usage in machining process.

2.6.5 Selection of cutting parameters

To machine a component, cutting velocity, feedrate and depth of cut have to be selected as process inputs. In selecting these variables the critical requirements are to avoid tool breakage or violating the capability of the machine tool. Within these requirements the process window can be narrowed down to improve tool life, achieve acceptable surface finish, machine to required tolerances, reduce machining cost, improve production rate or enhance profit rate. These factors are well known to industry and appear in published literature. However, the requirement to minimise the energy used in machining has not been adequately addressed or previously reported in literature.

Energy consumption can be reduced if suitable cutting parameters were selected. Significant work has been performed before in University of Manchester formerly UMIST forecast on selection of cutting conditions to satisfy the minimum cost criterion [58, 59]. Chapman [60] suggested that energy usage in a machining process can be evaluated and reduced by studying a particular process in detail. Nonetheless, in order to study the process in detail, one must understand the factors that affect energy consumed in the process. In a machining process, the cutting parameters are the most important variables. These must be optimised to reduce energy consumed in machining.

Chen et al [59] discussed in detail the heuristic method of determining optimum cutting conditions with minimum cost. In the paper, the critical constraints in determining optimum cutting parameters and also the cost model were presented. Example of constraints includes maximum tangential force due to tool breakage, machine power and setup, the maximum feedrate and depth of cut and etc. The results of this method gave a suitable cutting tool with optimum cutting conditions for a given turning operation.

Hinduja and Sandiford [58] presented optimum cutting parameters using two tools in milling process. The optimum cutting parameters satisfy the minimum cost criterion. The constraints involved in determining optimum cutting parameters were similar to Chen et al [59]. Unfortunately, the minimum energy criterion was not considered in determining these cutting parameters.

Lee and Tarng developed cutting model to maximise production rate or minimize production cost [61] using polynomial networks. In the polynomial network method finds relationships between cutting parameters (e.g. cutting speed, depth of cut, etc.) and cutting performance (e.g. surface roughness, cutting force and tool life). Mesquita et al [62] develop a different model which incorporates computer aided process planning in optimizing cutting parameters. In their paper, the same criteria (i.e. minimum production cost and minimum time for machining) were considered in turning processes.

Cus and Balic took the optimization of cutting parameters in milling a bit further by developing their model using genetic algorithms (GA) approach [63]. Chowdhury and Rao [64], on the other hand, presented a new approach for improving cutting tool life by optimising the cutting parameters in turning.

The research listed above gave substantial evidence of effect of optimising the cutting parameters towards minimising production cost and maximising production rate. Nevertheless, it was difficult to find researches that optimize the cutting parameter to minimise energy consumed in machining. This is a huge gap in optimization of cutting conditions.

CHAPTER THREE

ANALYSIS OF TURNING PROCESS FOR DIFFERENT TYPES OF WOKPIECE MATERIALS FROM ENERGY CONSUMPTION CONSIDERATIONS

3.1 Introduction

Recent global developments have heightened the need to choose the best sustainable manufacturing methods in order to mitigate the effects of industrial processes on the environment. Nevertheless energy consumption is seen as one of the key performance indexes for assessment of the environmental credentials of an enterprise. It is through energy consumption that the carbon emission penalty (amount of carbon emitted in generating the energy) can be estimated. Machining remains one of the keys discrete parts in manufacturing processes and its mechanics has received considerable attention in research and development. However, the energy analysis for machining processes is a relatively new area. In this chapter, the environmental impacts of machine utilisation are assessed through energy consumption. It considers the energy requirements in machining of a number of alloys according to recommended cutting conditions. The energy was accessed through the electrical power requirements of the machining process. The results clearly discuss the impact that high speed machining could have on energy consumption and hence a more sustainable machining industry.

From literature, it was suggested that the energy required for the material removal processes can be quite small compared with the total energy for the machine tool operation [18]. It was further suggested that the energy footprint for primary processes involved in material fabrication is usually higher than that for secondary shaping processes [19]. This emphasises the need for life cycle analysis in the evaluating energy footprint of products. Notwithstanding this factor, for manufacturing companies the raw material inputs are usually defined by the customer and sustainable innovations thus relate to improvements in the secondary production processes.

3.2 Effect of energy in machining different types of workpiece materials.

The research was inspired by previous research done by Gutowski et al. [18] who studied energy utilisation for milling machines. However, unlike his work, the work reported in this chapter was based on CNC lathe operations and focuses on energy consumption for machining different types of workpiece material. A 1988, MHP lathe machining centre was used to study the power consumption for a machine in standby mode (idle power with spindle off) and also while cutting selected industrial alloys. Five types of workpiece materials were used in this research, namely an EN8 steel, aluminium alloy, cast iron, titanium alloy and brass. To standardise the cutting tests and enable comparison between materials, a general purpose TiN coated CNMG 120408-WF carbide insert was used. This was mounted on Sandvik tool holder type PCLNL2020K12. Unified depth of cut of 1.2 mm and feedrate of 0.15 mm/rev were used within the range of cutting speeds recommended by Sandvik Corromat for the workpiece materials [65]. The final comparison of the power and hence energy requirements was done at the recommended/optimum cutting condition for each workpiece material.

The electrical power consumption was measured using a DT-266 digital clamp meter (Refer **Figure 3.1**). The clamp meter was clamped on one of the three live wires supplying electricity to the three phase motor of the MHP lathe machine. The clamp meter relies on the “hall effect” to measure the current flow through the life wire [66]. The clamp meter creates a magnetic field around the live wire causing a resulting force which can be measured as current by the clamp meter. The measurements were taken without physically touching the life electrical supply wire and hence reducing the risk of an electric shock.

Figure 3.1: DT-266 Digital clamp meter

Firstly, the total current flow through the live wire was measured when the machine is in an idle state (i.e. when the machine and control computer has been turned on and no cutting is occurring). The current drawn was measured for actions such as machine jog, positioning the tool and supplying the coolant. Current consumption was recorded for the machine running at various spindle speeds but in non-cutting modes. The experimental design enabled the calculation of the current drawn for each of the machine operations/functions. All current measurements were converted into power using the electrical power **equation 2.5** and into energy using **equation 2.6.**

3.3 Evaluation of specific energy constants

A number of cutting speeds for each of the materials were used to calculate the specific cutting energy, *k*, for each of the materials. The cutting speed used and detail specification for each of the material were shown in **Table 3.1 to 3.5**. From the cutting tests, the power required for machining was plotted against the material removal rates for the different cutting speeds used. **Figure 3.2** shows results for all the workpiece material. From such analysis, the specific energy for each material was evaluated and as shown in **Table 3.6**. These values reflect the relative machinability, i.e. how easy it is to cut materials to an acceptable tool life and workpiece quality.

Table 3.1 Cutting parameters for aluminium

V_c [m/min]	a_p [mm]	f [mm/rev]	Length of cut, l [mm]	Initial diameter, D_i [mm]	Final diameter, D_f [mm]	MRR (mm^3/s)	Machining power, P (net) [W]
150	1.2	0.15	100	76.3	73.9	443	934
175	1.2	0.15	100	73.9	71.5	516	1581
200	1.2	0.15	100	71.5	69.1	590	1796
225	1.2	0.15	100	69.1	66.7	663	2012
250	1.2	0.15	100	66.7	64.3	737	2227
275	1.2	0.15	100	64.3	61.9	810	2371
300	1.2	0.15	100	61.9	59.5	883	718

Table 3.2 Cutting parameters for cast iron

V_c [m/min]	a_p [mm]	f [mm/rev]	Length of cut, l [mm]	Initial diameter, D_i [mm]	Final diameter, D_f [mm]	MRR (mm^3/s)	Machining power, P (net) [W]
100	1.2	0.15	100	31.5	29.1	289	2156
110	1.2	0.15	100	29.1	26.7	316	2085
120	1.2	0.15	100	26.7	24.3	344	2228
130	1.2	0.15	100	24.3	21.9	371	2156
150	1.2	0.15	100	21.9	19.5	425	2085
175	1.2	0.15	100	19.5	17.1	493	2444

Table 3.3 Cutting parameters for steel

V_c [m/min]	a_p [mm]	f [mm/rev]	Length of cut, l [mm]	Initial diameter, D_i [mm]	Final diameter, D_f [mm]	MRR (mm^3/s)	Machining power, P (net) [W]
150	1.2	0.15	100	58.0	55.6	441	2084
175	1.2	0.15	100	55.6	53.2	514	2156
200	1.2	0.15	100	53.2	50.8	586	2372
225	1.2	0.15	100	50.8	48.4	659	2875
250	1.2	0.15	100	48.4	46.0	731	3450
275	1.2	0.15	100	46.0	43.6	803	4169
300	1.2	0.15	100	43.6	41.2	875	3306

Table 3.4 Cutting parameters for brass

V_c [m/min]	a_p [mm]	*f* [mm/rev]	Length of cut, *l* [mm]	Initial diameter, D_i [mm]	Final diameter, D_f [mm]	MRR (mm^3/s)	Machining power, *P* (net) [W]
100	1.2	0.15	60	25.4	23.0	286	1150
110	1.2	0.15	60	23.0	20.6	313	1150
120	1.2	0.15	60	20.6	18.2	339	1006
130	1.2	0.15	60	18.2	15.8	364	1294
140	1.2	0.15	60	15.8	13.4	388	1366

Table 3.5 Cutting parameters for titanium alloy

V_c [m/min]	a_p [mm]	*f* [mm/rev]	Length of cut, *l* [mm]	Initial diameter, D_i [mm]	Final diameter, D_f [mm]	MRR (mm^3/s)	Machining power, *P* (net) [W]
55	1.2	0.15	100	76.0	73.6	162	2588
75	1.2	0.15	100	73.6	71.2	221	2660
95	1.2	0.15	100	71.2	68.8	280	2947
115	1.2	0.15	100	68.8	66.4	339	3091
135	1.2	0.15	100	66.4	64.0	398	3235

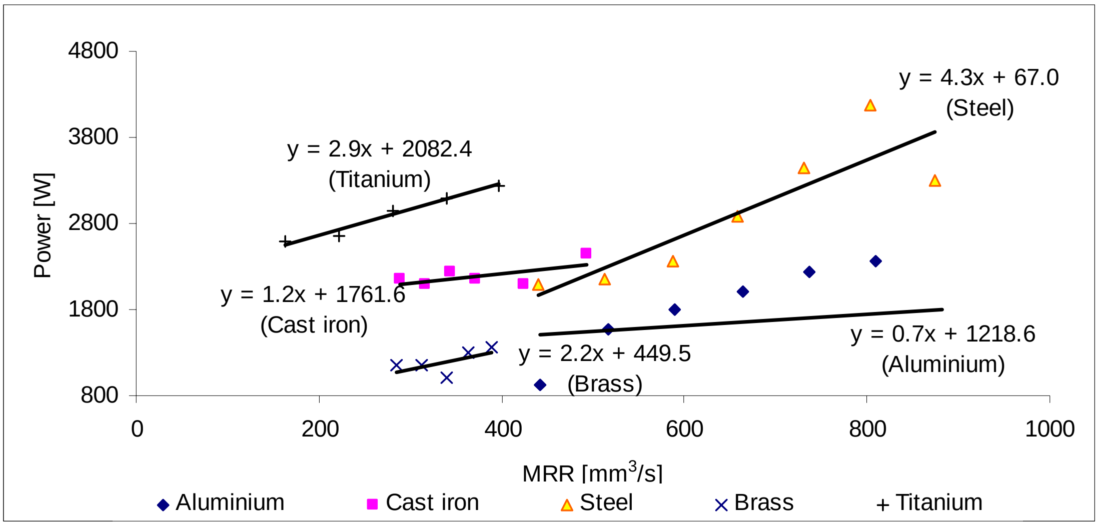


Figure 3.2: Variation of power with material removal rate

Table 3.6: Specific power requirements evaluated from cutting tests

Workpiece Material	Specific cutting energy, *k* [Ws/mm^3]
Aluminium	0.7
Cast Iron	1.2
Steel	4.3
Brass	2.2
Titanium alloy	2.9

Comparing the values in **Table 3.6** with the specific energy requirements in cutting operation given by Kalpakjian & Schmid [28] (**Table 3.7**) shows that the values for each of the materials are in the range hence adding credibility to the methodology adopted here for evaluating the specific energy.

Table 3.7 : Specific cutting energy for different materials [48]

Material	Specific cutting energy, *k* [Ws/mm^3]
Aluminium alloy	0.4 – 1
Cast irons	1.1 – 5.4
Copper alloys	1.4 – 3.2
High-temperature alloys	3.2 – 8
Magnesium alloys	0.3 – 0.6
Nickel alloys	4.8 – 6.7
Refractory alloys	3 – 9
Stainless steels	2 – 5
Steels	2 – 9
Titanium alloys	2 – 5

The second set of analysis examined the power and energy requirements for machining process for each of the materials at cutting conditions recommended by Sandvik [65] Coromant. In practice a number of machine shops follow recommendations from their tool supplier. Hence the analysis throws light into the relative energy requirements in industrial machining operations. Variations from the results reported here may emanate from the use of different cutting tools and tool geometry. However, carbide cutting tools are the most versatile in terms of a wide application over a range of cutting speeds and hence present the best option for a comparative study. Additionally, most of these tools are now coated.

3.4 Results and discussions

Figure 3.3 shows the relative percent of power consumption in a machining centre. **Figure 3.3 (a to e)** shows that only 13 % to 36 % of the total power drawn is used for actual machining. The bulk of power was spent for the non-cutting operations. Running the spindle and the control computer and cooling fans consumes most of the energy. This may be a feature of turning machines where the spindle is designed or selected to provide adequate power to rotate the workpiece. The design process should be one of the engineering challenges in order to improve the usefulness and reduce the impacts to the environment [67]. In this machine supplying the coolant uses 4 % to 9 % of the power requirement and hence a move to dry machining can save this power/energy. This share is comparable to a 2 % coolant pump energy reported by Gutowski [18] for a 1998 Bridgeport automated milling machine. The required power for cutting aluminium, cast iron, EN8 steel, brass and titanium alloys in this research were, 31 %, 28 %, 38 %, 13 % and 31 % respectively. All the tests showed that the non cutting operation power dominates the machining process. Yet, power/energy consumption is seldom considered as an optimisation priority in the design of machine tools.

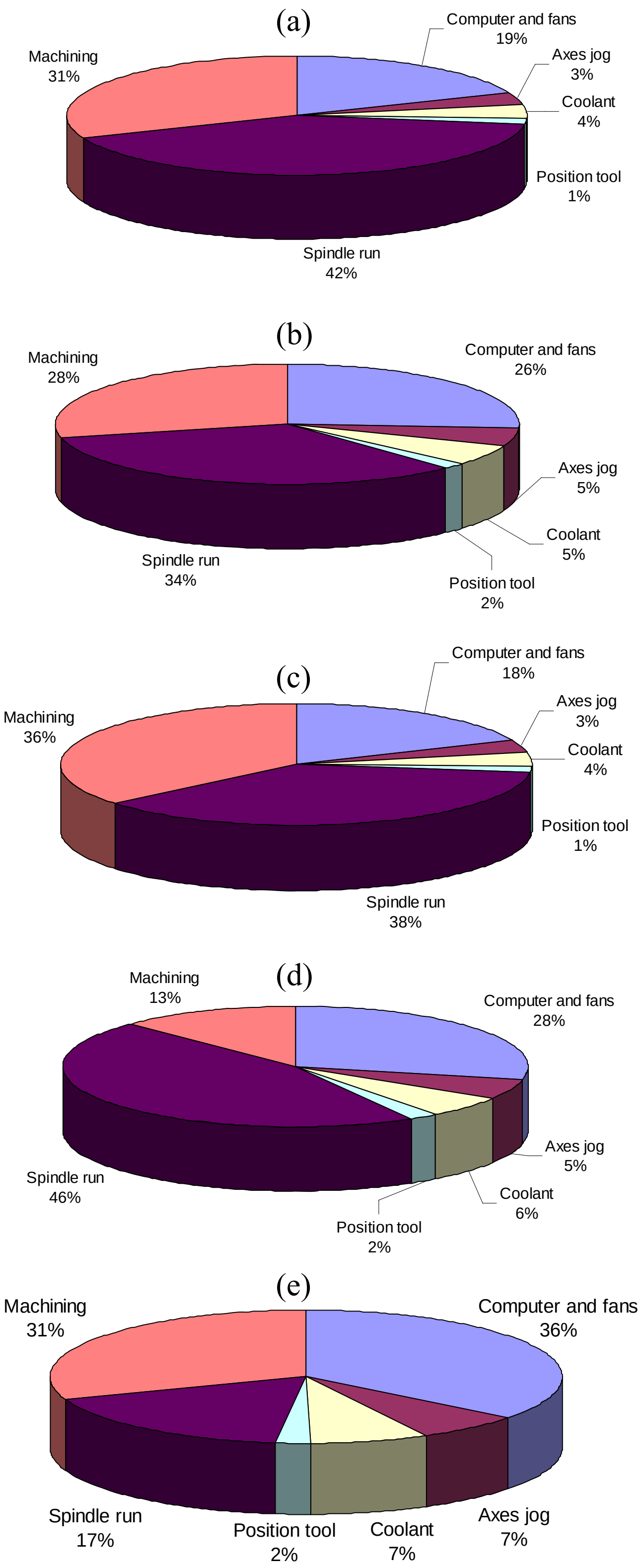


Figure 3.3: Power distribution for the MHP lathe for machining different workpiece materials: (a)Aluminium alloy, (b)Cast iron, (c) EN8 steel, (d)Brass, (e)Ti6Al4V alloy

To get a view on the energy required, evaluation was made of the energy to remove 10 cm^3 of material. Using the material removal rate to calculate the time taken to machine this quantity, it was then multiplied with the power consumed to get the energy requirement. **Table 3.8** showed the cutting parameters for finishing in turning operations adapted from recommended cutting parameters from tool supplier (i.e. Sandvik insert tools).

Table 3.8: Cutting parameters adapted from Sandvik [65]

	Aluminium	*Cast Iron*	*Steel*	*Brass*	*Titanium Alloy*
Feedrate (mm/rev)	0.30	0.30	0.25	0.15	0.15
Depth of cut (mm)	1.50	1.00	1.00	1.20	1.20
Cutting speed (m/min)	654	240	395	140	75

It can be seen in **Figure 3.4** that the total energy to remove 10 cm^3 of titanium alloy is significantly higher than for other materials. The amount of energy consumed was 39 MJ (Note that the detail calculation is shown in **Appendix 3**) or around 108 units of 100 W light bulbs being turned on for one hour. Among these alloys, titanium was machined at the lowest cutting speed and material removal rate. Thus low volumetric rate machining processes imply the need for a longer cutting time to remove a specified amount of material. Hence, this was done at a penalty of a higher energy use. It can be seen that one benefit of high speed machining or rapid machining would be to significantly reduce the energy footprint for a machined product. Aluminium alloy was machined at the highest cutting speed and has the lowest energy footprint. Even though the cutting speed of aluminium is the highest between all the selected materials, it does not necessarily give the highest amount of energy consumed in removing the same volumetric amount of materials. **Figure 3.4** reveals that the total energy for machining depends on the type of material to be machined. Referring to **Figure 3.3** and **Figure 3.4**, the non-cutting operations are the major contributor to the energy consumed in machining.

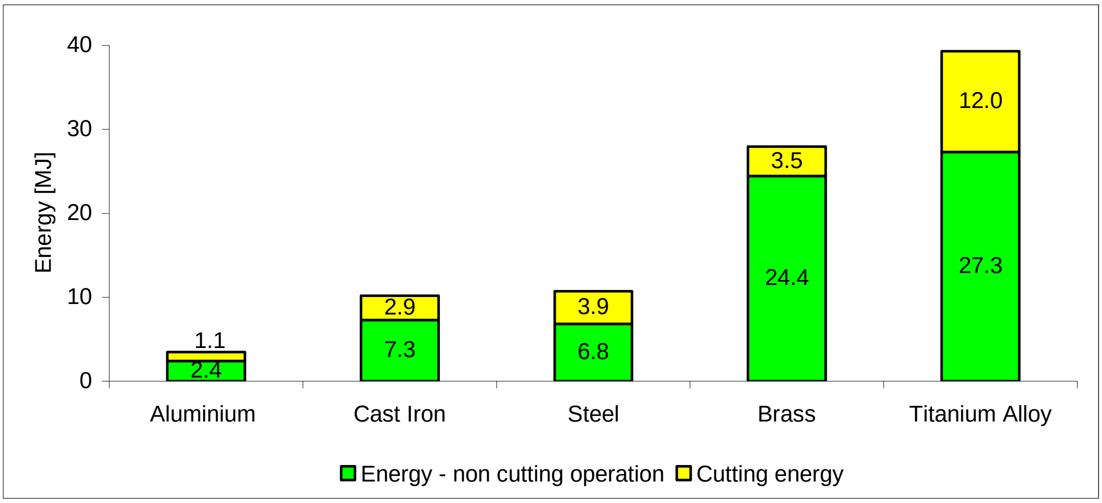


Figure 3.4: Total energy requirements to remove 10 cm^3 of material

The total machining energy consumed to remove 10 cm^3 of steel and cast iron are $1.07 \times 10^7\ J$ and $1.02 \times 10^7\ J$ respectively. Brass has a higher energy requirement compared with steel and cast iron with the total machining energy of $2.80 \times 10^7 J$. The reason behind these values is the feedrate during the machining process for each of these materials. Brass has a lower feedrate, i.e. 0.15 mm/rev compared to steel and cast iron. This factor caused the time taken for machining 10 cm^3 of brass is higher than time taken to remove 10 cm^3 of steel and cast iron. Eventually, it will result in lower material removal rate and increase the energy requirements. Gutoswki et. al. [18] suggested that to reduce the energy requirements for machining process, one should reduce the machining time by increasing throughput (i.e. MRR) rates. Reducing energy would reduced associated carbon emissions [68].

Reduction of carbon emissions is a very important factor towards sustainable manufacturing processes. Referring to this benefit, using **equation 2.2**, the predicted amount of carbon emissions in removing 10 cm^3 of materials were shown in **Figure 3.5**. In this case, machining 10 cm^3 of titanium alloy will give more than 10 times higher carbon emissions compared with machining aluminium alloy.

On the other hand, cast iron and steel give an almost similar amount of carbon emissions. As for brass, the lower feedrate which gave rise to higher time taken for machining causes the carbon emission to be higher than aluminium, cast iron and steel. This fact was a logical sense in which higher time taken in machining will increase the energy consumed and hence carbon emissions. High carbon emission gives an alarming sign on the effect of selecting different materials in machining processes. Until today this sign was often ignored due to various limitations, for example, the properties of the selected material and cost of production. It is essential that steps are taken to improve this problem and support sustainable manufacturing processes.

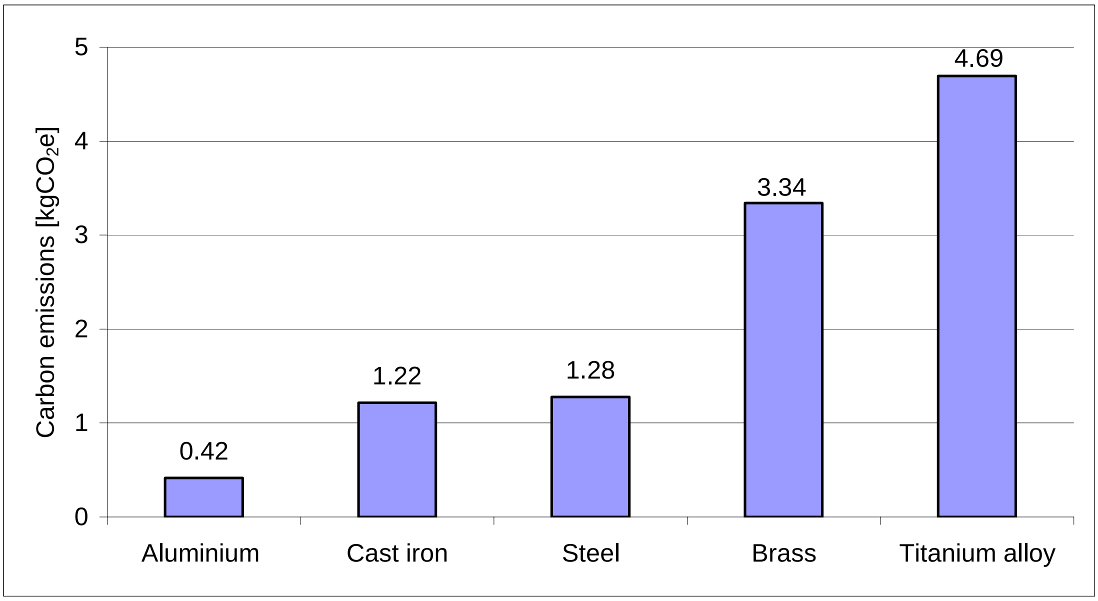


Figure 3.5: Carbon emissions in removing 10 cm^3 of material.

The results shown above have highlighted the effect of selecting different materials in power, energy and carbon emissions. The manufacturing industries might not have control in selecting the type of material for their product; this cannot be an excuse to be ignored. Steps should be taken to improve it and hence creates better and sustainable processes.

3.5 Conclusions

The energy consumed in the machining can be used as an indirect measure of the energy derived carbon footprint for a process. This is because in generating the power that is then used to drive machines carbon dioxide emissions are produced. Thus in the interest of energy availability and reducing carbon footprints it is essential to run production operations at the lowest energy consumption. Analysis of power/energy consumed on a CNC lathe shows that non cutting operations consume the bulk of the energy. For a range of workpiece materials, it was found that the actual cutting required only 13 % to 36 % of the total energy required by a machining process. Design of low energy footprint machines should be targeted as a strategy to improve sustainability of machining operations. In particular the energy required by the lathe spindle was found to be the dominant consumer. Implementing dry cutting instead of using coolants can reduce the power/energy consumption by at least 4 %. This is an additional sustainability benefit to the elimination of the contaminating fluids.

Comparing the energy required for different engineering alloys it was found that machining at higher volumetric removal rates or high speed machining results in lower energy consumption for an identified removal volume for product. In addition, the type of material machined affect energy consumption. If the origin of power supply to a machine shop is known then this work could be extended to accurately calculate the associated carbon footprint. Thus one strategy to reduce industrial activity related carbon emissions is to reduce the energy consumption in production processes.

CHAPTER FOUR

COMPARISON OF ENERGY CONSUMPTION IN MACHINING PROCESSES

4.1 Introduction: Energy consumption in machining Ti6Al4V alloy

Titanium alloys are increasingly being used in manufacturing especially in aerospace industries. However, it poses a difficult machining problem [69, 70] due to its material properties. The environmental impact of using this material is rarely discussed especially with regards to energy consumption and its contribution to carbon emissions. The poor machinability of titanium leads to lower material removal rate and longer machining time. Coupled with high carbon footprints encountered, in extracting this material from ore, clearly the environmental impact of using this material needs to be optimised. From Chapter 3, it was clear that machining titanium alloys had the highest environmental burden in terms of energy use compared to cutting a range of other materials. Thus there is a strong case for focusing on this alloy.

In the research reported here, cutting tests were undertaken on a lathe and milling machine using unified cutting conditions. The associated energy and carbon footprints were analysed and discussed with emphasis on high speed machining. The research clearly shows the impact of process choice and cutting speed on environmental footprints as a key performance measure in sustainable manufacturing.

Earlier work reported by the authors showed that the non cutting operation in lathe was the significant consumer of energy compared to the actual cutting process [32]. The motivation for this work was to explore how the energy and carbon footprint in machining a product from titanium alloy would vary for different cutting conditions and types of machining process. This information is essential in planning for manufacture of sustainable products.

4.1.1 Energy consumption in machining Ti6Al4V alloy;

A titanium 6Al-4V alloy block (85 mm long and 42 mm width) was end face milled on a CNC TAKISAWA milling machine. **Table 4.1** shows the range of cutting conditions used for the tests.

Table 4.1: Cutting conditions for the milling tests

Cutting variable	Range tested
Cutting speed, V_c [m/min]	30 - 80
Spindle speed, N [RPM]	298 – 796
Feedrate, f_z [mm/tooth]	0.15
Depth of cut, a_p [mm]	1
Width of cut, a_e [mm]	4
Tool diameter, D [mm]	32
Insert type (TPMN160308 H13A)	Uncoated carbide
Numbers of inserts on tool holder	1
Workpiece material	Titanium 6Al-4V
Composition of workpiece material	89.37% Ti, 6% Al, 4% V, 0.08%C, 0.3% Fe, 0.2 % O_2, 0.05% N

As shown in **Table 4.1**, in this part of the research, the depth of cut was kept constant at 1 mm and feed of 0.15 mm/rev, but the cutting speeds were varied. In total 8 different sets of cutting conditions were tested as shown in **Table 4.2**. To standardise the cutting tests and enable comparison between different cutting conditions, a general purpose uncoated (TPMN160308 H13A) carbide insert was used. The cutting conditions used were within the range of cutting speeds reported in literature [71]. The final comparison of the power and hence energy requirements was done at the recommended/optimum cutting condition for the tooling and workpiece material. After starting the machine, current consumption for the idle or non cutting operation was measured. The current was then recorded for the different cutting conditions.

Table 4.2: Cutting conditions in machining Ti6Al4V alloy in milling

Cutting speed V_c [m/min]	30	40	50	55	60	70	75	80
Feed [mm/tooth]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Table speed V_f [mm/min]	44.76	59.68	74.6	82.06	89.52	104.45	111.91	119.37
Speed [RPM]	298.42	397.89	497.36	547.1	596.83	696.3	746.04	795.77
MRR [mm^3/min]	179.05	238.73	298.42	328.26	358.1	417.78	447.62	477.46
Current average during m/c [A]	3.88	3.89	3.9	3.91	3.91	3.92	3.95	3.95
Current at idle spindle [A]	3.82	3.83	3.84	3.84	3.85	3.85	3.86	3.88
Total power during m/c [W]	2788.95	2796.14	2803.32	2810.51	2810.51	2817.7	2839.26	2839.26
Total power with idle spindle [W]	2745.82	2753.01	2760.2	2760.2	2767.38	2767.38	2774.57	2788.95
Power net for machining [W]	43.13	43.13	43.13	50.32	43.13	50.32	64.69	50.32

The electrical power consumption was measured using a DT-266 digital clamp meter. The clamp meter was clamped on one of the three live wires supplying electricity to the three phase motor of the CNC Takisawa milling machine. The current drawn was also measured for actions such as rapid movement of tool to original location (machine jog). In order to reduce the power consumption, dry cutting was adapted.

4.1.2 Results and discussions

To evaluate the specific energy for the material it was necessary to calculate the specific power for a range of material removal rates. **Figure 4.1** shows the variation of power consumption with material removal rate (MRR) for Ti6Al4V in milling using Takisawa milling machine. The power measured is the actual cutting power (net power for machining). The idle power (i.e. non-cutting operation and spindle power) was not considered for generating this graph. The power for turning on machine module was 2.7 kW (i.e. the current was 3.8 A). The power for turning on the spindle with no cutting operation was dependent on the spindle speed. From **Figure 4.1** the specific power requirement for machining the titanium alloy "*k*" is 3.7 Wsmm^{-3}. This value lies in the range of 2-5 Wsmm^{-3} as reported by Kalpakjian & Schmid [28]. The coefficient of determination (R^2) for Figure 4.1 is 0.55 showed good correlation between the data distributions and the linear line.

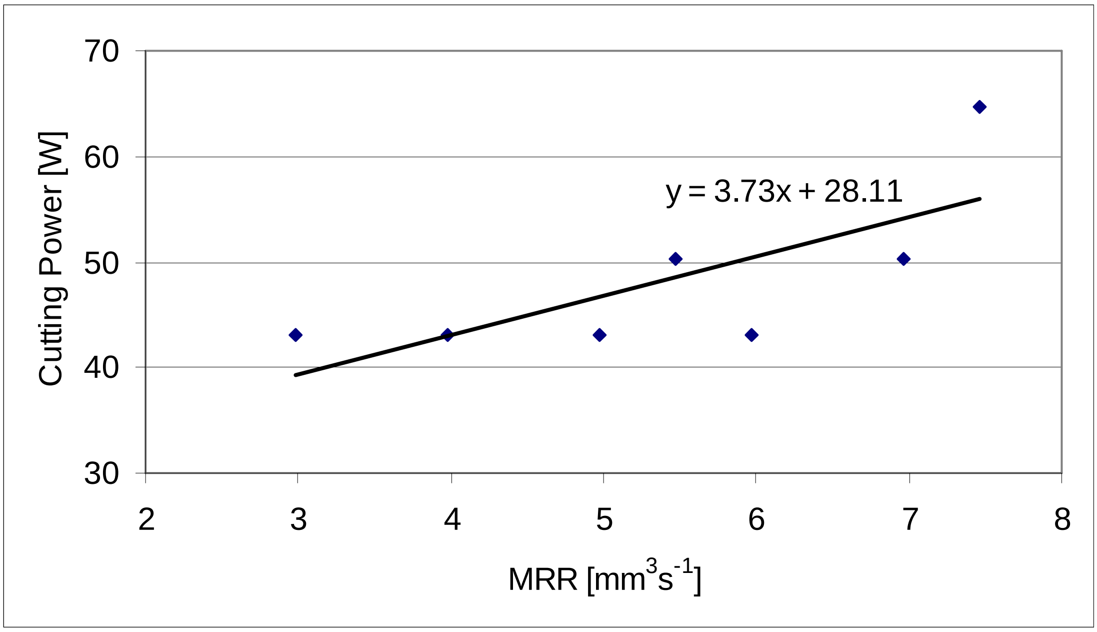


Figure 4.1: Variation of power consumed with material removal rate

The power value was then calculated for different cutting speeds. **Figure 4.2** shows a comparison between the total power consumption and cutting power. The difference between the total power and cutting power as shown in **Figure 4.2** is an indication of the non cutting power (power for operating the machine at zero loads). It also reveals almost 98 % of energy was consumed by the non-cutting operation. This means that net power for this particular milling process was less than 2 %. One of the reasons was due to the spindle which needs less power to rotate the light cutting tool to do the cutting operation compared to rotating a big workpiece in turning. The results also showed a direct proportional increase of the total machining power with the cutting speed.

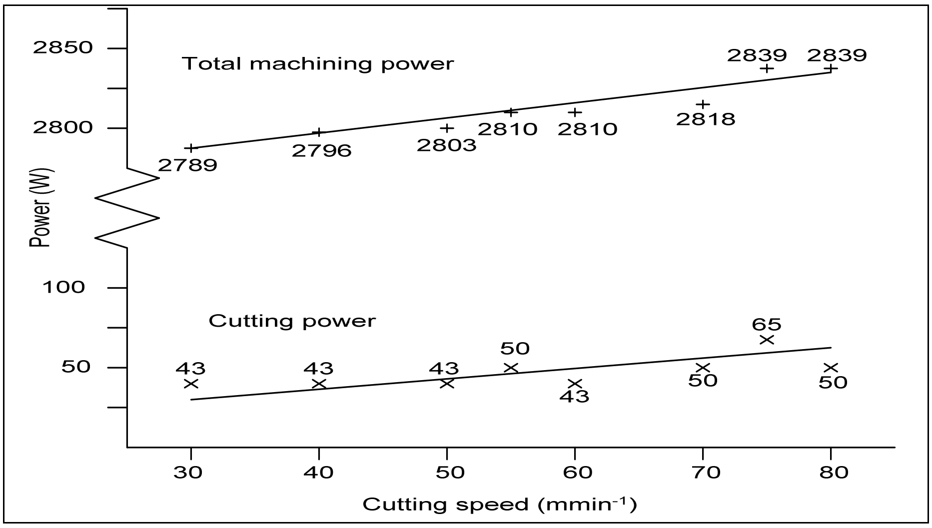


Figure 4.2: Power consumption on a CNC Takisawa milling machine at variable V_c

Further analysis of the cutting process was undertaken at the recommended set of cutting conditions of a cutting speed of 75 m/min, feed of 0.15 mm/tooth and depth of cut of 1 mm [71]. **Figure 4.3** shows the power distribution for this particular cutting condition.

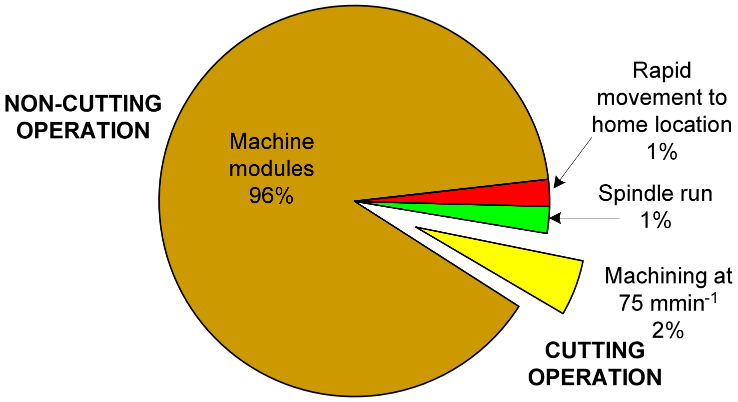


Figure 4.3: The power distribution on a CNC Takisawa milling machine at 746 RPM

The power distribution can be divided into two groups. The first group is the power for non-cutting operations. The non-cutting operation includes the power required to turn on the machine modules (for example, computer and fans, hydraulic pump, etc.). The current for turning on the machine modules was 3.8 A (i.e. *P* = 2.7 kW). Next was rapid movement to home location (axes jog) with a small current of 0.03 A (i.e. *P* = 21.56 W). Lastly was the rotating spindle without cutting (idle condition with spindle on) with current of 0.03 A (i.e. *P* = 21.56 W). For this research, this value consumes most of the power supply for the machining process, i.e. 98%. Only 2 % of the energy is used for the actual cutting process itself. Dahmus and Gutowski [27] found that the share of energy for machining process varied from 0 up to 48.1% depending on the load of machining. Since in this research, the machining process is an end milling process, the amount of energy used is less compared to machining a slot as in Kardonowy [66]. The results also show an interesting fact, that the milling machine consumes a bulk of the energy when it is in an idle condition. Thus turning on such a machine has major impact on the energy footprint for the process. From energy footprint consideration such machines should not be left in an idle position for a considerable amount of time.

The study also compared the energy profile for a milling machine to that of a lathe machine for similar material removal (cutting speed of 75 m/min, feedrate is 0.15 mm/rev and depth of cut 1 mm). The data for the lathe machine was published before [32]. **Figure 4.4** clearly shows that the milling machine uses less energy compared to lathe operations. In the lathe operation, the spindle holds the workpiece; therefore, a bigger workpiece will demand more power to rotate. In milling, the spindle holds typically a relatively small tool; hence it reduces the power required by the motor. Compared to other operations, positioning the tool consumes negligible power.

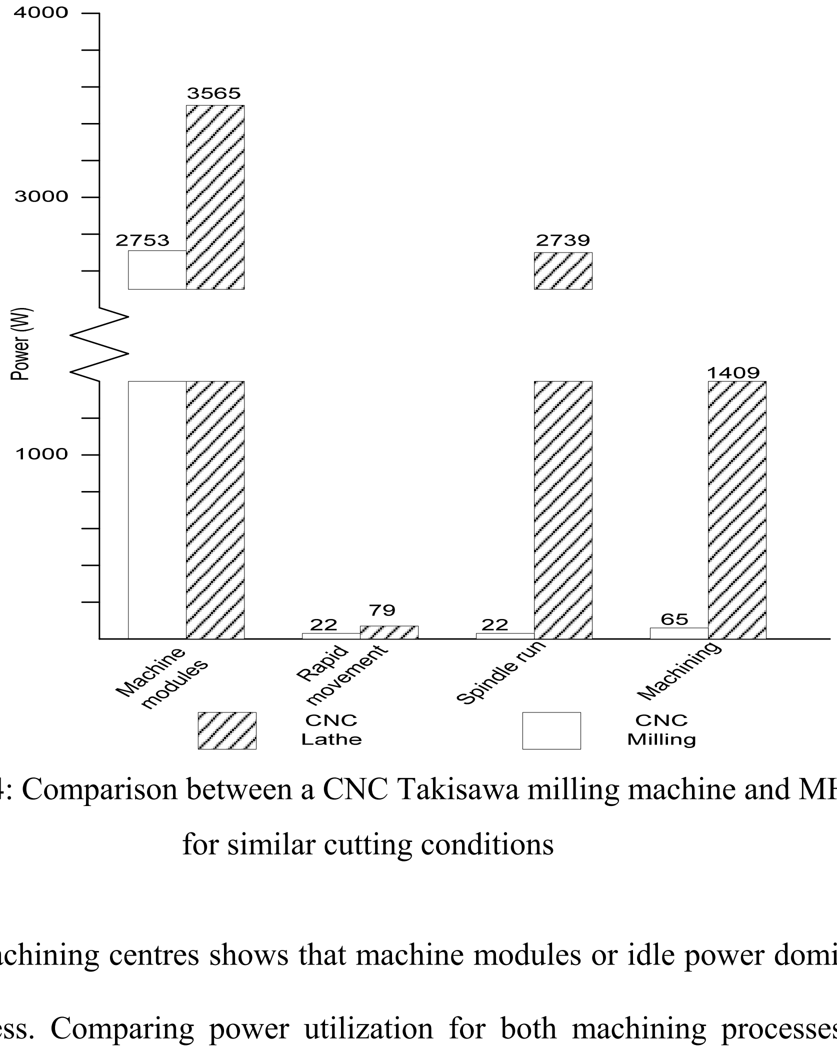


Figure 4.4: Comparison between a CNC Takisawa milling machine and MHP lathe for similar cutting conditions

Data for both machining centres shows that machine modules or idle power dominates the machining process. Comparing power utilization for both machining processes, clearly lathe machining process has better power utilization whereby almost 18% of energy is being used for actual cutting operation, whereas for milling only 2% of total power consumption is used for cutting process.

The energy to remove 10 cm^3 of Ti6Al4V for both machines was estimated as shown in **Table 4.3**. It clearly shows that energy to remove 10 cm^3 of Ti6Al4V for milling is higher than the lathe machining process. The reason for this result lies in the fact that the material removal rate in milling is lower. This factor leads to a higher time taken to remove 10 cm^3 of Ti6Al4V in milling (compared to the lathe) which results in higher energy consumption. The lathe has a higher power demand but better power distribution and less energy to remove 10 cm^3 of Ti6Al4V. The "spindle factor" affects the power distribution and machining energy consumption in machining. Another factor that needs a serious consideration is the material removal rate. As material removal rate increases, the time taken to remove a specific volume of material reduces. Hence, energy consumption for the whole machining process also decreased.

Table 4.3: Cutting parameters for milling and lathe operations

	Takisawa Milling	**MHP Lathe**
Feed	0.15 mm/tooth	0.15 mm/rev
Depth of cut [mm]	1	1
Cutting speed [m/min]	75	75
Spindle speed [RPM]	746	411
Material removal rate [mm^3/min]	447	11056
Time taken to remove 10 cm^3 [min]	22.3	0.9
Energy for actual cutting [MJ]	0.09	0.08
Total energy for machining [MJ]	**3.81**	**0.42**

The study further assessed the effects of higher cutting speeds on energy consumption. The energy required was calculated by considering the time taken to remove 10 cm^3 of workpiece material as well as the power consumption. Additionally, the carbon dioxide associated with the energy was calculated by taking carbon fuel emission factor of 0.43 kgCO_2e/kWh for the energy source [72]. The CO_2 emission was calculated excluding the amount of CO_2 emitted in producing 10 cm^3 raw material of titanium alloy in order to show differences in the machining process. **Figure 4.5** showed the relationship between machining energy and carbon emission with respect to different cutting speeds.

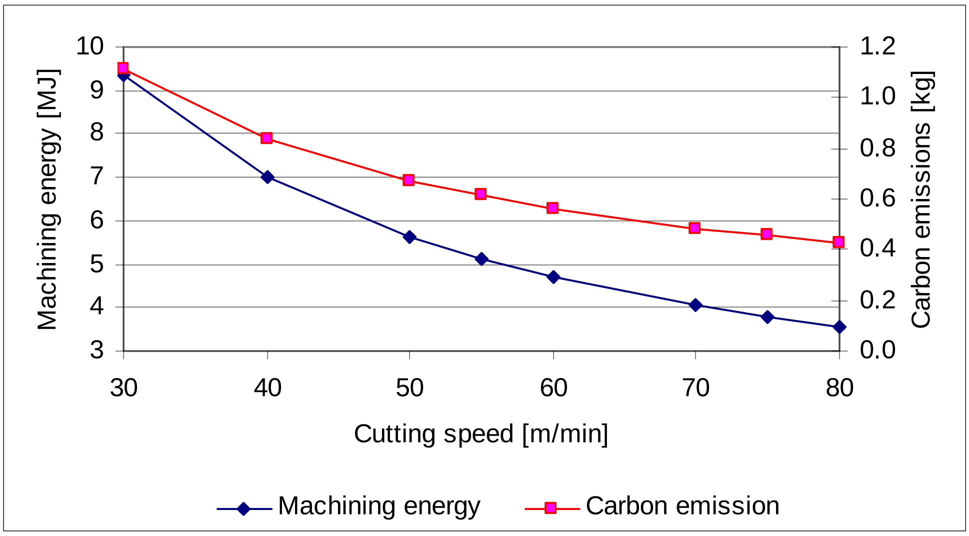


Figure 4.5: Machining energy and carbon emission for a Takisawa milling removing 10 cm^3 of Ti6Al4V alloy

It can be seen in **Figure 4.5** that the machining energy to remove 10 cm^3 of titanium alloy is reduced as the cutting speed increases. Carbon emissions are reduced proportionally as total energy for machining reduces. This information shows that cutting conditions should be evaluated to seek low energy footprint products. The amount of CO_2 emission is significantly reduced from 1.12 kg CO_2 when the cutting speed is 30 mmin^{-1} to 0.43 kg CO_2 when the cutting speed is at the highest tested (i.e. V_c is 80 m/min). This reduction of almost 62 % is a significant improvement in the environmental footprints.

4.2 Manual lathe versus CNC lathe machines

4.2.1 Traditional/manual machining versus CNC machining.

In total five manual lathe machines were tested. Pictures of the machines tested are included in **Appendix 1**. Of the 5 machines tested, two were manufactured by Harrison lathes while the remainders were under the Colchester brand. The machines were turned on with different spindle speeds and no load as shown in **Table 4.4**. The current for different spindle speed was recorded and compared with MHP lathe readings. The power consumed to rotate the spindle at different speeds was recorded using the clamp meter. Comparison was been made on the power consumed between the manual machines with MHP lathe.

Table 4.4: Spindle speed for different types of lathe machines

Machine	Spindle speed [RPM]
1960s Colchester Master 2500	235
	425
	770
1970 Harrison 155 Lathe	290
	410
	640
1971 Harrison VS330TR lathe	260
	470
	625
1980 Colchester Truimph 2000	260
	470
	625
1988 MHP Lathe	400
	600
	800
	1000

4.2.2 Results and discussions

Manual and CNC machines are widely used in machining industries. Manual machines are usually used as spare machines in the shop floor. They are also used to produce low quantities components. These parts may be custom components in the production.

However, referring to lathe machining process, the numerical control machines have a higher power consumption compared with the manual ones [73]. To verify this, an experiment was carried out to measure the power consumed by manual and CNC lathe machines at different spindle speeds. **Figure 4.6** showed the power consumed by 5 manual lathe and MHP lathe machine. The outcome was as expected whereby CNC lathe machine consumed higher electrical power compared to the manual lathe. For example, in the range of spindle speed between 400 RPM to 410 RPM, the power consumed by MHP lathe was 7 times higher than the 1970 Harrison 155 manual lathe. Obviously, as the spindle speed increases, the power consumed also slightly increased for these machines. Hence the CNC lathe always has higher power than their manual ones.

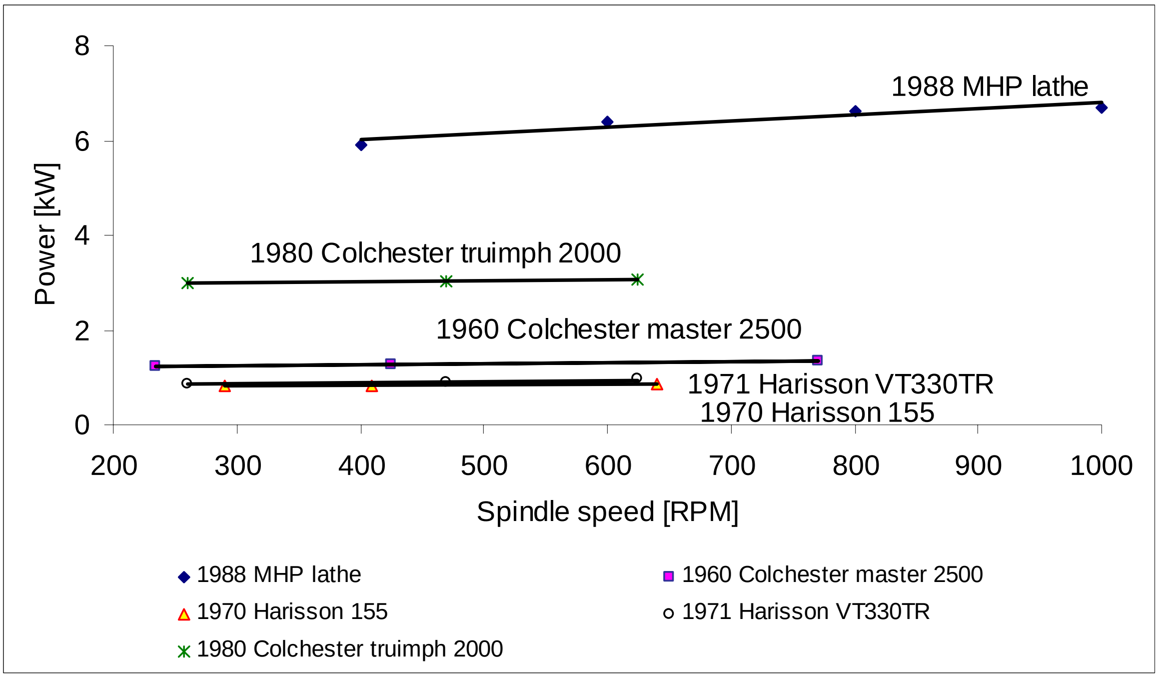


Figure 4.6: Power consumption for manual and CNC lathe machines at different spindle speeds with no load.

A factor that affects the high energy consumed in the CNC lathe machines was due to different types of auxiliary units installed in the machine modules. For example, the axis motor and motor used to hold the machine turret during machining processes. Given the high power consumed by CNC lathe machines, one undeniable question arises; Why the CNC lathe is more popular and widely used by industries compared to the manual lathe? One of the answers was due to the capability of CNC machines to produce higher quantity of components in shorter time compared to manual ones. On the other hand, high use of CNC lathe machines increases power consumption and hence makes the target of supporting sustainable machining difficult to reach. Therefore, to help in solving this problem, this research tries to reduce energy consumption especially in lathe machining process by optimising the cutting parameters in machining process. Nonetheless, it is important to notice that CNC machines do consume higher energy compared to manual lathe machines.

4.3 Conclusions

With increasing use of titanium alloys for their light weight and high strength, it is essential to assess manufacturing routes in order to reduce the energy and carbon footprints of products. Relative to other common engineering materials the carbon footprint for extracting titanium alloys is already very high, thus efforts should be put in cleaner methods of shaping the alloy. The energy consumed in machining can be used as an indirect measure of energy derived carbon footprints for a process. This is because in generating the power that is then used to drive machine tools, carbon dioxide is emitted to the atmosphere. Thus in the interest of energy availability, reducing energy costs and carbon footprints it is essential to run production operations at the lowest energy footprint (consumption) to promote a cleaner and more sustainable manufacturing industry.

- Keeping machines running while not cutting not only contributes to production waste but significantly increases the energy and carbon footprints of machine shops and machined products.

- It follows that production planning, process planning and machine loading are essential targets to be optimised in reducing environmental footprints of a machine shop.
- In designing or selecting a machine tool the functionality and loading of the spindle is a major factor in addressing power consumption.
- Comparing different machining conditions, improving the material removal rate has a very positive influence on reducing the energy/carbon footprints of a product.
- High speed machining lowers the time taken for completing the machining process. Since the energy is dependent on time taken for machining, reduced time taken will result in less energy consumed. Thus high speed machining not only reduces cycle times but can be a key strategy for sustainable machining facilities.

Design of machines with low energy consuming modules has the highest impact in reducing energy and carbon footprint from machining operations. Machines should be designed to utilise less energy and also to have a higher percentage of energy dedicated to actual material removal activity.

CNC machines have more modules and functionality and hence consume more energy compared to manual machines. Thus the case for reducing energy in machining is even more important for CNC operations.

CHAPTER FIVE

EFFECT OF UNCOATED AND RE-USED COATED TOOL ON ENERGY CONSUMPTION AND CARBON FOOTPRINT IN TURNING PROCESS

5.1 Introduction

In engineering, sustainable use of strategic resources can be enhanced by developing tooling with extended life as well as where appropriate re-use of tools. To extend the life of cutting tools, promote the use of higher cutting speeds and in some cases dry machining, physical vapour deposition (PVD) coatings such as titanium nitride (TiN) are widely used in high performance machining. Compared to the use of uncoated carbide tools, TiN coating improves the surface finish, wear resistance and tool life during cutting [74, 75]. TiN also improves the tribological conditions by reducing contact length and hence heat partition into the cutting tool [76]. However, when coatings need to be re-applied, e.g. when faults arise in the coating process (unacceptable material composition / uneven thickness), or when the tool needs to re-used after service, it is often necessary to remove the coatings and subsequently recoat the repaired surfaces.

The removal of these coatings from the substrate while preserving the latter's properties is always a challenging task due to strong adhesion to the substrate and low film thickness. The removal of such coatings are normally performed using wet chemical processes [77].

Although this method is widely used in industry, it has some concerns such as, processing of waste residue, uneven removal, long lead times (in the order of hours) and environmental issues associated with chemical residue disposal. To overcome these difficulties an alternative, dry technique is explored by using laser irradiation. Laser stripping has attracted much attention in science and engineering [78-80] because of its advantages of high speed of processing, selective removal on small areas and dry processing which eliminates the use of hazardous chemicals. The Excimer laser stripping of thin films, oxides, ceramics and paints [81-83] has gained increasing interest because of its ability to ablate materials in a well controlled manner. So far, there is hardly any reported work focussing on the laser removal of coatings from cutting tools to facilitate the re-use. For other applications not concerned with machining, the benefits and criteria for product re-use were articulated by Umeda et al in their CIRP paper [84].

There are other methods in reducing energy consumption in manufacturing processes. Among others is the selection of raw workpiece material, cutting condition and tool selection [27, 54]. Grzesik [54] stated that coated tools generally reduces friction between workpiece and tool hence reduces energy consumption in machining. However, the effect of re-use coated tools on energy consumption is not discussed. In this research effect of uncoated, coated and re-coated tools on energy consumption is presented.

5.2 Effect of uncoated, original coated and recoated tool in machining.

Machining process was done using MHP Lathe machine that uses a three phase motor to rotate its spindle. The workpiece was a bar of EN8 steel, which has an initial diameter of 77.5mm. The length of cut was 150mm. This experiment used four types of carbide tools which are the uncoated, original coated, chemical de-coated and recoated tool and laser decoated and recoated tool. The tool used in this research was CNMA120404 HTi10 WC made my Mitsubishi. The inserts were coated with TiN and part of the batch was decoated and then recoated to evaluate the effect on machining. Conventional way for removing thin layer of titanium nitride which covered the tool, is by using wet chemical process or reactive gases [77, 85, 86]. The disadvantages using this particular method involve the processing of waste residue and environmental concerns.

An alternative method of removing the coating is using laser irradiation. Laser stripping is an interesting technique [80, 87] which can be applied for selective removal on small areas and also eliminates the use of hazardous chemicals. This was achieved by using an excimer laser to strip the thin layer of titanium nitride coating from tool tips. The stripped insert is shown in **Figure 5.1**.

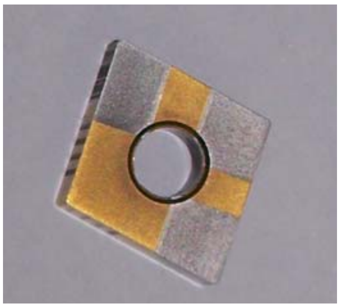


Figure 5.1: Optical photograph of the laser de-coated insert

The inserts used were classified as shown in **Table 5.1.**

Table 5.1: Inaserts tool classification

Uncoated carbide tool	**Original TiN coated tool**	**Chemical de-coated and recoated tool**	**Laser de-coated and recoated tool**
Carbide insert that had never been coated	Carbide insert with TiN coating	Carbide insert with TiN coating and decoated chemically and than recoated with TiN	Carbide insert with TiN coating and decoated using laser and than recoated with TiN

Current measurement was taken in every single pass throughout the machining process. Clamp meter model DT266 was used by clamping on one of three life wire that supply current to three phase motor for the MHP lathe machine. The cutting conditions were unified at cutting speed of 50 to 500 m/min, depth of cut of 0.5 mm and feed of 0.075 mm/rev.

5.3 Evaluation of wear performance

To test the effectiveness of using re-coated tools, cutting tests were performed on an MHP CNC lathe. Traditional wear assessment is often based on average flank wear or tool life. However, this comparison is not standardized or normalized because it may not take into account the true length of cut or the amount of material removed. One such approach of normalizing the effect is based on taking the logarithm of a ratio of the flank wear to the actual length of cut for material removed. This normalises the variability in the spiral length of cut as experienced when the workpiece diameter changes in turning. The assumption here is that the width of the flank wear land will be the same as the width of cut.

From **Figure 5.2** it is clear that compared to the coated tools, the uncoated tool experiences a higher wear rate especially at higher cutting speeds. Compared to the first generation (i.e. not previously re-worked) coated tools, the tools coated after laser and chemical de-coating show a relatively comparable wear rate. Coating generally produces lower friction at the tool-chip interface which leads to lower cutting energy, contact temperature and tool wear [54]. At higher cutting speeds the first generation coated tools give the best wear performance while the laser decoated and re-coated tools are the second best. It is clear from these results that re-coating of tools after laser or chemical de-coating does not significantly compromise the wear performance when compared to first generation coated tooling.

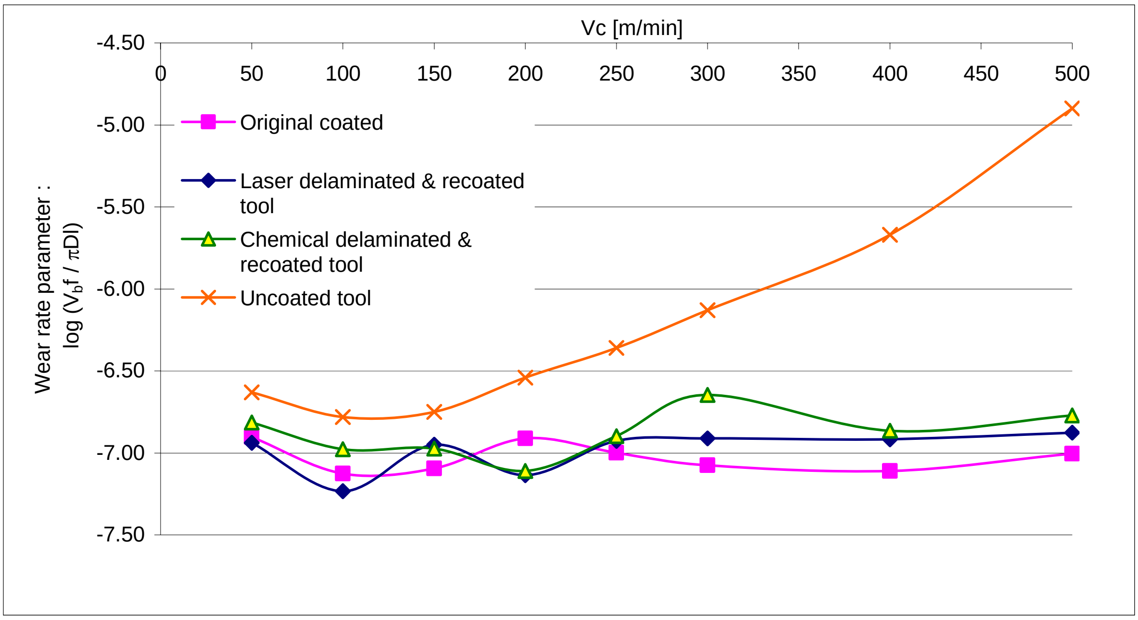


Figure 5.2: Wear rate parameter in turning

5.4 Surface roughness of machined parts

Figure 5.3 shows the average surface roughness of the machined EN8 steel surfaces measured using a Taylor Hobson Surtronic 3+ surface roughness measuring instrument with a cut-off value of 0.8 mm and transverse length of 8 mm. As expected the coated inserts generated superior surface finish on the workpiece compared to uncoated tools throughout the range of cutting speeds investigated. At higher cutting speeds, the laser decoated inserts gave a marginally better performance than the first generation coated tools and chemical decoated/re-coated tools. Compared to first generation coated tools, re-coating tools after laser or chemical de-coating does not significantly compromise the surface finish of the machined parts.

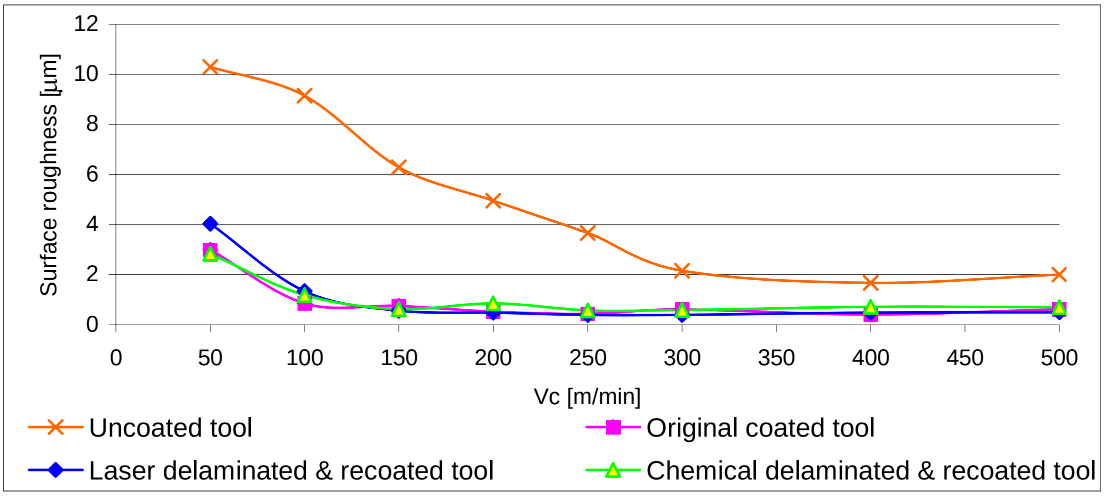


Figure 5.3: Surface roughness of the machined surface

5.5 Power and energy consumed for uncoated and coated tool.

From the cutting test the power against material removal rate for each of the tools was plotted to determine the value of specific cutting energy for EN8 steel. This power only refers to the actual cutting power and not the total power for machining EN8 steel. **Figure 5.4** shows that specific cutting energy of the each tool lies in the range of 3 to 4.4 Wsmm^{-3}. Kalpakjian & Schmid define the specific cutting energy for EN8 to be in the range of 2-9 Wsmm^{-3} [28]. The other fact that can be observed from the graph is that the use of different type of coated tool did not change the specific cutting energy for EN8 steel. In terms of power consumption in specific cutting speed, **Figure 5.4** shows that uncoated tool uses more power compared to coated tool. **Figure 5.4** clearly showed that cutting using the uncoated tool has a higher specific cutting energy compared with different type of coated tools. This is because coated tools have a lower wear-rate compared to the uncoated tool which eventually affects the economics of cutting EN8 steel using this particular tool.

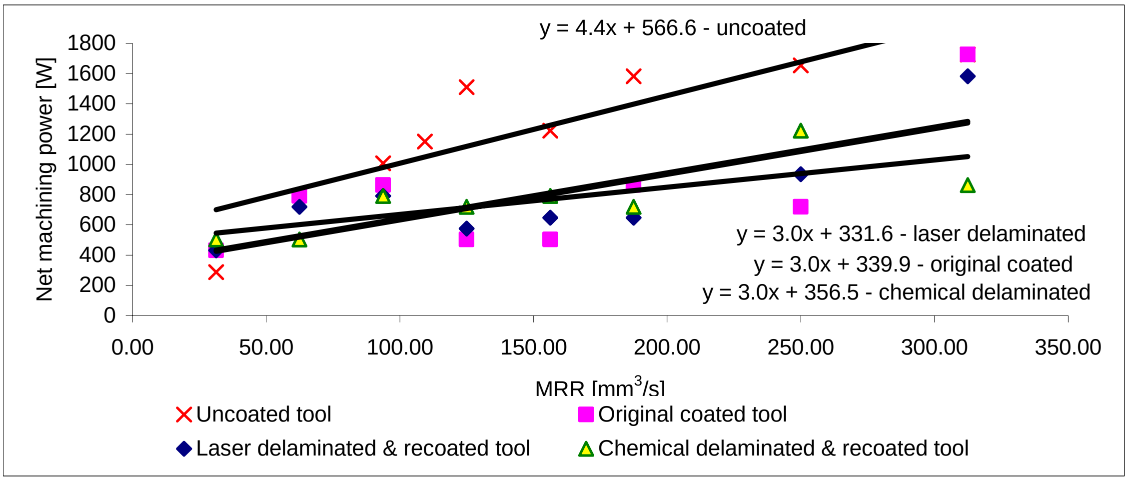


Figure 5.4: Net machining power for different types of cutting tools

To predict the energy consumption for machining process, the energy consumed to remove 1 cm^3 of EN8 steel using different types of tools is shown in **Figure 5.5**. Different cutting speeds at the same depth of cut and feedrate of 0.5 mm and 0.075 mm/rev respectively were used in this calculation. Machining at higher cutting speeds leads to shorter cycle times and reduced energy footprints. The use of TiN coated tools reduce the energy footprint compared to the uncoated tools for most of the higher cutting speeds tested. Moreover, re-coating the tools after either laser or chemically stripping does not significantly compromise the reduction in energy footprints to be gained from the use of coated tools. High tool wear and poor component surface finish were the main disadvantages of using the uncoated tool.

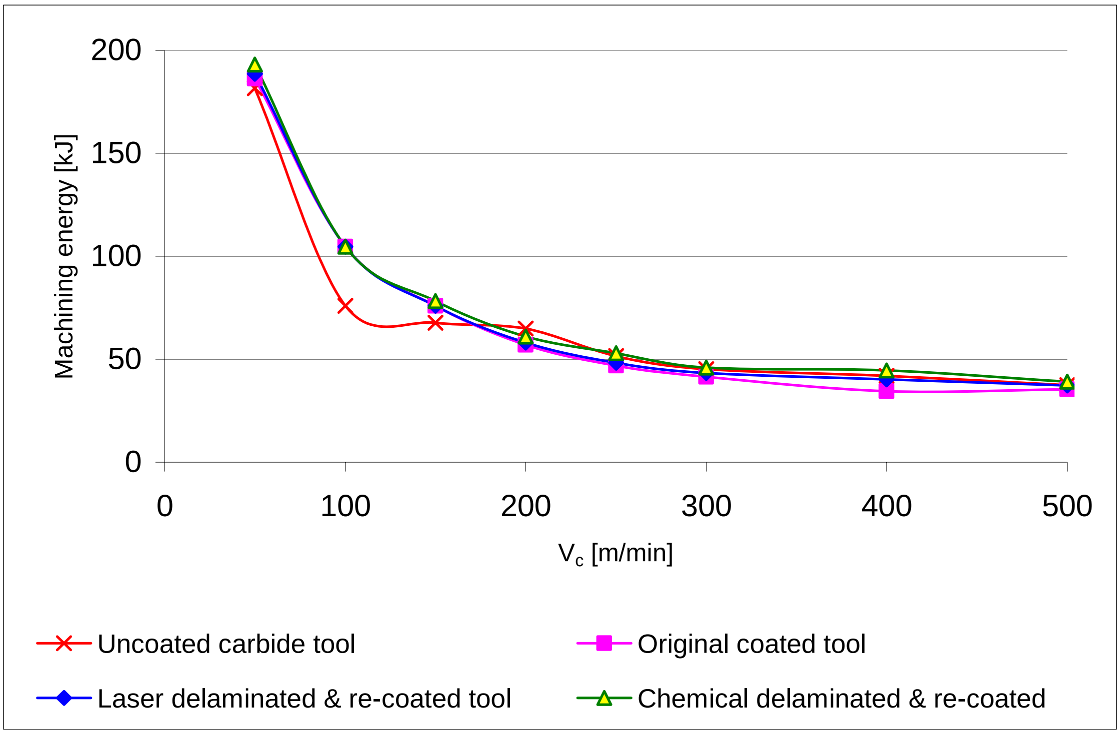


Figure 5.5: Machining energy consumption for removing 1 cm^3 of material

Reducing energy footprints is important for controlling cost as well as in minimising carbon footprints in machining. The energy footprints can be used to evaluate the carbon footprints associated with the energy generation. However, the carbon equivalent for electrical energy delivered to a machine shop depends on the energy source mix (the balance between nuclear, gas, coal, hydro, and wind, etc – i.e. power generation station suppliers). This erodes a basis for a universal quantitative comparison of carbon footprints for a product. However, since carbon footprints are evaluated from energy footprints by an appropriate geographical carbon intensity factor, the conclusions arrived at above with respect of energy footprints will be mirrored in comparing carbon footprints.

Carbon emission for machining process can be calculated by multiplying the energy consumption in machining with the factor of 0.43 $kgCO_2e/kWh$ as defined by DEFRA

[72]. **Figure 5.6** shows that carbon emission reduces as cutting speed increases. The advantage of using coated tools is the reduced carbon emissions attributable to the process.

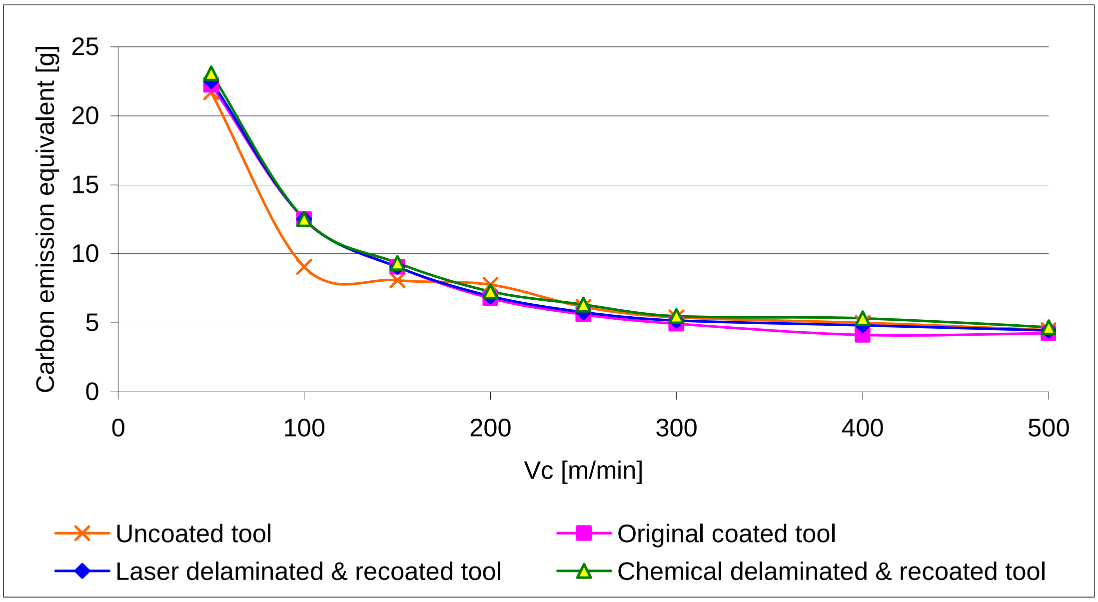


Figure 5.6: Carbon emissions in machining 1 cm^3 of material

5.6 Energy footprints for laser decoating

The power and energy consumed by the laser machine during the decoating process was noted and is displayed in **Figure 5.7**. This figure shows the variation of power consumption and laser output energy with various input voltage at a constant frequency of 50 Hz (corresponds to the operating condition for laser decoating of tools). The power consumption and output laser energy increases with increase in the input voltage. During the decoating process, an input voltage of 28 kV corresponding to output laser energy of 5 mJ was used to obtain a laser fluence of 2 J/cm^2 at the irradiation spot.

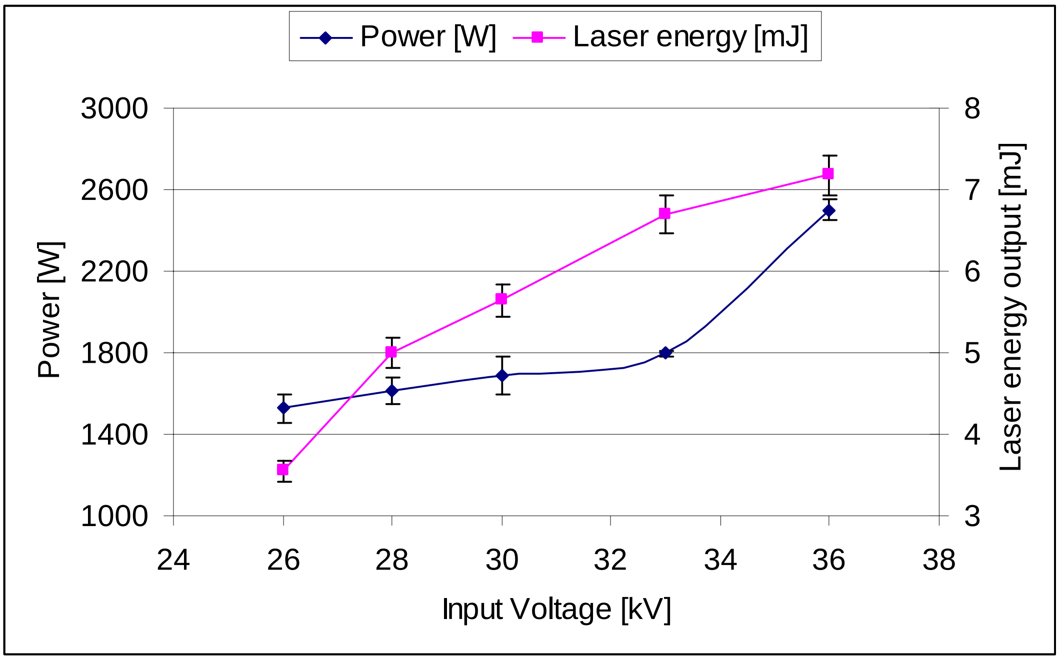


Figure 5.7: Variation of power consumption with laser energy (frequency = 50 Hz)

The time required for decoating 2 µm thick TiN coating was 20 seconds per mm^2. The area removed for each of the cutting edge using laser decoating is 16 mm^2 hence time taken for decoating was 320 seconds. Using 28 kV input voltage, the total energy input was found to be **516.4 kJ**. Comparing the energy required for the material re-use steps, clearly the energy consumed by the laser in the decoating process (**Figure 5.7**) is higher than the energy footprint for the machining process (**Figure 5.5**). These results are in agreement with the findings by Gutowski et al [18] who reported that newer machining processes consumed greater amount of energy compared to traditional processes. Gutowski et al presented energy data for conventional processes, newer micro-electronics and advanced machining processes. These more modern processes can work to finer dimensions and smaller scales, but also work at lower rates, resulting in very large specific electrical energy requirements. In short, the historical trend seems to be towards more energy-intensive manufacturing processes. In case of chemical decoating, it takes approximately 60 minutes for decoating a batch of tools. As chemical decoating process was done for a batch of tools, the decoating rate cannot be compared directly. Additionally, since no big machine tools are used in the chemically stripping process, the energy consumption is not significant in relation to that of the laser process or metal cutting machine tools.

In establishing the process window for laser decoating, minimum energy footprint was not the key objective. The results show that there is a need for further work to improve the efficiency of the laser decoating process. However, these results are in agreement with the work reported by Gutowski [18] who asserted that the newer processes are generally less energy efficient.

Generally, decoating remains more energy efficient compared to recycling the materials by remelting. This works show that cutting tool re-use is possible by laser assisted decoating or chemical decoating and further improvements in the energy usage in processing may be possible through research.

5.7 Energy summary for the different steps

A comparison of the energy footprints was undertaken for the process steps involved in the study. This comparison shown in **Figure 5.8**, was based on the information presented before, the use of a laser in the de-coating process and the energy footprints for cutting tools as presented by Dahmus and Gutowski [27]. The graph shows the embodied energy for the carbide material is the highest footprint followed by the energy for sintering and coating of the inserts. The energy for de-coating is the third largest with the energy used in machining being the smallest footprint. Again, these data shows that manufacturing processes such as machining despite being traditional, and no longer considered as innovative are actually very competitive with regards to energy footprints and environmentally emissions. More importantly the data shows that the laser de-coating process utilises far less energy compared to the sintering process or material extraction from ore. Thus use of laser ablation in cleaning cutting tools for re-coating does not appear to compromise machining performance and is more energy efficient compared to primary processes from tooling manufacture.

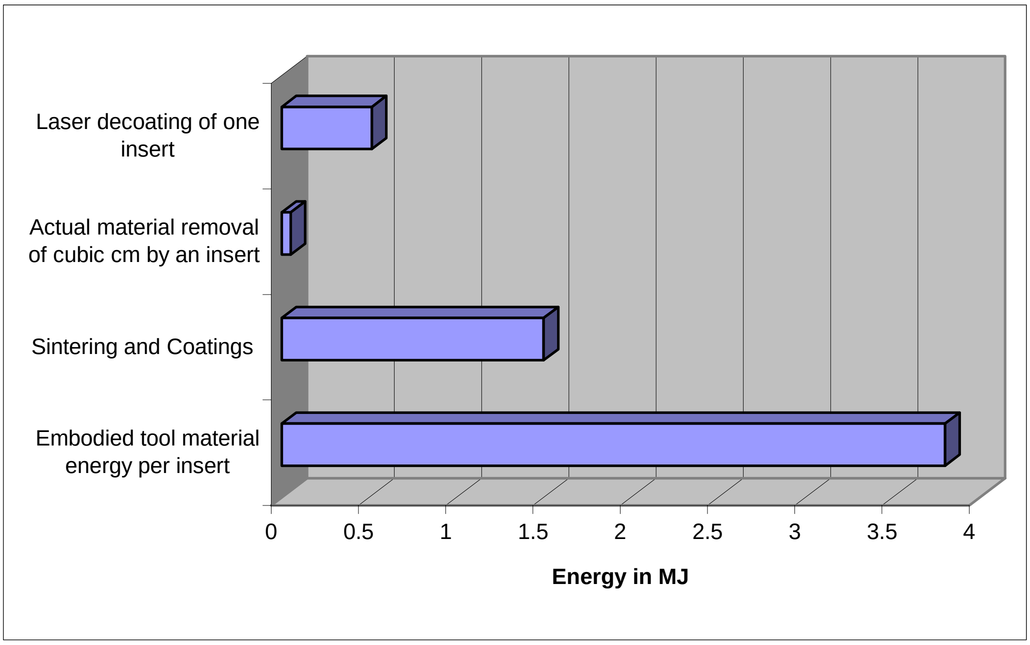


Figure 5.8: Comparison of energy footprints for different process steps

5.8 Conclusions

In this chapter, inserts were coated, decoated and then recoated. The machining evaluation shows that:

- Use of recoated tools does not compromise machining performance.
- First generation and recoated tools have lower energy footprint in machining compared to uncoated tool. This is due to their enhanced machining performance.
- Laser decoated tools marginally perform better than chemical decoated tools when the recoated generation were evaluated.

- The material removal process has lower energy usage compared to decoating carbide tool, sintering and decoating or carbide raw material manufacture.

CHAPTER SIX

DEVELOPMENT OF NEW MINIMUM ENERGY CRITERION FOR TURNING OPERATION

6.1 Introduction

The aim of the work reported in this chapter was to develop a new model and methodology for optimising the energy footprint for a machined product. The total energy of machining a component by the turning process was modelled and optimized to derive an economic tool-life that satisfies the minimum energy footprint requirement.

The work clearly identifies critical parameters in minimising energy use and hence reducing the energy cost and environmental footprint. Additionally, the chapter explores and discusses the conflict and synergy between economical and environmental considerations as well as the effect of system boundaries in determining optimum machining conditions.

6.2 Formulation of new energy footprint calculation formula

Energy generation as driven by consumption demand is a key contributor to carbon dioxide emissions and climate change. Hence reducing energy usage is an essential consideration in sustainable manufacturing. For example, in a recent study, Pusavec et al suggested a number of ways to improve sustainability in manufacturing [4]. Reducing the energy consumed by machining processes was identified as one of the strategies. Reducing the energy footprint leads to a reduction of carbon dioxide emissions. The link between the carbon dioxide emissions and energy footprints is established by a carbon emission signature (CES) as presented by Jeswiet and Kara [23]. In the US, Devoldere et al reviewed the energy consumption by different manufacturing sectors [88]. The data which was derived from the US Energy Information Administration [89] showed that fabrication of metal products consumed 47 billion kWh, which were equivalent to 5 % of the total industrial electricity consumption. In the UK, in the year 2008, the total electricity consumption was 342 billion kWh with 8 billion kWh attributable to mechanical engineering operations [90]. Metal fabrication contributes to the energy used in the mechanical engineering sector. However, distinct classification for national energy use in machining is not found in literature.

In the year 2000, energy related carbon dioxide equivalent (CO_2e) emissions represented about 65 % of the global green house gas emissions [7]. From this percentage, about 24 % and 14 % of CO_2e emissions were attributed to power generation and industrial activity respectively. In the UK, in the year 2007, the Department of Environment, Food and Rural Affairs (DEFRA) reported that energy supply sectors which include power stations, refineries and other energy industries contributed to 39.7 % of total UK carbon dioxide emissions [91].

Energy used in manufacturing has to be reduced in order to cut down carbon emissions derived from energy generation. In literature, the energy consumed for non-cutting operations dominates the total energy consumption in machining [27, 32]. For machining processes, the energy requirement decreases as the material removal rate increases [18, 92]. Liow [57] compared the energy required by a conventional Mazak VTC-41 machine to that of a micro milling facility in machining a micro device. The conventional machine used 800 times more energy than the micro milling facility. The bulk of the energy used by the Mazak machine was for driving the spindle where most of the torque available was not required for the job. This example illustrates the importance of machine selection in reducing the energy footprint of a machined product. However, industries may not have the money to invest in new energy efficient machines. Moreover, large components cannot be made on the low energy footprint micro machining centres. Therefore, improvement of energy efficiency has to be found using existing machines.

Reducing energy consumption contributes to sustainable manufacturing. Alting and Jogensen [11] defined sustainable production as the management of the whole product life cycle starting from designing, production, distribution to the disposal stage. This involves minimising material and energy resources. Another view of sustainable development was put forward by the World Commission on Environmental Development. They defined sustainable development as a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are made consistent with the future as well as present needs [93]. To achieve this notion of global sustainability, each industry must aim to be sustainable [94].

Another aspect of sustainability is the societal issues. Gutowski [95] split carbon emissions into four contributing factors of population, GDP per energy use, energy use per population and the carbon intensity of energy. As the population increases, the consumption of technical products increases and manufacturing output has to be boosted to meet this demand [5]. To manufacturers, increase in demand is a good indication for business growth. On the other hand, increases in demand will trigger higher overall energy consumption. It follows that as the population increases, there is a need to seek higher energy efficiencies in order to reduce the overall demand for energy and the impact of energy generation to the environment.

It is essential to optimise and improve manufacturing productivity while simultaneously mitigating the effect of manufacture on the environment. In the past in manufacturing, metal cutting operations have been mainly optimised based on economical and technological considerations without the environmental dimension. The aim of this research was to investigate how the energy footprint of a manufacturing resource can be minimised. The optimisation methodology was developed by analysing energy use in turning operations.

6.3 Optimisation of machining operations

In literature [28, 58], machining optimisation is reported based on minimum cost criterion and technological considerations. A classical example is to consider selection of optimum cutting conditions to satisfy the minimum cost criterion in single pass turning operations. For example, the total cost, *C*, shown in **equation 6.1**, for single pass turning operations is obtained from adding the non-productive cost, actual cutting cost, tool change cost and the cost of tooling. In this equation, the material cost is neglected since this is independent of cutting speed. The idea is to select cutting conditions for specified workpiece materials and component geometry.

$$C = x\left(t_1 + \frac{\pi D_{avg} l}{f V_c} + t_3 \frac{\pi D_{avg} l}{A_t} V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}\right) + \frac{y_c \pi D_{avg} l}{A_t} V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)} \qquad (6.1)$$

where x is the machine cost rate [£/min], t_1, t_2 and t_3 are setup time, actual cutting time and tool change time respectively [s], D_{avg} is the average workpiece diameter, l is the length of cut [mm], f is federate [mm/rev], V_c is cutting speed [m/min], $\frac{1}{\alpha}$ is the cutting velocity exponent, $\frac{1}{\beta}$ is the feed exponent in the extended Taylor's tool-life equation, y_c is the tooling cost per cutting edge and A_t is a constant.

In this analysis, the cost of workpiece material remains constant when comparing the effect of cutting conditions for single pass turning operations. A more comprehensive model focused on the cost of machining was presented by Jonsson et al [96]. Their model includes, for example, scrap rate and average down time per part. Jonsson et al acknowledged that the difficulty in using their model was the unavailability of accurate input data. For the case considered here, obtaining accurate scrap rate data can be difficult. The scrap rate is influenced by the industrial practice and process plan. However, for the purposes of selecting optimum variables, it can be assumed that these additional factors can be considered constant. There are other examples in literature that highlight that the machining process can be modelled as the deterministic process or a complex closed loop machining system [97]. This research uses the deterministic approach. The optimisation philosophy is to obtain an optimum tool-life that satisfies the minimum cost criterion. This is done by differentiating with respect to cutting velocity, the equation for total machining cost. By differentiating the total cost with respect to cutting velocity, the optimum tool-life T_{opt-C} for minimum cost in single pass turning operations can be obtained as shown on **equation 6.2**.

$$T_{opt-C} = \left(\frac{1}{\alpha} - 1\right)\left(\frac{xt_3 + y_C}{x}\right) \tag{6.2}$$

It is clear from **equation 6.2** that if expensive tooling (i.e. the tool cost per cutting edge, y_C is high) or a machine with a high cost rate (x) is used, the calculated optimum tool-life increases. This implies that a more conservative cutting velocity has to be adopted, and this can compromise an effort to reduce cycle time.

6.4 New minimum energy criterion

In this research, for evaluating the minimum energy criterion, a dry turning process was considered. This is the preferred choice where feasible, because the use of oil based cooling/lubricant fluids is one of the most unsustainable elements of the machining process [4]. Additionally, the steel workpiece considered is a good candidate for dry machining. The total energy E used in turning operations can be evaluated from the energy consumed by the machine during setup operation E_1, during cutting operations E_2, during tool change E_3, to produce a cutting tool and normalised per cutting edge E_4 and produce workpiece material E_5. In practice, the workpiece material is fixed depending on the product. Similar to previous treatment [22], the energy of the workpiece material was not considered as it is independent of the machining strategy and does not affect the optimization of production parameters. Moreover, manufacturers have limited opportunities of reducing energy embodied in the workpiece material.

The energy in single pass turning operation can be calculated as shown in **equation 6.3**.

$$E = E_1 + E_2 + E_3 + E_4 \tag{6.3}$$

The energy E_1 is the energy consumed by a machine during setup, and is evaluated from the power consumed by the machine and total time taken for tool and workpiece setup. It is assumed that setup is done when the spindle speed has not yet been turned on. The energy E_2 during machining is evaluated from the energy consumed for powering the machine modules and the energy for material removal as modelled by Gutowski in **equation 6.4** [18].

$$E_2 = \left(P_0 + k\dot{v}\right) t_2 \tag{6.4}$$

where P_o is the power consumed by machine modules [W], k is the specific energy requirement in cutting operations [Ws/mm^3], $\dot{v}$ is material removal rate [mm^3/s] and t_2 is time [s] taken for cutting. The energy consumed during tool change E_3 is evaluated from a product of machine power and time for tool change. In turning, the tool is usually replaced while the spindle is turned off. This assumption makes the power during tool change equal to the power when the machine is in an idle condition. The parameter E_4 is defined as the energy footprint of the cutting tool divided by the number of cutting edges. This is evaluated from the energy embodied in the cutting tool material, the energy used during tool manufacture and the energy of any supplementary processes such as coating. The quantity E_4 is evaluated from the product of the energy per cutting edge y_E multiplied by the number of the cutting edges required to complete the machining pass. From the above discussion, a new equation for energy consumed in single pass turning operations is shown in **equation 6.5.**

$$E = P_0 t_1 + \left(P_0 + k\dot{v}\right) t_2 + P_0 t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right) \tag{6.5}$$

where t_1 is machine setup time [s], t_3 is tool change time [s] and T is the tool-life [s]. **Equation 6.5** can further be expanded by incorporating the models for cutting time and tool-life. For single pass turning operations, the effect of depth of cut can be neglected and a modified form of Taylor's extended tool-life equation [23] is used as shown in **equation 6.6**.

$$T = \frac{A}{V_c^{\frac{1}{\alpha}} f^{\frac{1}{\beta}}} \tag{6.6}$$

where A is a constant and $\frac{1}{\beta}$ is the feed exponent in the tool-life equation, with the other parameters retaining their usual meanings as defined before.

The cutting time for a single pass is modelled by **equation 6.7**.

$$t = \frac{\pi D_{avg} l}{f V_c} \tag{6.7}$$

where D_{avg} is the average diameter for workpiece [mm], calculated from D_i and D_f which are the initial diameter and final diameter for workpiece [mm] respectively, l is the length of cut [mm], f is the feedrate [mm/rev] and V_c is the cutting speed [m/min].

Substituting **equations 6.5, 6.6 and 6.7 into equation 6.4** leads to **equation 6.8** for the energy footprint of machining. It should be noted that the parameters and magnitude of the power used depend on the type of machine and the load on the spindle during the respective operations.

$$E = P_0 t_1 + P_0 \cdot \frac{\pi D_{avg} l}{f V_c} + k \cdot \frac{\pi}{4}\left(D_i^2 - D_f^2\right)\frac{f V_c}{\pi D_{avg}} \cdot \frac{\pi D_{avg} l}{f V_c} + P_0 t_3 \left(\frac{\dfrac{\pi D_{avg} l}{f V_c}}{\dfrac{A}{V_c^{1/\alpha} f^{1/\beta}}} \right) + y_E \left(\frac{\dfrac{\pi D_{avg} l}{f V_c}}{\dfrac{A}{V_c^{1/\alpha} f^{1/\beta}}} \right) \quad (6.8)$$

Equation 6.8 **simplifies to equation 6.9**.

$$E = P_0 t_1 + \frac{P_0 \pi D_{avg} l}{f V_c} + \frac{k \pi l \left(D_i^2 - D_f^2\right)}{4} + \frac{P_0 t_3 \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} + \frac{y_E \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} \quad (6.9)$$

The philosophy for optimisation is to obtain an optimum tool-life that satisfies the minimum energy criterion. This tool-life can then be used in the tool-life equation to obtain an optimum cutting velocity for minimum energy. The optimum tool-life for minimum energy is obtained by differentiating *E* with respect to cutting velocity and equating it to zero, $\frac{\partial E}{\partial V_c} = 0$. This yields **equation 6.10**.

$$\frac{\partial E}{\partial V_c} = -\frac{P_0 \pi D_{avg} l}{f V_c^2} + \left(\frac{1}{\alpha} - 1\right)\frac{P_0 t_3 \pi D_{avg} l \, f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A} + \left(\frac{1}{\alpha} - 1\right)\frac{y_E \pi D_{avg} l \, f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A}$$

(6.10)

Equation 6.10 can be further simplified to **equation 6.11**

$$\frac{A}{f^{\left(\frac{1}{\beta}\right)} V_c^{\left(\frac{1}{\alpha}\right)}} = \left(\frac{1}{\alpha} - 1\right) \cdot \left(\frac{P_0 t_3 + y_E}{P_0}\right) \tag{6.11}$$

By substituting Taylor's equation (**equation 6.6**) into **equation 6.11**, the equation of optimum tool-life for minimum energy can be obtained as shown in **equation 6.12**.

$$T_{opt-E} = \left(\frac{1}{\alpha} - 1\right) \cdot \left(\frac{P_0 t_3 + y_E}{P_0}\right) \tag{6.12}$$

The cutting velocity exponent ($\frac{1}{\alpha}$), is derived from tool wear test. P_0 is measured from machine energy consumption and y_E is calculated from the energy footprint of cutting tools. From **equation 6.12** the tool-life velocity exponent (the rate at which tool-life reduces with cutting speed increase), the power used by a machine during non cutting operations, total time for tool change and energy footprint for cutting tools are the key factors influencing the selection of optimum tool-life for achieving minimum energy consumption.

Figure 6.1 summarised how the energy use in machining varies with cutting speeds. The optimum V_c is determined by the minimum total energy consumed in machining processes.

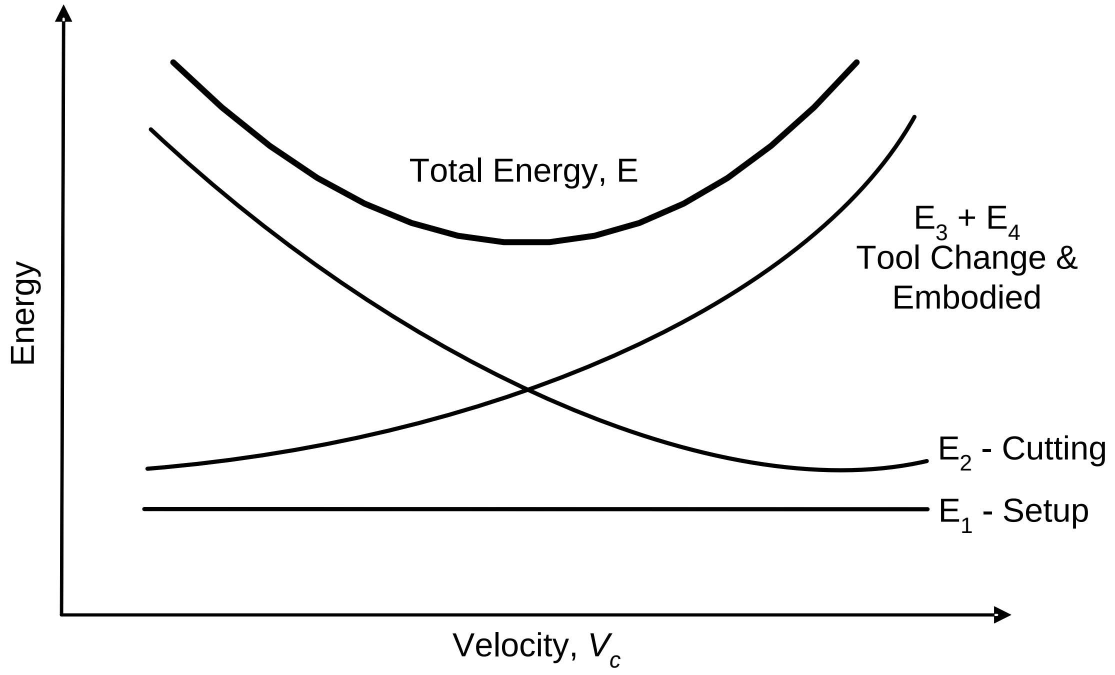


Figure 6.1: Total energy versus cutting speed

6.5 Estimated energy footprint for tooling

The energy for manufacture of the cutting tool does not represent direct energy consumption in the machining process. However, it influences the total energy for the system (inputs to the machining process) which needs to be optimized. Energy for tool manufacture mainly consists of energy embodied in tool material, sintering (and grinding for some tools) and coating process energy. There is hardly any work reported in literature except that by Dahmus and Gutowski [27] that presents reference data for energy footprint of tooling. In this research, the energy footprint from Dahmus and Gutowski was used as a basis to estimate the energy footprint for tooling. Two cases were considered, Case 1 whereby the energy embodied in the tooling material is included and Case 2 in which only the energy for tooling manufacture was considered. These cases are shown in **Table 6.1**. In this study, the inserts used, were as expected assumed to be manufactured from a sintering process. Each insert was coated. The total weight of the insert was measured to be an average of 9.5 g.

Table 6.1: Energy to produce an insert tool

	Case 1 (material and manufacturing) Dahmus and Gutowski [27]	**Case 2 (manufacturing only)**
Embodied tool material energy (MJ/kg)	400	-
Sintering and Coatings (MJ per process per cutting insert)	1 to 2 (avg 1.5)	1 to 2 (avg 1.5)
Total energy per insert (MJ)	5.3	1.5

6.6 Tool life optimisation for turning process

To study the effect of cutting conditions on the optimum tool-life and hence optimum cutting velocity, turning operations were undertaken. The experiments were based on 900 mm length EN8 steel (AISI 1040) cylindrical billet, which was cut into three workpieces for machining. The composition of the workpiece material is shown in **Table 6.2**. The hardness was measured using Vickers instrument and calculated to be an average of 156 HV. The bars had a diameter of 130 mm and length of 300 mm. The workpieces were machined on an MHP CNC lathe machine. Cutting tools used in the experiment were Sandvik CNMG120408-WF grade 1015 inserts, and the tool holder was PCLNL2020K12. The cutting tests were undertaken in dry machining for reasons discussed before.

Table 6.2: The composition of EN8 (AISI 1040) workpiece material

Iron Fe	**Manganese Mn**	**Carbon C**	**Molybdenum Mo**	**Silicon Si**	**Sulfur S**	**Phosphorous P**
98.5 %	0.8 %	0.4 %	0.1 %	0.1 %	0.05 %	0.05 %

It is well established that in conventional machining, in comparison to the depth of cut and feedrate, cutting speed is a dominant parameter on tool wear. Hence, in studying wear progression, the cutting speed was varied (300, 400 and 500 m/min) while the feedrate and depth of cut were kept constant at 0.15 mm/rev and 1 mm respectively. These cutting conditions were within the operating window recommended by Sandvik Coromant, the tool supplier.

The electrical power consumption was measured using a DT-266 digital clamp meter which was clamped onto electricity supply wires to the MHP lathe machine. The procedure to evaluate the power consumed involved first taking measurements of the current after switching the machine on. The powered machine module includes the operation of computer, fans and three phase motor for the MHP lathe machine. It should be noted that at this moment the spindle had not yet been turned on. The tools were loaded before the spindle was turned on. Subsequently, the current was then measured while the spindle was running and without a cutting operation. To assess axis jog, current during positioning of the cutting tool to the initial point of engagement was measured.

Finally, during machining, the total current drawn by the machine tool was recorded. Inserts were examined periodically in between cutting passes according to the experimental plan and finally at the end of cutting. This was done using Polyvar optical microscope to measure flank wear.

6.7 Flank wear

Flank wear plays a significant role in determining tool-life for a range of industrial cutting conditions. According to the ISO3685 standard for tool-life testing with single-point turning tools, an average flank wear tool-life criterion of 0.3 mm is recommended [98]. **Figure 6.2** shows an example of flank wear on an insert used for a cutting speed of 300 m/min and after machining for 16 minutes. **Figure 6.3** shows the quantitative assessment of maximum flank wear for the three cutting speeds. The graph shows that flank wear increases with cutting speed. This is an expected outcome as reported by other researchers [99, 100]. The tool-life criterion based on an average flank wear land of 0.3 mm was reached at 33, 21 and 9.5 minutes for cutting speeds of 300, 400 and 500 m/min respectively.

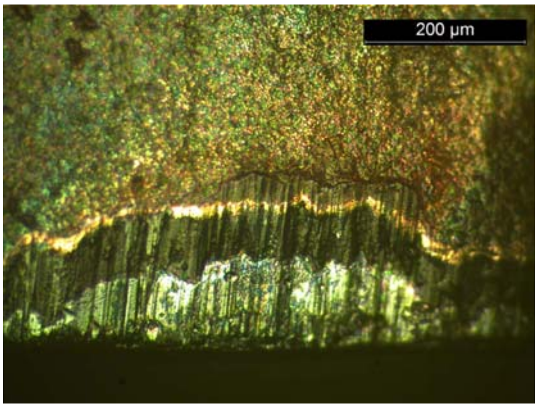


Figure 6.2: Flank wear observed from Polyvar microscope

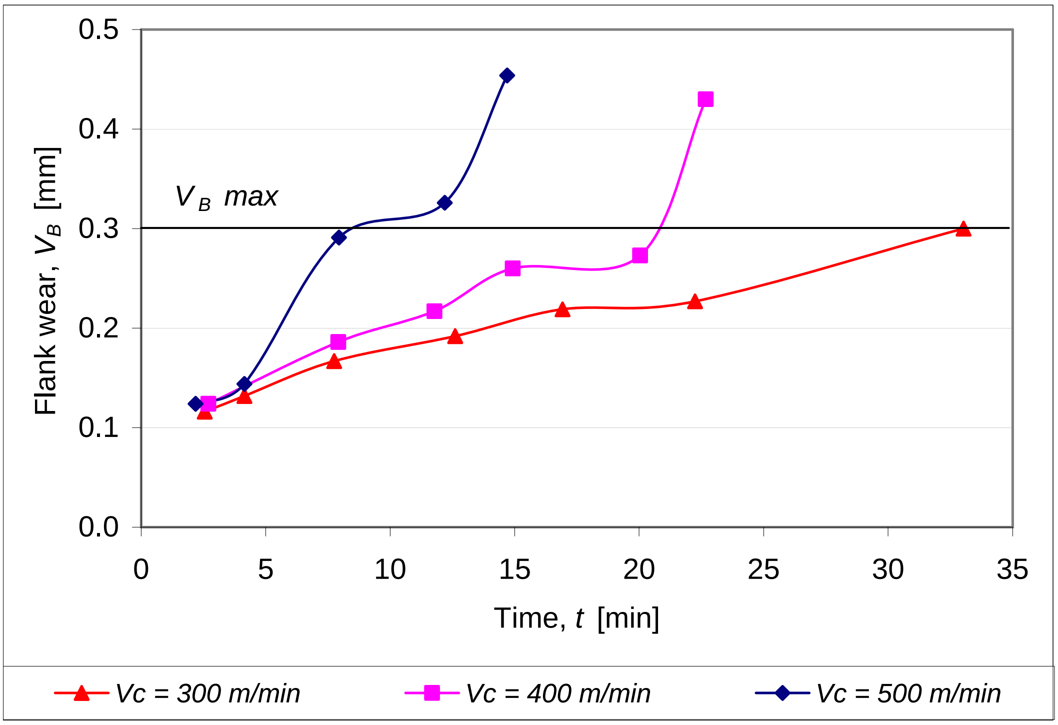


Figure 6.3: Flank wear for different cutting speeds

6.8 Tool-life equation

The cutting velocity exponent $\left(\frac{1}{\alpha}\right)$ for the tool-life equation can be evaluated by a linear relationship between log scale of tool-life (log *T*) and cutting speed (log V_c) [101] as shown in **Figure 6.4**. This linear relationship is shown in **equation 6.13**. Hence the magnitude of cutting velocity exponent for these inserts in machining EN8 steel is 2.4. This value will be used to determine the optimum tool-life for minimum energy.

$$\log T = -2.4 \log V_c + 7.5 \qquad (6.13)$$

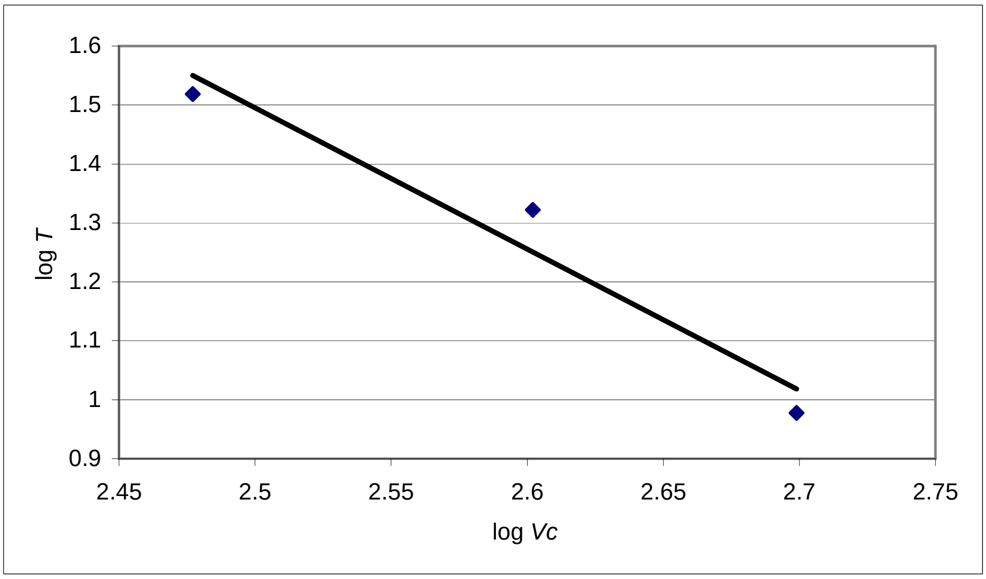


Figure 6.4: Tool-life for different cutting speeds

6.9 Power distribution for each cutting speed

Power distributions for each of the cutting speeds are shown in **Figure 6.5**. The power designated as for machine modules are that recorded when the machine was turned on but the spindle is turned off. The idle power is the power of the machine modules plus the power required to run the spindle. The power for machining is the power attributable to material removal (excluding that consumed by the machine). The machining power depends on material removal rate and the workpiece material. It is clear from this pie chart that non-cutting operations dominate power use in the machining process. The percentage of power consumed by the actual machining process was 31%, 35% and 39% for cutting speed of 300, 400 and 500 m/min respectively. These results are in the range reported in literature by Kordonowy [66] and Dahmus and Gutowski [27] who indicated that power distribution for machining lies in the range of 0% up to 48.1% depending on machine loads. The data presented in this study suggest that machine modules are major power and energy consumers in the cutting process. Thus selection and design of low energy footprint machines of high power efficiency would be a significant advantage in reducing of environmental footprints in machining.

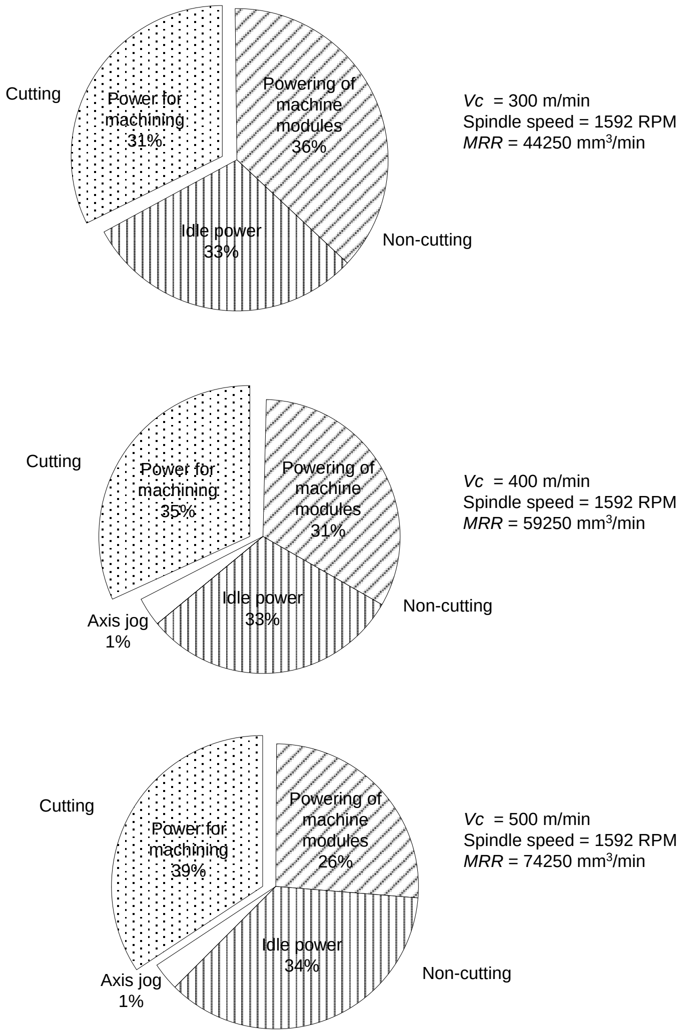


Figure 6.5: Power distribution for different cutting speeds

6.10 Selection of optimum cutting speed based on the minimum energy criterion

The optimum tool-life for minimum energy can be evaluated from previously developed **equation 6.12**. To determine the optimum tool-life for minimum energy, the parameters required are the power for running machine modules (P_0), tool change time (t_3) and the energy per tool cutting edge (y_E) as well as the cutting velocity exponents$\left(\frac{1}{\alpha}\right)$.

For the cutting test conducted on the MHP Lathe, the insert change time was 2 minutes, P_0 was 3.594 kW and the cutting velocity exponent (2.4) was calculated before from the tool-life studies. **Figure 6.6** shows the optimum tool-life for minimum energy for two cases considered (Case 1 includes tool material embodied energy and this is excluded in Case 2). The optimum tool-life for minimum energy was evaluated to be 11.4 minutes considering the energy for tooling material and tool manufacturing process. When the system boundaries are shifted and the energy embodied in the cutting tool material is not considered the optimum tool-life becomes 5.2 minutes. For comparative purposes the optimum tool-life according to the minimum cost criterion is equal to 10 minutes. Using these optimum values, the corresponding optimum cutting velocity was evaluated from the tool-life equation and the results are shown in **Figure 6.7**. In this figure, the optimum velocity that satisfies the minimum cost criterion was 511 m/min. For the minimum energy criterion, optimum cutting velocities of 484 and 671 m/min were evaluated when including and excluding respectively the energy embodied in the tool material. Considering only the energy for manufacturing inserts (Case 2) as shown in **Table 6.1**, leads to an optimum cutting velocity that is higher that the recommended range from the tool supplier (i.e. 335 m/min to 555 m/min). It implies that the synergy in the attainment of the minimum energy criterion and maximum production rates is influenced by how the energy footprint for the cutting tool is accounted for.

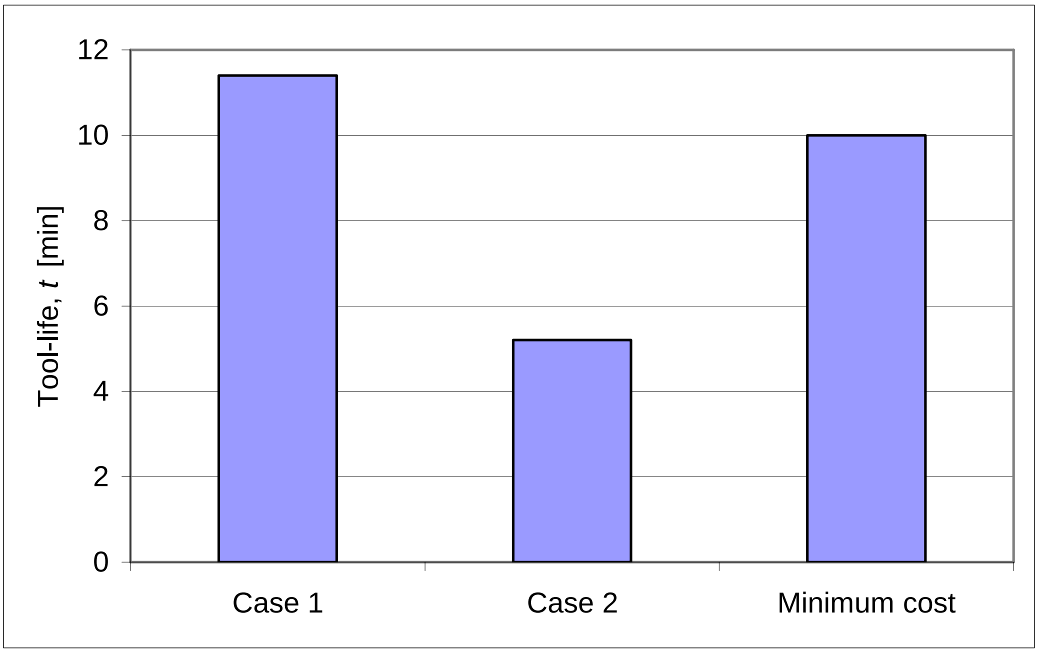


Figure 6.6: Optimum tool-life with different criteria

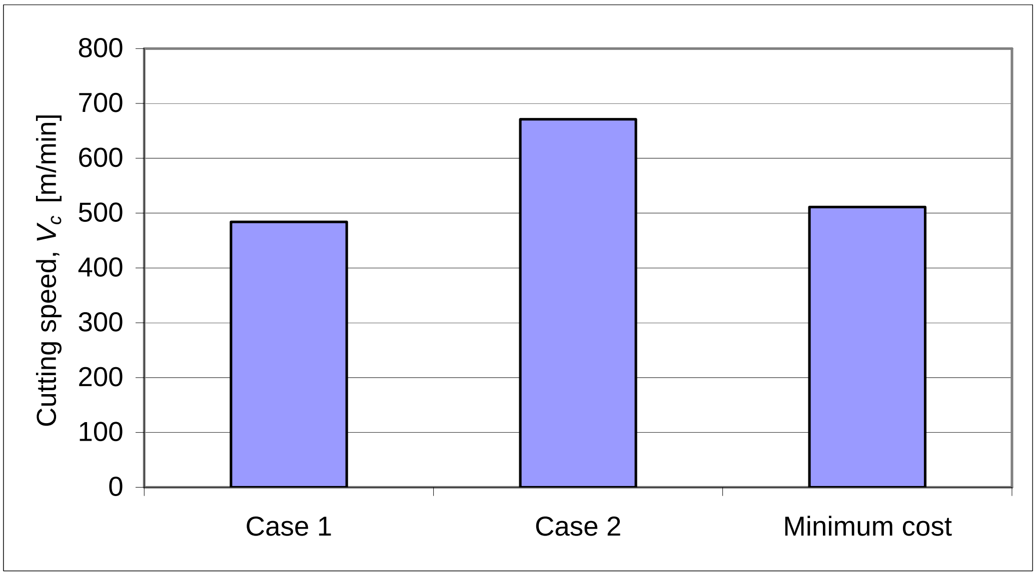


Figure 6.7: Cutting velocity with different criteria

The point made in this research is that the size of the system under consideration determines the perceived optimum solution. Of course the best situation is to fully consider all the significant relevant inputs to the cutting process. With regards to the environment, it is the global optimum which is important and hence a more inclusive system is better.

6.11 Conclusions

Optimization of machining operations has been undertaken for a considerable number of years based on technological and economic considerations. The current and urgent need to reduce energy and carbon footprints in manufacture requires a knowledge base for selection of minimum environmental footprint processing conditions. In this research, optimum tool-life for minimum energy of a turning process was evaluated by considering the energy budget in manufacture of a product. The critical parameters for the optimum tool-life for minimum energy are the power required to start the machine tool and put it in an idle condition, the energy footprint for tool manufacture, tool change time and cutting velocity exponents in the tool-life equation. The optimum condition for minimum costs does not necessarily satisfy the minimum energy criterion.

The cutting velocity for minimum energy and consequently, machining cycle time is strongly influenced by the way in which the energy of the cutting tool is accounted for. This study shows that it is essential to have some consensus on the system boundaries that are essential for optimizing energy footprint in order not to result in conflicting outcomes. In general, the more inclusive/comprehensive the energy requirements for tooling are accounted for, the more likely the machining process has to be performed at relatively lower cutting speed to extract more value out of high energy tooling. Additionally, in seeking cutting conditions that satisfy both minimum energy and minimum cost criterion, the energy footprint of cutting tools needs to be fully accounted for. This could be attributed to the fact that both objectives are underpinned by the need for resource efficiency. For the case considered in this thesis, the optimum cutting speed for minimum energy fell within the recommended range for cutting conditions. This implies that manufacturers can use tools that are currently on the market and select cutting conditions to satisfy the minimum energy criterion.

This study shows that the traditional minimum cost criterion does not necessarily satisfy the requirement for minimum energy. In reflecting on the results of the optimization, clearly if a tool with a higher energy footprint is used then the optimum cutting speed is reduced. In the case presented, if multiple processing steps for tooling are considered this leads to a higher energy footprint of the tool and a lower optimum cutting velocity. Thus, optimizing energy footprint in machining is a trade-off between the use of rapid machining to reduce cycle times and the need to apportion the energy footprint of inputs (i.e. tooling) to longer machining activity (using the cutting tool at conservative speeds).

On reflection, this study shows that in evaluating energy footprint in manufacturing, the issue of system boundaries needs further debate and clarification. Specifically, the issue that arises is to what degree the user should consider the environmental rucksack of the tools used. For instance, should manufacturers only optimize the energy of transformation processes without considering raw material inputs or not. The case study for machining presented here shows that shifting the system boundaries alter the optimum parameters for the process window.

CHAPTER SEVEN

A METHODOLOGY FOR SELECTION OF OPTIMUM CUTTING PARAMETERS BASED ON MINIMUM ENERGY FOOTPRINT AND COST CONSIDERATION

7.1 Introduction

In Chapter Six, a model for the evaluation of optimum tool life that satisfies the minimum energy requirement was developed. The purpose of this Chapter was to utilise the model in a case study on selection of cutting conditions and to develop the methodology for optimum cutting parameters selection process. This methodology can then be the back bone for software development to enable end users to select cutting conditions that can deliver minimum energy footprint for machined products.

7.2 Optimisation philosophy: Direct search method

In this optimisation the objective function is to reduce the energy footprint of a machine product. An objective function (as derived in Chapter Six) for optimisation is used to calculate the desired tool life for a given tool and cutting operation so that by using an appropriate tool life equation (optimum tool life), the corresponding optimum cutting conditions can be selected. The optimisation is then done within a process window to select a feasible combination of depth of cut (a_p), feed (f), and velocity (V_c) which satisfies the minimum energy criterion and process constraints.

In single pass turning a_p, f and V_c are independent variables, and hence in an unconstrained situation there is no unique combination of these variables which satisfies the economic objective function. **Figure 7.1** shows the optimisation procedure to determine the cutting parameters based on minimum energy criterion.

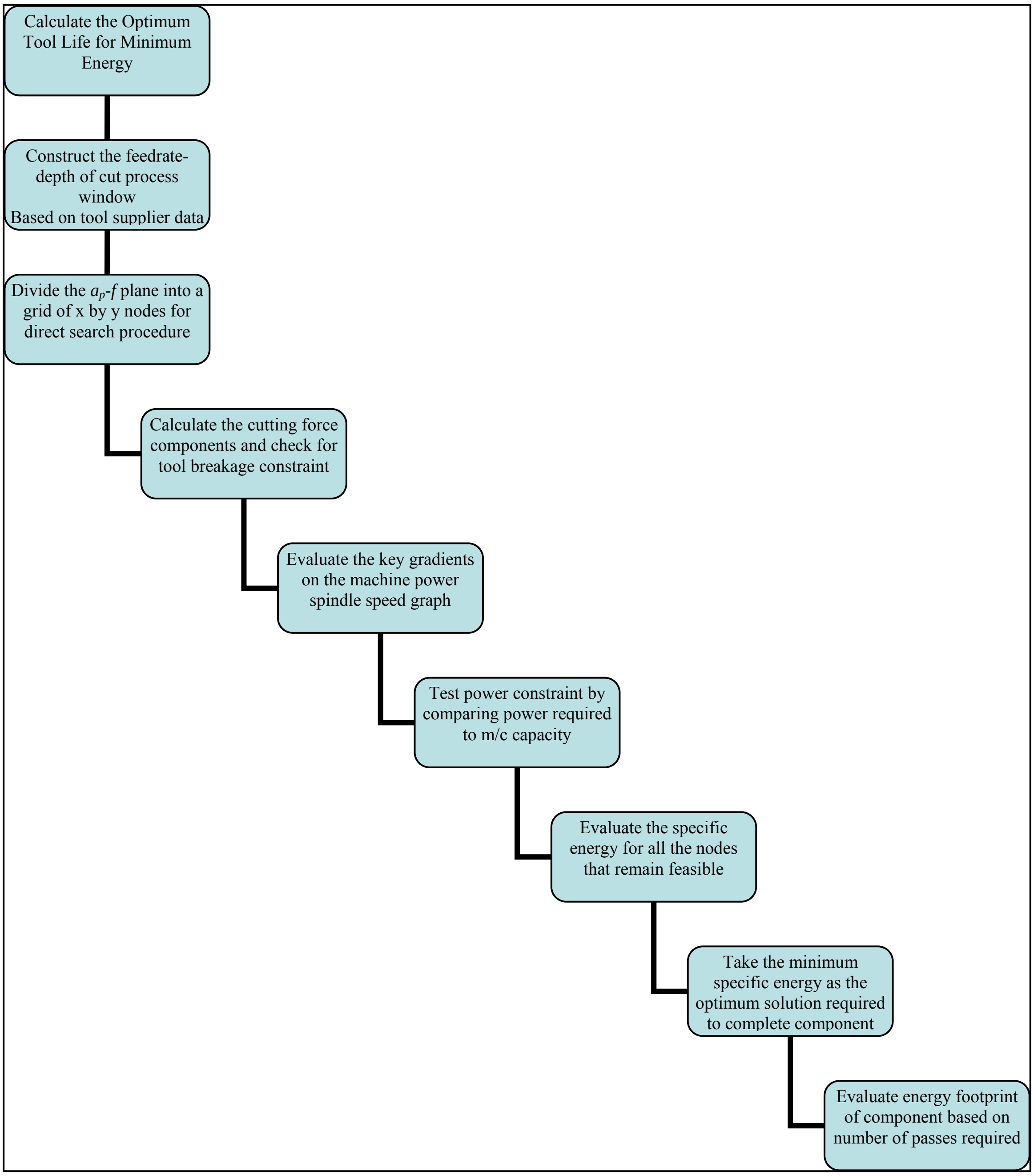


Figure 7.1: Selection of cutting parameters based on minimum energy criteria

7.3 Workpiece details

For the case study a workpiece as shown in Figure 7.2 was designed for the machining tests. This was essentially a stepped shaft. A midrange and common EN8 steel (AISI 1040) was selected. The original billets were 64 mm long with 100 mm diameter.

Figure 7.2: The stepped shaft component

The EN8 steel billets were machined using a MHP-CNC lathe machine centre. The insert used was CNMG120408 WF grade 4215 supplied by Sandvik Coromant. To mimic industrial practice, the turning process was undertaken using flooded coolant. The current drawn by the machine and the cutting process was recorded using Kyoritsu current logger model KEW5020.

7.3.1 Process window: Insert tool

The process window was determined from tool supplier recommendations as specified on the supplied inserts. The insert (CNMG120408 –WF) was supplied by Sandvick and the recommended cutting parameters were shown in **Table 7.1**.

Table 7.1: Recommended cutting parameters from tool supplier

	Minimum	Maximum	Optimum
V_c [m/min]	335	555	415
f [mm/rev]	0.1	0.5	0.3
a_p [mm]	0.25	4.0	1.0

The projected cutting edge length of the insert was 12 mm; hence the maximum a_p for the insert is given in equation 7.1:

$$a_p = \frac{2}{3} l \, sin 50 \tag{7.1}$$

Where l is the projected cutting edge length. The two thirds ensure that only a fraction of the projected cutting edge length is used so that chips do not flow over the insert clamping device. This gives a cutting edge length of 6.13 mm being imposed by the insert size and the insert tool holder approach angle to the workpiece axis. The maximum depth of cut according to the component geometry was 23 mm. Comparing all three constraints, the depth of cut according to the component requirement and the projected cutting edge length was 23 mm and 6.13 mm respectively, while the recommended maximum a_p by Sandvick was 4 mm. Hence the maximum a_p for the process window was 4 mm.

The maximum recommended feed, f, by tool supplier is 0.5 mm. Considering the insert tool nose radius ($r_\varepsilon = 0.8$ mm) gives a maximum f of 0.64 mm/rev (i.e. $f = 0.8 \times r_\varepsilon$). The f should not exceed 0.6 mm/rev or 0.5 mm/rev and hence the maximum f selected is 0.5 mm/rev. The process window for the cutting parameters is than established by the selected upper limits and the supplier given lower limits. This process window is shown in **Figure 7.3**.

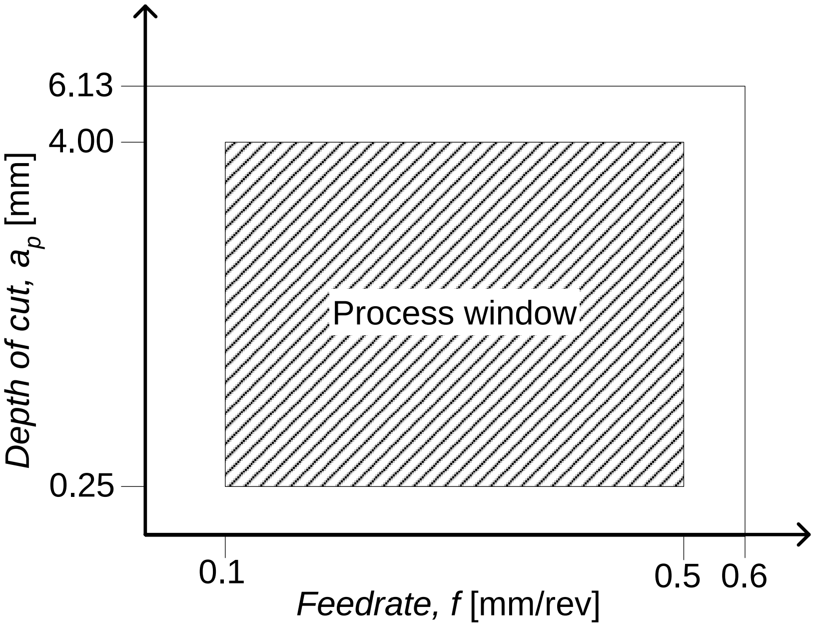


Figure 7.3: Cutting process window

The direct search procedure is used and the process window is converted into grid points where the optimum tool life for minimum energy footprint is used to define cutting parameters. Constraint are then checked and the point with minimum specific energy footprint (energy footprint/volume removed) gives the optimum solution.

7.4 Calculation of cutting forces

The tool breakage constraint is checked by evaluating the cutting forces. The cutting forces involved include the tangential force in the velocity direction F_v, feed force in the feed direction F_f and force in the depth of cut direction, F_a and these are evaluated by empirical models are shown in equation 7.2, 7.3 and 7.4 respectively. The resultant force, F_r, can be calculated using **equation 7.5**. These empirical equations were taken from [102] cutting tests for the insert CNMG120408.

$$F_v = 1717 f^{0.75} a_p \tag{7.2}$$

$$F_f = 650 f^{0.35} a_p \tag{7.3}$$

$$F_a = 350 f^{0.25} a_p \tag{7.4}$$

$$F_r = \sqrt{F_v^2 + \left(F_f^2 + F_a^2\right)} \tag{7.5}$$

where *f*, a_p and V_c retain their usual meaning as defined before. Table 7.2 to 7.5 shows the forces evaluated.

Table 7.2: Tangential force [N]: $F_v = 1717 f^{0.75} a_p$

a_p [mm]	4.00	1221	1655	2054	2428	2784	3125	3454	3773	4084
	3.75	1145	1552	1926	2276	2610	2930	3239	3538	3829
	3.50	1069	1448	1797	2125	2436	2735	3023	3302	3573
	3.25	992	1345	1669	1973	2262	2539	2807	3066	3318
	3.00	916	1242	1541	1821	2088	2344	2591	2830	3063
	2.75	840	1138	1412	1669	1914	2149	2375	2594	2808
	2.50	763	1035	1284	1518	1740	1953	2159	2358	2552
	2.25	687	931	1155	1366	1566	1758	1943	2123	2297
	2.00	611	828	1027	1214	1392	1563	1727	1887	2042
	1.75	534	724	899	1062	1218	1367	1511	1651	1787
	1.50	458	621	770	911	1044	1172	1295	1415	1531
	1.25	382	517	642	759	870	977	1080	1179	1276
	1.00	305	414	514	607	696	781	864	943	1021
	0.75	229	310	385	455	522	586	648	708	766
	0.50	153	207	257	304	348	391	432	472	510
	0.25	76	103	128	152	174	195	216	236	255
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		f [mm/rev]								

Table 7.3: Feed force [N]: $F_f = 650 f^{0.35} a_p$

a_p [mm]	4.00	1161	1338	1480	1600	1706	1801	1887	1966	2040
	3.75	1089	1255	1388	1500	1599	1688	1769	1843	1912
	3.50	1016	1171	1295	1400	1493	1575	1651	1720	1785
	3.25	944	1087	1203	1300	1386	1463	1533	1597	1657
	3.00	871	1004	1110	1200	1279	1350	1415	1475	1530
	2.75	798	920	1018	1100	1173	1238	1297	1352	1402
	2.50	726	837	925	1000	1066	1125	1179	1229	1275
	2.25	653	753	833	900	960	1013	1061	1106	1147
	2.00	581	669	740	800	853	900	943	983	1020
	1.75	508	586	648	700	746	788	825	860	892
	1.50	436	502	555	600	640	675	707	737	765
	1.25	363	418	463	500	533	563	590	614	637
	1.00	290	335	370	400	426	450	472	492	510
	0.75	218	251	278	300	320	338	354	369	382
	0.50	145	167	185	200	213	225	236	246	255
	0.25	73	84	93	100	107	113	118	123	127
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		f [mm/rev]								

Table 7.4: Force in depth of cut direction: $F_a = 350 f^{0.25} a_p$ [N]

a_p [mm]	4.00	787	871	936	990	1036	1077	1113	1147	1177
	3.75	738	817	878	928	971	1010	1044	1075	1104
	3.50	689	762	819	866	907	942	974	1003	1030
	3.25	640	708	761	804	842	875	905	932	957
	3.00	590	653	702	742	777	808	835	860	883
	2.75	541	599	644	681	712	740	765	788	809
	2.50	492	545	585	619	648	673	696	717	736
	2.25	443	490	527	557	583	606	626	645	662
	2.00	394	436	468	495	518	538	557	573	589
	1.75	344	381	410	433	453	471	487	502	515
	1.50	295	327	351	371	389	404	418	430	441
	1.25	246	272	293	309	324	337	348	358	368
	1.00	197	218	234	247	259	269	278	287	294
	0.75	148	163	176	186	194	202	209	215	221
	0.50	98	109	117	124	130	135	139	143	147
	0.25	49	54	59	62	65	67	70	72	74
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		f [mm/rev]								

Table 7.5: Resultant force [N]: $F_r = \sqrt{F_v^2 + \left(F_f^2 + F_a^2\right)}$

a_p [mm]	4.00	1860	2300	2699	3072	3426	3764	4090	4407	4714
	3.75	1744	2156	2531	2880	3211	3529	3835	4131	4420
	3.50	1628	2013	2362	2688	2997	3294	3579	3856	4125
	3.25	1511	1869	2193	2496	2783	3058	3324	3580	3830
	3.00	1395	1725	2025	2304	2569	2823	3068	3305	3536
	2.75	1279	1581	1856	2112	2355	2588	2812	3030	3241
	2.50	1163	1438	1687	1920	2141	2353	2557	2754	2946
	2.25	1046	1294	1518	1728	1927	2117	2301	2479	2652
	2.00	930	1150	1350	1536	1713	1882	2045	2203	2357
	1.75	814	1006	1181	1344	1499	1647	1790	1928	2062
	1.50	698	863	1012	1152	1285	1412	1534	1653	1768
	1.25	581	719	844	960	1070	1176	1278	1377	1473
	1.00	465	575	675	768	856	941	1023	1102	1179
	0.75	349	431	506	576	642	706	767	826	884
	0.50	233	288	337	384	428	471	511	551	589
	0.25	116	144	169	192	214	235	256	275	295
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.5
		f [mm/rev]								

The maximum force to break the insert was 6500N and hence it is clear from Table 7.5 that all the nodes do not violate the force constraint.

7.5 Optimum tool life for minimum energy.

The optimum tool life for minimum energy was calculated from the model developed before and this is recalled again and shown below.

$$T_{opt-E} = \left(\frac{1}{\alpha} - 1\right)\left(\frac{P_o t_3 + y_E}{P_o}\right)$$

Where; $1/\alpha = 3.02$, the tool change time for the machine t_3 was estimated as 2.9 minutes. The current consumed for turning on the machine and getting it in idle mode and ready to start cutting was measured to be on average 5 A, hence, $P_o = 5 \times 415 \times \sqrt{3} = 3594\, W$.

The energy to produce an insert tool was discussed in Chapter 6 (i.e. in **Table 6.1**). Hence energy to produce a single tip of insert tool is $y_E = \frac{5.3\, MJ}{4} = 1325 \times 10^3$ J. Hence

$$T_{opt-E} = (3.02 - 1)\left(\frac{3594 \times 2.9 \times 60 + 1325 \times 10^3}{3594}\right) = 18\ min \qquad (7.6)$$

The optimum cutting velocity V_{c-opt} **equation 7.7** was calculated and shown in **Table 7.6**.

$$V_{c-opt} = \sqrt[3.02]{\frac{3.43 \times 10^8}{f^{1.15} a_p^{0.26} T_{opt}}} \qquad (7.7)$$

Table 7.6: Optimum cutting speed (minimum energy) [m/min], $V_c = \sqrt[3.02]{\dfrac{3.43\times 10^8}{f^{1.15}a_p^{0.26}T}}$

a_p [mm]	4.00	546	468	420	385	360	339	322	308	296
	3.75	549	471	422	388	362	341	324	310	298
	3.50	553	474	424	390	364	343	326	312	299
	3.25	556	477	427	392	366	345	328	314	301
	3.00	560	480	430	395	369	348	330	316	303
	2.75	564	483	433	398	371	350	333	318	306
	2.50	569	487	437	401	374	353	336	321	308
	2.25	574	492	441	405	378	356	339	324	311
	2.00	580	497	445	409	382	360	342	327	314
	1.75	587	503	451	414	386	364	346	331	318
	1.50	594	509	457	419	391	369	351	335	322
	1.25	604	517	464	426	397	375	356	341	327
	1.00	616	527	473	434	405	382	363	347	333
	0.75	631	541	485	445	415	392	372	356	342
	0.50	653	560	502	461	430	406	385	368	354
	0.25	694	594	533	489	456	430	409	391	376
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Figure 7.4 show the maximum power available of the spindle motor for the MHP-CNC machine centre used in this research. Other related machine component such as computer, motor to hold the turret, coolant and hydraulic pump also consumed current. The maximum total current for this machine was 75 A (i.e maximum power of 53.9 kW). According to the machine supplier, it was advisable that the machine operates below 55 A (power equal to 39.5 kW). Machining operation should be done within the boundaries of the machine power and spindle power.

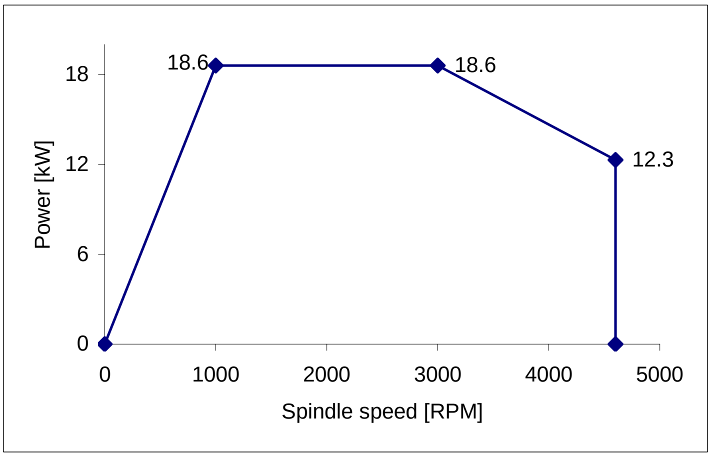


Figure 7.4: Maximum power for spindle motor of MHP lathe machine

Cutting tests were undertaken to study the electrical energy demands of the machine tool. **Figure 7.5** shows the current profile in operating the machine. A rapid increase in current consumed occurs when the machine spindle is started or stopped. The peak current did not exceed the maximum allowable safety limit current of 75 A. Each of the passes operates below 55 A which was the recommended current operation limits. The average current from each pass was used to calculate the power consumed. From this, the energy consumed can be calculated by multiplying by the time taken for each of the passes.

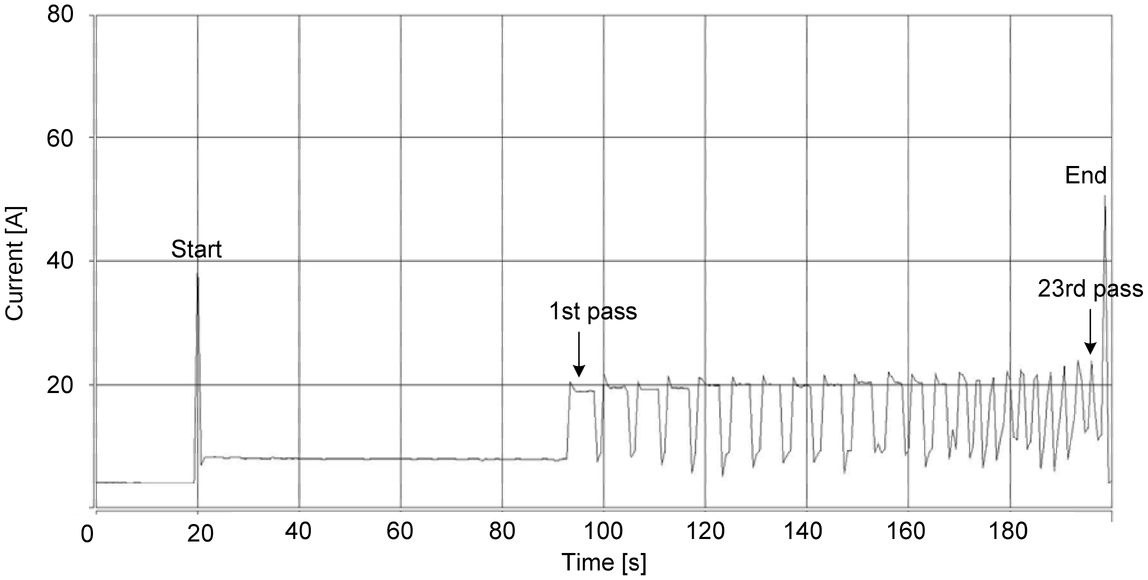


Figure 7.5: Current consumed based on tool supplier parameter

The total energy consumed is evaluated by calculating the area under the graph. The beginning of the graph before the first cutting passes is the effects of starting the machine and then the spindle. To further obtain clarity on the energy consumed by the spindle, the spindle was rotated at different spindle speed without any workpiece/load. The recorded required power was shown in **Figure 7.6.**

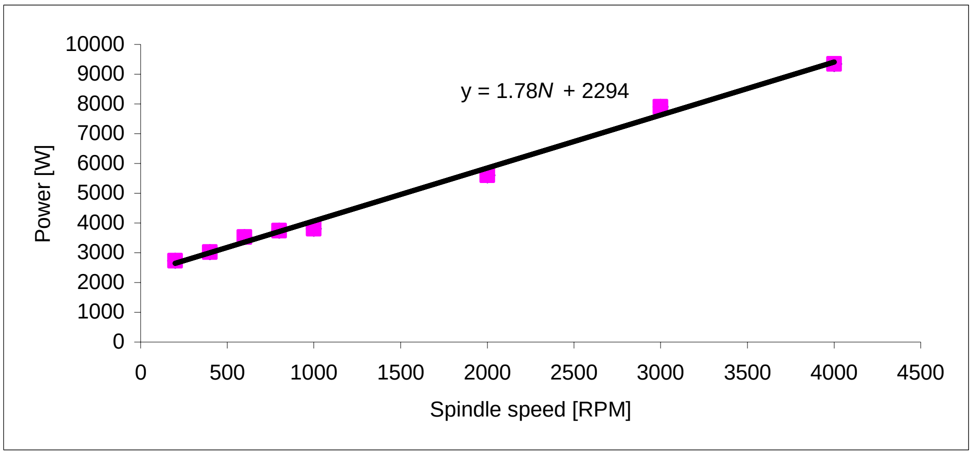


Figure 7.6: Spindle power without any load at different spindle speed

Figure 7.6 clearly shows that the no load power required by the spindle is directly proportional to the spindle speed. From this information, an equation for spindle power without load was formulated and is shown in **equation 7.8.**

$$\mathrm{y} = 1.78N + 2294 \tag{7.8}$$

Given that the maximum spindle power with load was 18600 W hence:

Net for power machining + Power consumed by the running spindle with no load < 18600

$$\frac{F_v V_c}{60} + 2294 + 1.78N < 18600$$

$$\frac{F_v V_c}{60} + 1.78N < 16306$$

$$\left(\frac{F_v \pi D_{avg}}{60 \times 1000} + 1.78\right) N < 16306 \tag{7.9}$$

This is an interesting results as it shows that the usual power expression which multiplies the cutting force by the cutting velocity needs an additional term that accounts for increased power drawn by the spindle at higher spindle speeds.

The minimum power gradient, k_i, is defined by **equation 7.10**.

$$k_i = \frac{F_v \pi D_{avg}}{60 \times 1000} + 1.78 \tag{7.10}$$

Assuming the safety factor in machining power is 70 % from 16306 W, hence the maximum available power will be 11414 W. **Figure 7.7** shows the maximum power for the spindle with load as shown in **equation 7.9**. To evaluate the power constraint, two reference power gradients are defined as follow:

$$k_1 = \frac{18600}{1000} = 18.6 \tag{7.11}$$

$$k_2 = \frac{11400}{4600} = 2.5 \tag{7.12}$$

In evaluating the power for the minimum energy footprint, k_i is compared to k_1 and k_2. Three conditions were determined as follow:

<u>Condition 1:</u>

If $k_i > k_1$; then the set of cutting conditions is not feasible. This is because the minimum energy gradient can not fall inside the machine power envelope.

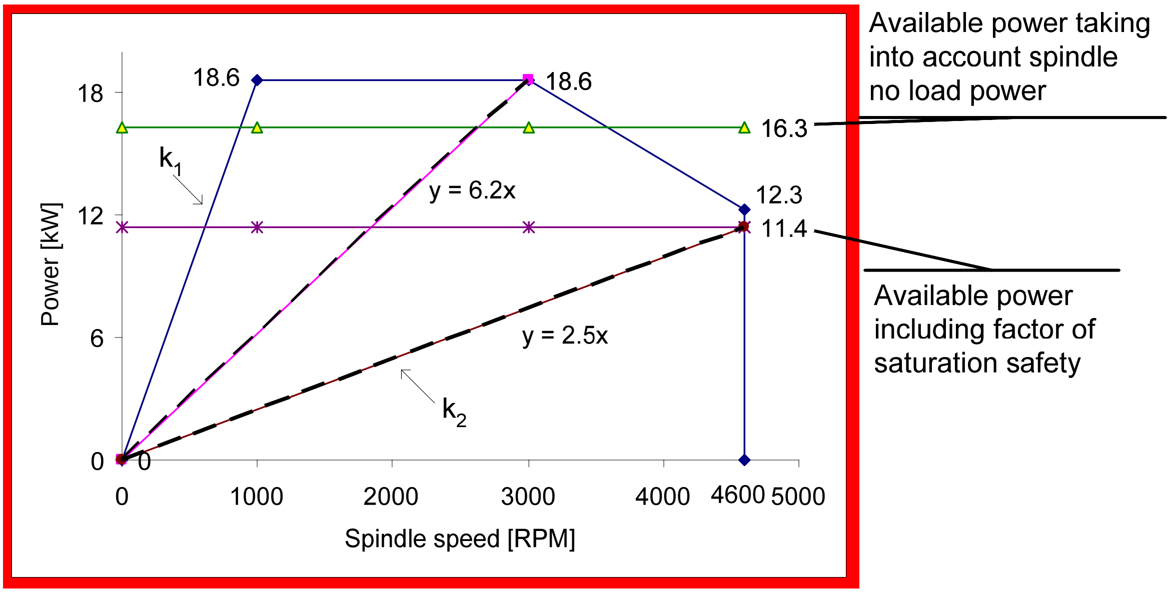
<u>Condition 2:</u>

If $k_1 > k_i > k_2$; then node is feasible if: optimum spindle speed (N_{opt}) < N_{break}, otherwise, N_{opt} becomes N_{break} as a sub-optimum condition. N_{break} is the crossing point for the minimum energy gradient.

Condition 3:

If $k_i < k_2$; If $N_{opt} > 4600$ rpm then use 4600 rpm as $N_{sub\text{-}opt}$ otherwise keep N_{opt}.

After considering the three conditions above, the optimum spindle speeds, the optimum cutting velocity and tool life is updated accordingly from the relevant linking equations.



Available power taking into account spindle no load power

Available power including factor of saturation safety

Figure 7.7: The maximum spindle power with load

Referring to **Figure 7.7,** any gradient above 18.6 is not feasible and coloured in red as shown in **Table 7.7**. Any gradient below 2.5 might be still feasible if the calculated spindle speed was less than 4600 RPM. This was highlighted in green.

Table 7.7 : Gradient, $k_i = \dfrac{F_v \pi D_{avg}}{60 \times 1000} + 1.78$

a_p [mm]	4.00	7.9	10.1	12.1	14.0	15.8	17.5	19.1	20.7	22.3
	3.75	7.6	9.6	11.5	13.3	14.9	16.5	18.1	19.6	21.1
	3.50	7.2	9.1	10.9	12.5	14.1	15.6	17.1	18.5	19.8
	3.25	6.8	8.6	10.2	11.8	13.2	14.6	16.0	17.3	18.6
	3.00	6.4	8.1	9.6	11.0	12.4	13.7	14.9	16.2	17.3
	2.75	6.1	7.6	9.0	10.3	11.5	12.7	13.9	15.0	16.1
	2.50	5.7	7.1	8.3	9.5	10.7	11.8	12.8	13.8	14.8
	2.25	5.3	6.5	7.7	8.8	9.8	10.8	11.7	12.6	13.5
	2.00	4.9	6.0	7.0	8.0	8.9	9.8	10.6	11.5	12.3
	1.75	4.5	5.5	6.4	7.2	8.0	8.8	9.6	10.3	11.0
	1.50	4.1	5.0	5.8	6.5	7.2	7.8	8.5	9.1	9.7
	1.25	3.8	4.5	5.1	5.7	6.3	6.8	7.4	7.9	8.4
	1.00	3.4	3.9	4.4	4.9	5.4	5.8	6.3	6.7	7.1
	0.75	3.0	3.4	3.8	4.1	4.5	4.8	5.1	5.5	5.8
	0.50	2.6	2.9	3.1	3.4	3.6	3.8	4.0	4.2	4.4
	0.25	2.2	2.3	2.5	2.6	2.7	2.8	2.9	3.0	3.1
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

The calculated optimum spindle speed, $N_{sub\text{-}opt}$ is shown in **Table 7.8**. **Table 7.9** showed the original optimum N_{opt} which then compared with **Table 7.8**. The new optimum spindle speed in **Table 7.10** is introduced by comparing the results to **Table 7.8** and **Table 7.9** using the three conditions stated previously. The modified original N_{opt}, was shaded with green region.

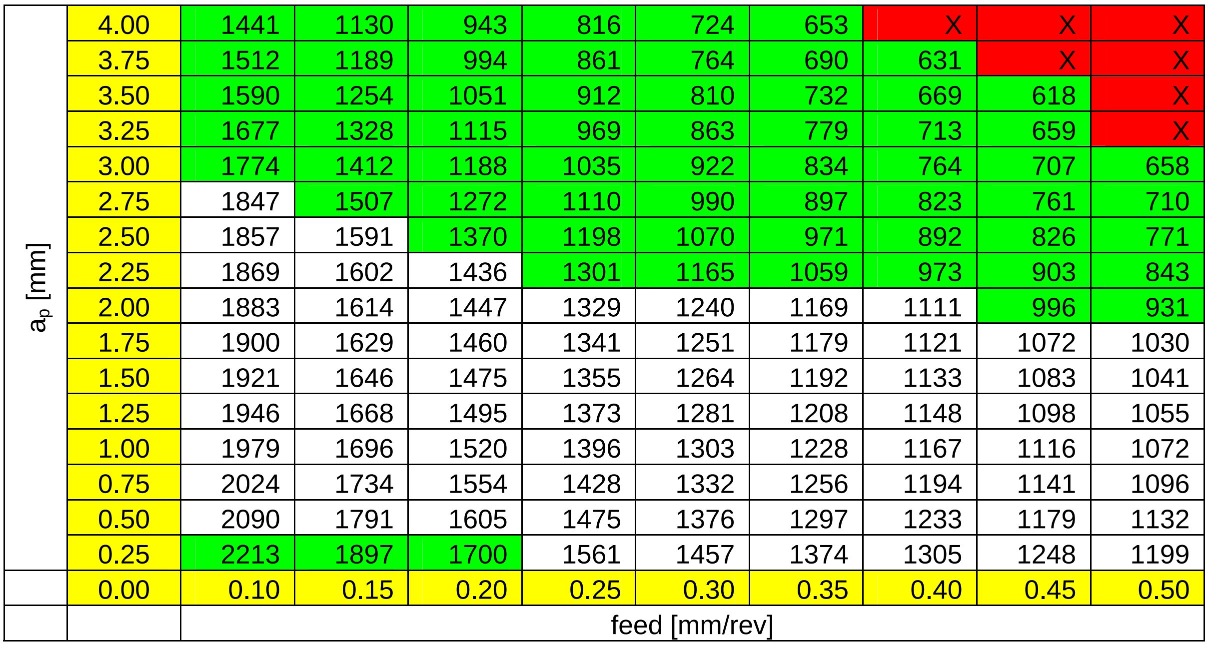
Table 7.8: $N_{sub-opt}\,[\,RPM\,] = \dfrac{11414}{\left(\dfrac{F_v \pi D_{avg}}{60\times 1000}+1.78\right)}$

a_p [mm]	4.00	1441	1130	943	816	724	653	X	X	X
	3.75	1512	1189	994	861	764	690	631	X	X
	3.50	1590	1254	1051	912	810	732	669	618	X
	3.25	1677	1328	1115	969	863	779	713	659	X
	3.00	1774	1412	1188	1035	922	834	764	707	658
	2.75	1885	1507	1272	1110	990	897	823	761	710
	2.50	2011	1616	1370	1198	1070	971	892	826	771
	2.25	2155	1744	1484	1301	1165	1059	973	903	843
	2.00	2323	1894	1619	1425	1279	1165	1072	996	931
	1.75	2520	2073	1783	1575	1419	1295	1195	1111	1040
	1.50	2756	2291	1984	1762	1593	1459	1349	1257	1179
	1.25	3041	2562	2239	2001	1818	1671	1550	1449	1362
	1.00	3394	2908	2570	2317	2118	1958	1824	1711	1614
	0.75	3843	3364	3018	2753	2541	2366	2218	2092	1983
	0.50	4432	3994	3661	3396	3177	2992	2833	2694	2571
	0.25	5239	4919	4658	4437	4245	4076	3926	3790	3666
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.9: Original $N_{opt}\,[\,RPM\,] = \dfrac{V_c \times 1000}{\pi \times D_{avg}}$

a_p [mm]	4.00	1811	1552	1391	1278	1192	1124	X	X	X
	3.75	1817	1557	1395	1282	1196	1127	1072	X	X
	3.50	1823	1562	1400	1286	1200	1131	1075	1028	X
	3.25	1830	1568	1405	1291	1204	1136	1079	1032	X
	3.00	1838	1575	1411	1296	1209	1140	1084	1036	996
	2.75	1847	1582	1418	1303	1215	1146	1089	1041	1001
	2.50	1857	1591	1426	1310	1222	1153	1095	1047	1006
	2.25	1869	1602	1436	1319	1230	1160	1103	1054	1013
	2.00	1883	1614	1447	1329	1240	1169	1111	1062	1020
	1.75	1900	1629	1460	1341	1251	1179	1121	1072	1030
	1.50	1921	1646	1475	1355	1264	1192	1133	1083	1041
	1.25	1946	1668	1495	1373	1281	1208	1148	1098	1055
	1.00	1979	1696	1520	1396	1303	1228	1167	1116	1072
	0.75	2024	1734	1554	1428	1332	1256	1194	1141	1096
	0.50	2090	1791	1605	1475	1376	1297	1233	1179	1132
	0.25	2213	1897	1700	1561	1457	1374	1305	1248	1199
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

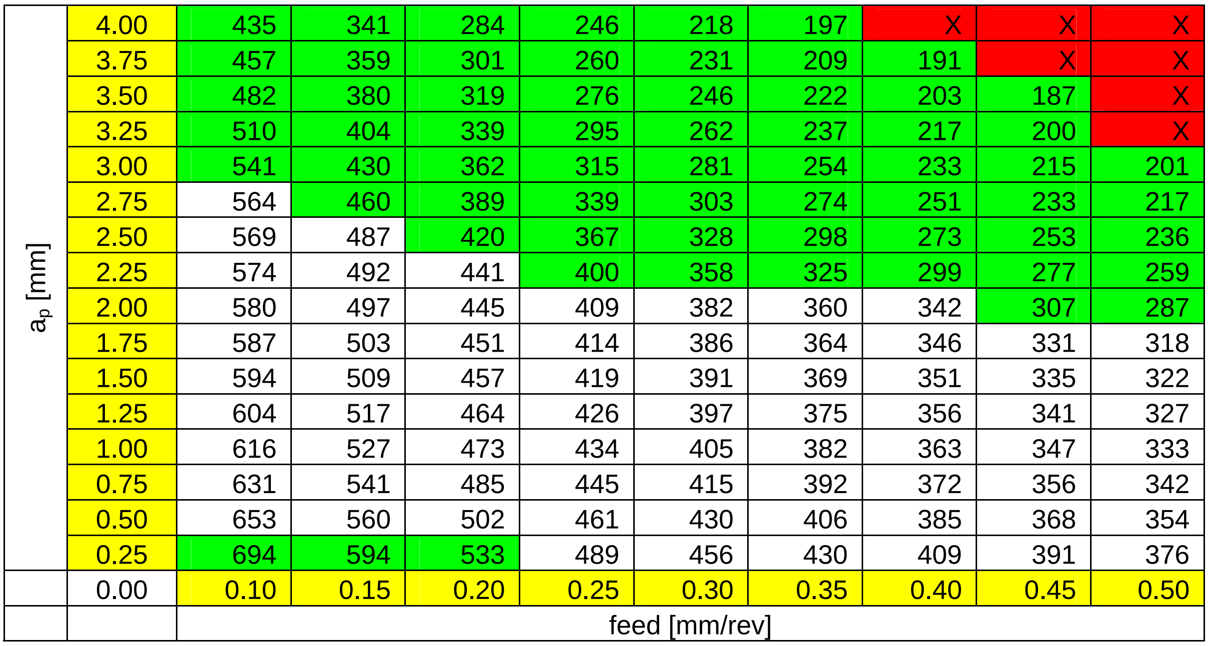
Table 7.10: The modified *N* considering P_{max} of 11.4 kW:



a_p [mm]	4.00	1441	1130	943	816	724	653	X	X	X
	3.75	1512	1189	994	861	764	690	631	X	X
	3.50	1590	1254	1051	912	810	732	669	618	X
	3.25	1677	1328	1115	969	863	779	713	659	X
	3.00	1774	1412	1188	1035	922	834	764	707	658
	2.75	1847	1507	1272	1110	990	897	823	761	710
	2.50	1857	1591	1370	1198	1070	971	892	826	771
	2.25	1869	1602	1436	1301	1165	1059	973	903	843
	2.00	1883	1614	1447	1329	1240	1169	1111	996	931
	1.75	1900	1629	1460	1341	1251	1179	1121	1072	1030
	1.50	1921	1646	1475	1355	1264	1192	1133	1083	1041
	1.25	1946	1668	1495	1373	1281	1208	1148	1098	1055
	1.00	1979	1696	1520	1396	1303	1228	1167	1116	1072
	0.75	2024	1734	1554	1428	1332	1256	1194	1141	1096
	0.50	2090	1791	1605	1475	1376	1297	1233	1179	1132
	0.25	2213	1897	1700	1561	1457	1374	1305	1248	1199
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

The new V_c based on modified N is shown in **Table 7.11**. V_c which have values above or below the recommended range (i.e. minimum V_c = 335 m/min and maximum V_c = 555 m/min) based on tool supplier recommendation was coloured in blue text. The speeds were not applicable in machining processes.

Table 7.11: The new cutting speed [m/min]; $V_c = \frac{\pi D_{avg} N}{1000}$



a_p [mm]	4.00	435	341	284	246	218	197	X	X	X
	3.75	457	359	301	260	231	209	191	X	X
	3.50	482	380	319	276	246	222	203	187	X
	3.25	510	404	339	295	262	237	217	200	X
	3.00	541	430	362	315	281	254	233	215	201
	2.75	564	460	389	339	303	274	251	233	217
	2.50	569	487	420	367	328	298	273	253	236
	2.25	574	492	441	400	358	325	299	277	259
	2.00	580	497	445	409	382	360	342	307	287
	1.75	587	503	451	414	386	364	346	331	318
	1.50	594	509	457	419	391	369	351	335	322
	1.25	604	517	464	426	397	375	356	341	327
	1.00	616	527	473	434	405	382	363	347	333
	0.75	631	541	485	445	415	392	372	356	342
	0.50	653	560	502	461	430	406	385	368	354
	0.25	694	594	533	489	456	430	409	391	376
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

According to the tool supplier, the maximum V_c is 555 m/min and the minimum V_c is 335 m/min. Referring to **Table 7.11**, values that is outside the recommended V_c is not feasible and hence indicated by ‘X’. The cutting parameters based on minimum energy consideration with machine spindle load criterion were determined by the least value of total energy per volume removed. The calculated value in determining these parameters was shown in **Table 7.12 to 7.16**.

Table 7.12: Material removal rate (considering spindle load) [mm^3/s],

$$MRR = \frac{V_c a_p f_n \times 1000}{60}$$

a_p [mm]	4.00	2898	3408	X	X	X	X	X	X	X
	3.75	2857	3370	X	X	X	X	X	X	X
	3.50	2811	3328	X	X	X	X	X	X	X
	3.25	2761	3280	3672	X	X	X	X	X	X
	3.00	2704	3226	3622	X	X	X	X	X	X
	2.75	X	3165	3563	3887	X	X	X	X	X
	2.50	X	3047	3496	3822	X	X	X	X	X
	2.25	X	2767	3306	3747	4026	X	X	X	X
	2.00	X	2485	2969	3409	3816	4199	4561	X	X
	1.75	X	2199	2628	3017	3378	3716	4037	X	X
	1.50	X	1910	2283	2621	2934	3228	3506	3771	X
	1.25	X	1617	1932	2219	2484	2733	2968	3193	X
	1.00	X	1319	1576	1809	2026	2228	2420	2604	X
	0.75	X	1014	1211	1391	1557	1713	1861	2002	2137
	0.50	X	X	836	960	1075	1183	1285	1382	1475
	0.25	X	X	444	510	571	628	682	733	783
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.13: Cutting time (considering spindle load) [min] = $\frac{l}{f_n N_{opt}}$

a_p [mm]	4.00	0.34	0.29	X	X	X	X	X	X	X
	3.75	0.32	0.27	X	X	X	X	X	X	X
	3.50	0.31	0.26	X	X	X	X	X	X	X
	3.25	0.29	0.25	0.22	X	X	X	X	X	X
	3.00	0.28	0.23	0.21	X	X	X	X	X	X
	2.75	X	0.22	0.19	0.18	X	X	X	X	X
	2.50	X	0.21	0.18	0.16	X	X	X	X	X
	2.25	X	0.20	0.17	0.15	0.14	X	X	X	X
	2.00	X	0.20	0.17	0.15	0.13	0.12	0.11	X	X
	1.75	X	0.20	0.17	0.15	0.13	0.12	0.11	X	X
	1.50	X	0.20	0.17	0.14	0.13	0.12	0.11	0.10	X
	1.25	X	0.20	0.16	0.14	0.13	0.12	0.11	0.10	X
	1.00	X	0.19	0.16	0.14	0.13	0.11	0.10	0.10	X
	0.75	X	0.19	0.16	0.14	0.12	0.11	0.10	0.10	0.09
	0.50	X	X	0.15	0.13	0.12	0.11	0.10	0.09	0.09
	0.25	X	X	0.14	0.13	0.11	0.10	0.09	0.09	0.08
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.14: Tool life (considering spindle load):
Referring to **Table 7.10**, if N is equal to N_{opt} then, $T_{opt} = 18.3$ min (i.e. from optimum tool life with minimum energy equation)

otherwise, if N is equal to $N_{sub\text{-}opt}$ then, $T_{sub-opt} = \frac{3.43\times10^{8}}{V_c^{3.02} f^{1.15} a_p^{0.26}}$ [min] (shaded in green)

a_p [mm]	4.00	36.4	47.7	X	X	X	X	X	X	X
	3.75	31.8	41.3	X	X	X	X	X	X	X
	3.50	27.6	35.4	X	X	X	X	X	X	X
	3.25	23.8	30.2	36.7	X	X	X	X	X	X
	3.00	20.3	25.4	30.7	X	X	X	X	X	X
	2.75	X	21.2	25.4	29.6	X	X	X	X	X
	2.50	X	18.3	20.7	23.9	X	X	X	X	X
	2.25	X	18.3	18.3	19.0	21.5	X	X	X	X
	2.00	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	1.75	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	1.50	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	X
	1.25	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	X
	1.00	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	X
	0.75	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.50	X	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.25	X	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.15 : Total energy [kWs]:

$$E = \left(P_o 60 t_1 + \left(P_o + k\dot{v} \right) 60 t_2 + P_o 60 t_3 \left(\frac{60 t_2}{60T} \right) + y \left(\frac{60 t_2}{60T} \right) \right) \div 1000$$

where : $P_0 = 3594$ W ; $t_1 = 2$ min; $t_3 = 2.9$ min ; $k = 4.3$ Ws/mm^3 and

$$y = \frac{5.3\ MJ}{4} = 1325 \times 10^3\ J$$

a_p [mm]										
	4.00	777	760	X	X	X	X	X	X	X
	3.75	760	742	X	X	X	X	X	X	X
	3.50	743	725	X	X	X	X	X	X	X
	3.25	726	708	698	X	X	X	X	X	X
	3.00	710	692	681	X	X	X	X	X	X
	2.75	X	675	665	658	X	X	X	X	X
	2.50	X	659	648	641	X	X	X	X	X
	2.25	X	643	632	625	620	X	X	X	X
	2.00	X	626	616	609	603	600	597	X	X
	1.75	X	610	599	592	587	583	580	X	X
	1.50	X	593	583	576	571	567	564	561	X
	1.25	X	576	566	559	554	550	547	545	X
	1.00	X	559	549	542	537	534	531	528	X
	0.75	X	541	531	525	520	516	514	511	509
	0.50	X	X	513	507	502	499	496	494	492
	0.25	X	X	494	488	484	481	478	476	474
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.16: Volume removed in single pass [mm^3] = $\pi \times l \times \left(r_i^2 - \left(r_i - a_p \right)^2 \right)$

where : l = 49 mm , $r_i = 50$ mm

a_p [mm]										
	4.00	59112	59112	X	X	X	X	X	X	X
	3.75	55562	55562	X	X	X	X	X	X	X
	3.50	51993	51993	X	X	X	X	X	X	X
	3.25	48404	48404	48404	X	X	X	X	X	X
	3.00	44796	44796	44796	X	X	X	X	X	X
	2.75	X	41169	41169	41169	X	X	X	X	X
	2.50	X	37522	37522	37522	X	X	X	X	X
	2.25	X	33857	33857	33857	33857	X	X	X	X
	2.00	X	30172	30172	30172	30172	30172	30172	X	X
	1.75	X	26468	26468	26468	26468	26468	26468	X	X
	1.50	X	22744	22744	22744	22744	22744	22744	22744	X
	1.25	X	19002	19002	19002	19002	19002	19002	19002	X
	1.00	X	15240	15240	15240	15240	15240	15240	15240	X
	0.75	X	11459	11459	11459	11459	11459	11459	11459	11459
	0.50	X	X	7658	7658	7658	7658	7658	7658	7658
	0.25	X	X	3839	3839	3839	3839	3839	3839	3839
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 7.17: Total energy per mm^3 [Ws/mm^3] = $\frac{E \times 1000}{volume\ removed}$

a_p [mm]	4.00	13.14	12.85	X	X	X	X	X	X	X
	3.75	13.68	13.36	X	X	X	X	X	X	X
	3.50	14.29	13.95	X	X	X	X	X	X	X
	3.25	15.01	14.63	14.43	X	X	X	X	X	X
	3.00	15.85	15.44	15.21	X	X	X	X	X	X
	2.75	X	16.40	16.14	15.98	X	X	X	X	X
	2.50	X	17.56	17.27	17.09	X	X	X	X	X
	2.25	X	18.98	18.66	18.45	18.31	X	X	X	X
	2.00	X	20.76	20.40	20.17	20.00	19.87	19.77	X	X
	1.75	X	23.04	22.64	22.38	22.19	22.04	21.93	X	X
	1.50	X	26.08	25.62	25.31	25.09	24.93	24.79	24.69	X
	1.25	X	30.32	29.78	29.42	29.16	28.96	28.81	28.68	X
	1.00	X	36.67	36.01	35.57	35.25	35.01	34.82	34.66	X
	0.75	X	47.24	46.37	45.80	45.39	45.07	44.83	44.62	44.45
	0.50	X	X	67.04	66.21	65.61	65.16	64.80	64.50	64.26
	0.25	X	X	128.75	127.19	126.06	125.21	124.53	123.97	123.51
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Referring to **Table 7.17**, the minimum energy per volume removed was 12.85 Ws/mm^3. The cutting parameters V_c, a_p and f for this value was, 341 m/min, 4 mm and 0.15 mm/rev. **Table 7.18** shows the summarised cutting parameters of different criteria and tool supplier recommendation. Detail calculation of the parameter based on tool supplier and parameter based on minimum cost can be found in **Appendix 4**. The results showed that parameter based on minimum energy and minimum cost was preferable due to the least energy per volume removed compare with parameter based on tool supplier. Cutting parameter for both criterion (i.e. minimum cost and minimum energy) are the same due to the same value of modified N (**refer to Table 7.10**). This condition results in the same value of $T_{sub\text{-}opt}$ which then used to calculate E.

Table 7.18: Comparison of optimum cutting parameter with recommended parameter based on tool supplier

	Parameter based on tool supplier	Mid range process parameter	Parameter based on minimum cost	Parameter based on minimum energy
V_c [m/min]	415	382	341	341
a_p [mm]	1	2	4	4
f [mm/rev]	0.3	0.3	0.15	0.15
MRR [mm^3/s]	2075	3816	3408	3408
Volume removed * [mm^3]	15240	30172	59112	59112
Total energy [kWs]*	535.8	603	760	760
Energy per volume removed [Ws/mm^3]	35.16	20	12.85	12.85
% difference from parameter based on tool supplier	-	43 %	63 %	63 %

* for single pass only

Table 7.18 clearly showed the saving of 63 % on energy consumption in single pass machining compared with recommended cutting parameter based on tool supplier. This highlight the amount of energy saved if the minimum energy criterion was selected in machining process. This reduction will help industries in making machining process more sustainable and help to reduce the cost of production.

7.6 Cutting parameters based on minimum energy criterion for removing a step shaft

In reality machining does not only involves one passes. If the component involves several passes, for example a step shaft machined from a cylindrical billet with initial diameter of 100 mm to 92 mm as shown in **Figure 7.8**, the machining process will occupy 4 passes (i.e. if the recommended cutting parameter from tool supplier were selected). The cutting parameters are shown in **Table 7.18**.

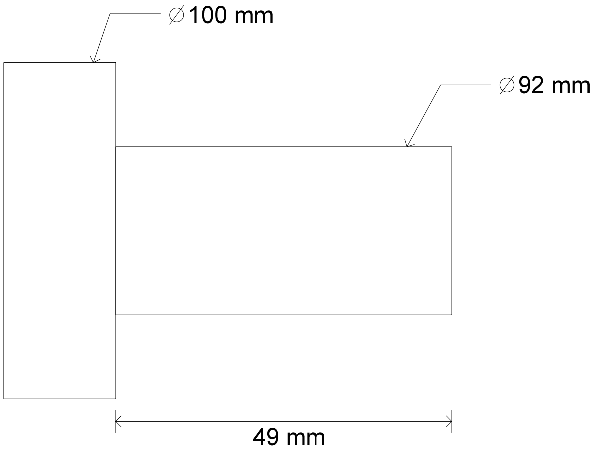


Figure 7.8: Step shaft

Table 7.19 and 7.20 showed the comparison of different selected cutting parameters. The results showed higher energy and cost consumed if the cutting parameter based on tool supplier were selected. This practice is clearly inefficient in terms of energy footprint and should be avoided.

Table 7.19: Value based on recommended cutting parameter from tool supplier

Pass	1st	2nd	3rd	4th	Total
MRR [mm^3/s]	2075.00	2075.00	2075.00	2075.00	-
N [RPM]	1334.33	1361.84	1390.51	1420.42	-
t_2 [min]	0.12	0.12	0.12	0.11	0.47
Total Energy [kWs]	537.85	535.70	533.55	531.40	2138.50
Cost [£]	1.09	1.09	1.09	1.09	4.35

Table 7.20: Comparison for different selected cutting parameters

	Parameter based of tool supplier	Mid range process parameter	Parameter based on minimum cost	Parameter based on minimum energy
Number of passes	4	2	1	1
Total volume removed [mm^3]	59112	59112	59112	59112
Total energy [kWs]	2138.5	1206	760	760
Energy per volume removed [Ws/mm^3]	36.18	20.40	12.85	12.85
% difference from parameter based on tool supplier	-	**44 %**	**64 %**	**64 %**
Cost per volume removed [£/mm^3]	7.36×10^{-5}	3.72×10^{-5}	1.98×10^{-5}	1.98×10^{-5}
Total cost [£]	4.35	2.20	1.17	1.17

7.7 Conclusions

This research has highlighted the need of selecting best machining parameters towards sustainable manufacturing processes. Several conclusions can be made from it as follows:

- The optimum tool life for minimum energy footprint can be used to constrain other cutting variables and select optimum cutting conditions using the direct search method.
- A methodology has been introduced for selecting cutting conditions based on minimum energy considerations.
- In optimising energy not only the machine spindle power should be considered but the current and hence power drawn by the whole machining resource needs to be considered and the dependency of spindle power on energy spindle speed.

- In machining the energy used by machine and spindle module is dependent on the spindle speed [RPM]
- The case presented showed that selecting cutting conditions based on minimum energy footprint criterion can lead to 63 % reduction in energy footprint of a machined product compared to using recommended cutting data from tool suppliers.
- The process window can further be reduced on the lower depth of cut and feedrate corner if the cutting velocity range for the insert is introduced as a constraint.
- When the energy footprint of tooling is comprehensively taken into account then there appears to be some synergy in terms of the outcome when comparing minimum cost and minimum energy criteria these are driven by the same trends.

CHAPTER EIGHT

CONCLUSIONS

8.1 Conclusions

This study set out to investigate energy use by a machining process and to optimise the energy footprints of machined products. Some of the key findings are as follows:

- This study has shown that different types of workpiece gave diverse energy requirements in their machining. The energy footprint depends on the properties of the workpiece materials. For example, tougher material such as titanium alloy uses higher energy in machining processes compared with other materials such as aluminium and steel.
- In terms of distribution of energy in machining, more than 50 percent was used for non-cutting operations. Further improvement, for example in machine design is needed to reduce the energy intensive of machining operations. Designing spindles, which use less power maybe one of the key solutions to reduce energy consumed by non-cutting operations.
- Given that non-cutting operations consumed most of the energy in machining, keeping machines powered up but not cutting contributes to energy waste and must be minimised where possible. Thus process planning may play a key role in reducing the energy demand for a machine shop.
- The results showed that in general, manual machines consumed less energy compared with CNC machines when removing the same amount of material at identical spindle speeds. CNC machines have more modules and functionality compared with manual machines. Thus the increased productivity of CNC machines may compromise attempts

for reducing the energy usage on the machine. Thus for reducing the energy footprint of a machine shop it may be essential to use manual machines when as much as possible where the quality requirements and productivity targets can be met.

- Uncoated tool uses more energy as compared with the coated tool in machining processes this is driven by tool wear rates.
- Higher cutting speed reduces the energy consumed in removing the same volume of workpiece material. Reduction in energy consumption leads to lower carbon emission hence support sustainable machining processes. Thus high speed machining can be a strategy for reducing the energy used by a machine to complete a machining process.
- De-coating and recoating use for re-use cutting tools does not compromise the machining performance or energy intensity of process. Thus selective removal of coating can be used to enable re-use of coated tools.
- The optimization of cutting parameters based on minimum energy criterion can have significant impact on reducing the energy footprint of a machined product.

8.2 Novel and new research contributions to body of knowledge

The following can be indentified as the novel and new contributions to knowledge.

- Development of an energy footprint model for a machined component that enables the effects of tooling to be added to the energy needs of the actual cutting process.
- The development of an equation for an optimum tool life that satisfies the minimum energy requirements.
- The development and testing of a methodology for selection of optimum cutting conditions based on minimum cost considerations.

- Quantifying the effects on energy saving of dry machining, high speed machining, and process optimisation.
- An assessment of the feasibility of using de-coated and recoated tooling and the associated energy footprints.

8.3 Research Boundaries

The research will have wide range appeal but it should be emphasised that it was undertaken within the following boundaries.

- The results relates to the turning and the milling process. More work needs to be done to adapt it to other processes though some conclusions may be related.
- The carbon calculation is based on the long term average carbon intensity factor for electricity (i.e. 0.43 CO_2e/kWh) which is an estimation of carbon emission. An accurate measure of carbon emission can be calculated if each source for energy generation used in machining were determined.
- The energy consumed in producing the insert tool is just an estimate as obtained from adapted from published literature. Nevertheless, it provides a good basis to estimate total energy consumed to manufacture the product.
- The energy consumed for producing the raw workpiece material is based on data from the Cambridge Engineering Selector (CES).

8.4 Future work and recommendation.

This research has generated interest in sustainable manufacturing processes. Therefore, there is a lot more advancement that can be done. Examples of future research that can be done are,

- To study the energy footprint for different types of machines given the same component to manufacture.
- Development of energy footprint map for different types of machining processes. This can be used as a standard for machining industries.
- Improvement in machine design which includes the spindle and machine modules that can reduce the non-cutting energy in machining processes.
- Methods of determining the energy sources used by the manufacturing industries to calculate the carbon emission in machining processes.
- Improving the energy footprint model by modelling the different energy budgets for the machine tool.

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APPENDIX 1

List of machines and current loggers

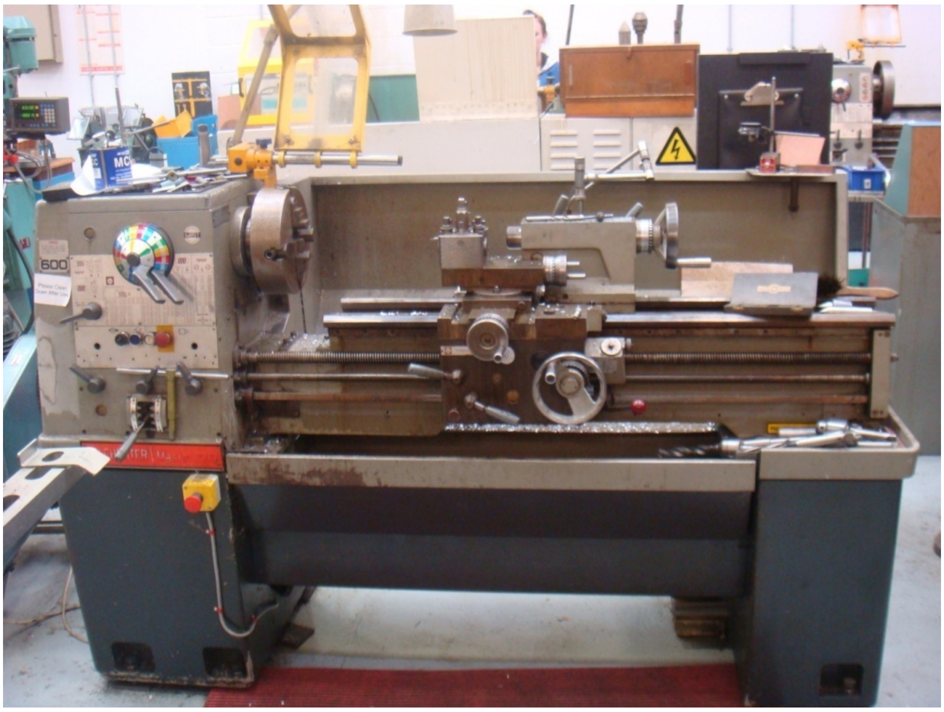
1.1 MHP CNC turning centre

	Feature	Specifications
1	**Turret**	12 Station turret
2	**Motors:**	
	Spindle drive	18 kW DC servo motor
	Cross slide (x-axis)	1.1 kW DC servo motor
	Longitudinal (z-axis)	1.8 kW DC servo motor
3	**Rapid positioning :**	
	Cross slide (x-axis)	5 m/min
	Longitudinal (z-axis)	10 m/min
4	**Weight**	4000 kg (approx.)
5	**Machine capacity:**	
	Swing diameter	450 mm
	Longitudinal travel	550 mm
	Cross travel	200 mm
6	**Max. component weight**	80 kg
7	**Headstock:**	
	Spindle speed	50 – 4500 RPM
	Chuck size (diameter)	200 mm
	HP available	25 HP
8	**Tailstock:**	
	Quill diameter	72 mm
	Hydraulic end pres.	750 kg

1.2 Takisawa MAC-V3 Vertical CNC milling centre

	Feature	Specifications
1	**Automatic tool changer :**	
	Tool accommodation	12
	Tool holder	MAS BT 40
	Max. tool diameter	80 mm
	Max. tool length	250 mm
	Max. tool weight	7.5 kg
2	**Motors:**	
	Main motor	AC 5.5 kW
	Feed motor (x-y axis)	0.85 kW DC servo motor
	Feed motor (z-axis)	1.2 kW
3	**Feeds speeds:**	
	Rapid traverse (x-y axis)	12000 mm/min
	Rapid traverse (z axis)	10000 mm/min
4	**Weight**	4300 kg (approx.)
6	**Machine size:**	
	Height	2726 mm
	Floor space	1730 mm x 2445 mm
7	**Machine capacity:**	
	Table size	600 mm x 400 mm
	Table x-y travel	510 mm x 400 mm
	Spindle head (z) travel	300 mm
	Max. load on table	200 kg
8	**Spindle:**	
	Spindle diameter	55 mm
	Spindle speed	60 – 6000 RPM
	Spindle drive motor	7.5 HP
	Max. power supply	20 kW

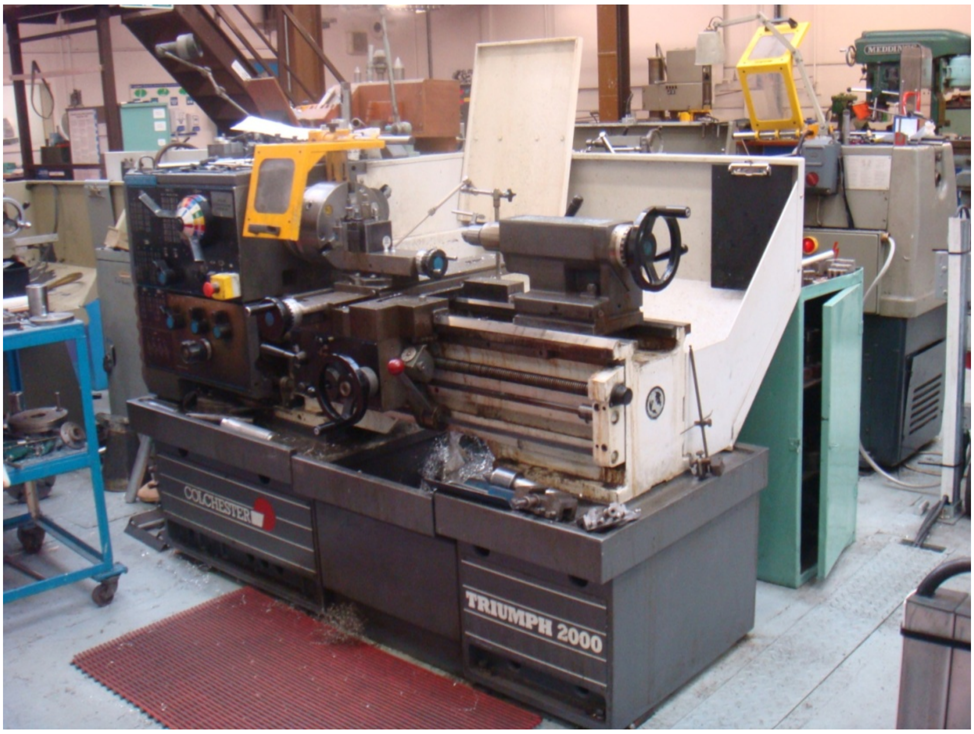
1.3 1960s Colchester Master 2500 lathe



1.4 1970 Harrison 155 lathe

1.5 1970s Harrison VS330TR lathe

1.6 1980 Colchester Triumph 2000 lathe



1.7 1980s Colchester Triumph 2500 lathe

1.8 DT-266 clamp meter

	Features	Specifications
1	AC clamp range	0 A – 200 A (1 decimal) or 0 A -1000 A (0 decimal)
2	AC voltage range	0 V – 750 V
3	DC voltage range	0 V – 1000 V
4	Weight	310 g (approx.)
5	Size	23 cm x 7 cm x 3.7 cm

1.9.1 Kyoritsu KEW 5020 current/voltage logger

	Features	Specifications
1	Number of channel	3
2	Data storing capacity (1 channel used)	60 000
3	Possible measurement time	10 days (approx.)
4	Dimension	111 mm x 60 mm x 42 mm
5	Weight	265 g (approx.)

1.9.2 Kyoritsu KEW 8147 current clamp sensors

	Features	Specifications
1	Measuring range	0 A – 70 A
2	Clamp diameter	40 mm (approx.)
3	Dimension	128 mm x 81 mm x 36 mm
4	Weight	240 g (approx.)

APPENDIX 2

List of Formulas

Equation 2.1	$Carbon = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{Carbon}{Energy}$
Equation 2.2	Carbon emission = EC_{part} [GJ] x CES™ [kgCO_2/GJ]
Equation 2.3	$CES = \frac{\sum \left(P_s \times F_e\right)}{\eta}$
Equation 2.4	$P = P_0 + k\dot{v}$
Equation 2.5	$P = V \cdot I \cdot \sqrt{3}$
Equation 2.6	$E = (P_0 + k\dot{v})t$
Equation 6.1	$C = x\left(t_1 + \frac{\pi D_{avg} l}{f V_c} + t_3 \frac{\pi D_{avg} l}{A_t} V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)} \right) + \frac{y_c \pi D_{avg} l}{A_t} V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}$
Equation 6.2	$T_{opt-C} = \left(\frac{1}{\alpha} - 1\right)\left(\frac{x t_3 + y_C}{x}\right)$
Equation 6.3	$E = E_1 + E_2 + E_3 + E_4$
Equation 6.4	$E_2 = \left(P_0 + k\dot{v}\right) t_2$
Equation 6.5	$E = P_0 t_1 + \left(P_0 + k\dot{v}\right) t_2 + P_0 t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right)$
Equation 6.6	$T = \frac{A}{V_c^{\frac{1}{\alpha}} f^{\frac{1}{\beta}}}$
Equation 6.7	$t = \frac{\pi D_{avg} l}{f V_c}$
Equation 6.8	$E = P_0 t_1 + P_0 \cdot \frac{\pi D_{avg} l}{f V_c} + k \cdot \frac{\pi}{4}\left(D_i^2 - D_f^2\right) \frac{f V_c}{\pi D_{avg}} \cdot \frac{\pi D_{avg} l}{f V_c} + P_0 t_3 \left(\frac{\frac{\pi D_{avg} l}{f V_c}}{\frac{A}{V_c^{1/\alpha} f^{1/\beta}}} \right) + y_E \left(\frac{\frac{\pi D_{avg} l}{f V_c}}{\frac{A}{V_c^{1/\alpha} f^{1/\beta}}} \right)$
Equation 6.9	$E = P_0 t_1 + \frac{P_0 \pi D_{avg} l}{f V_c} + \frac{k \pi l \left(D_i^2 - D_f^2\right)}{4} + \frac{P_0 t_3 \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} + \frac{y_E \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A}$
Equation 6.10	$\frac{\partial E}{\partial V_c} = -\frac{P_0 \pi D_{avg} l}{f V_c^2} + \left(\frac{1}{\alpha} - 1\right) \frac{P_0 t_3 \pi D_{avg} l\, f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A} + \left(\frac{1}{\alpha} - 1\right) \frac{y_E \pi D_{avg} l\, f^{\left(\frac{1}{\beta}-1\right)} V_c^{\left(\frac{1}{\alpha}-2\right)}}{A}$

Equation 6.11	$\frac{A}{f^{\left(\frac{1}{\beta}\right)} V_c^{\left(\frac{1}{\alpha}\right)}} = \left(\frac{1}{\alpha} - 1\right) \cdot \left(\frac{P_0 t_3 + y_E}{P_0}\right)$
Equation 6.12	$T_{opt-E} = \left(\frac{1}{\alpha} - 1\right) \cdot \left(\frac{P_0 t_3 + y_E}{P_0}\right)$
Equation 6.13	$\log T = -2.4 \log V_c + 7.5$
Equation 7.1	$a_p = \frac{2}{3} l \sin 50$
Equation 7.2	$F_v = 1717 f^{0.75} a_p$
Equation 7.3	$F_f = 650 f^{0.35} a_p$
Equation 7.4	$F_a = 350 f^{0.25} a_p$
Equation 7.5	$F_r = \sqrt{F_v^2 + \left(F_f^2 + F_a^2\right)}$
Equation 7.6	$T_{opt-E} = 18 \text{ min}$
Equation 7.7	$V_{c-opt} = \sqrt[3.02]{\frac{3.43 \times 10^8}{f^{1.15} a_p^{0.26} T_{opt}}}$
Equation 7.8	$y = 1.78N + 2294$
Equation 7.9	$\left(\frac{F_v \pi D_{avg}}{60 \times 1000} + 1.78\right) N < 16306$
Equation 7.10	$k_i = \frac{F_v \pi D_{avg}}{60 \times 1000} + 1.78$
Equation 7.11	$k_1 = 18.6$
Equation 7.12	$k_2 = 2.5$

APPENDIX 3

Detail cutting parameters for machining of different materials according to tool supplier recommendations.

	Aluminium	Cast Iron	Steel	Brass	Titanium Alloy
f [mm/rev]	0.30	0.30	0.25	0.15	0.15
a_p [mm]	1.50	1.00	1.00	1.20	1.20
V_c [m/min]	654.00	240.00	395.00	140.00	75.00
k [W.s / mm^3]	1.00	1.16	4.33	2.20	2.90
MRR [mm^3/s]	4783.07	1164.18	1578.65	388.10	221.30
$P_0 + P_s$	11500.82	8481.85	10782.02	9488.17	6037.93
P	5175.37	3378.37	6109.81	1365.72	2659.56
Time to remove 10 cm^3 of material	209.07	858.97	633.45	2576.65	4518.75
Non cutting energy [J]	2.40E+06	7.29E+06	6.83E+06	2.44E+07	2.73E+07
Energy for machining [J]	1.08E+06	2.90E+06	3.87E+06	3.52E+06	1.20E+07
% energy idle condition	69.0	71.5	63.8	87.4	69.4
% energy for machining	31.0	28.5	36.2	12.6	30.6
Total Energy to remove 10 cm^3 of material [J]	3.49E+06	1.02E+07	1.07E+07	2.80E+07	3.93E+07

APPENDIX 4

4.1 Detail calculation based on tool supplier recommended cutting parameters.

Initial diameter = 100 mm

Length of cut = 49 mm

Calculation for parameter based on tool supplier:

$$MRR = \frac{V_c a_p f_n \times 1000}{60}$$
$$= \frac{415 \times 1 \times 0.3 \times 1000}{60}$$

= 2075 [mm^3/s]

$$N = \frac{V_c}{\pi D_{avg}}$$
$$= \frac{415 \times 1000}{\pi \times 99}$$

= 1334 RPM

$$t_2 = \frac{l}{fN}$$
$$= \frac{49}{0.3 \times 1334}$$

= 0.12 min

$$E = P_o t_1 + (P_o + k\dot{v})t_2 + P_o t_3 \left(\frac{t_2}{T}\right) + y\left(\frac{t_2}{T}\right)$$
$$= 3594 \times 2 \times 60 + (3594 + 4.3 \times 2075)0.12 \times 60 + 3594 \times 2.9 \times 60\left(\frac{0.12}{16.3}\right) + 1325000\left(\frac{0.12}{16.3}\right)$$

= 535.8 kWs

4.2 Direct search method: Calculation of cutting parameter based on minimum cost

Table 4.1 : Gradient, $k_i = \dfrac{F_v \pi D_{avg}}{60 \times 1000} + 1.78$

a_p [mm]	4.00	7.9	10.1	12.1	14.0	15.8	17.5	19.1	20.7	22.3
	3.75	7.6	9.6	11.5	13.3	14.9	16.5	18.1	19.6	21.1
	3.50	7.2	9.1	10.9	12.5	14.1	15.6	17.1	18.5	19.8
	3.25	6.8	8.6	10.2	11.8	13.2	14.6	16.0	17.3	18.6
	3.00	6.4	8.1	9.6	11.0	12.4	13.7	14.9	16.2	17.3
	2.75	6.1	7.6	9.0	10.3	11.5	12.7	13.9	15.0	16.1
	2.50	5.7	7.1	8.3	9.5	10.7	11.8	12.8	13.8	14.8
	2.25	5.3	6.5	7.7	8.8	9.8	10.8	11.7	12.6	13.5
	2.00	4.9	6.0	7.0	8.0	8.9	9.8	10.6	11.5	12.3
	1.75	4.5	5.5	6.4	7.2	8.0	8.8	9.6	10.3	11.0
	1.50	4.1	5.0	5.8	6.5	7.2	7.8	8.5	9.1	9.7
	1.25	3.8	4.5	5.1	5.7	6.3	6.8	7.4	7.9	8.4
	1.00	3.4	3.9	4.4	4.9	5.4	5.8	6.3	6.7	7.1
	0.75	3.0	3.4	3.8	4.1	4.5	4.8	5.1	5.5	5.8
	0.50	2.6	2.9	3.1	3.4	3.6	3.8	4.0	4.2	4.4
	0.25	2.2	2.3	2.5	2.6	2.7	2.8	2.9	3.0	3.1
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

The calculated optimum spindle speed, N_{break}, is shown in **Table 4.2**. **Table 4.3** showed the original optimum N (N_{opt})which then compared with **Table 4.2**. The optimum spindle speed in **Table 4.3** is introduced by comparing the results to **Table 4.2** using the three conditions stated previously. The modified N was shown in **Table 4.4**. The changes in original N_{opt}, was shaded with green box.

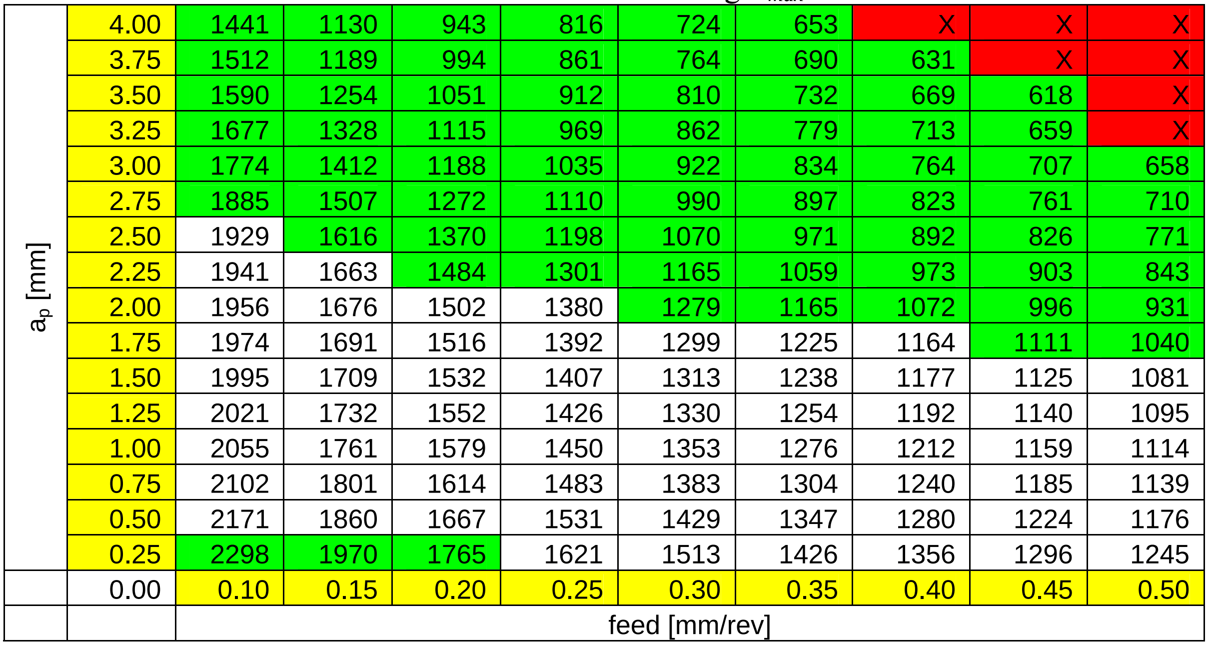
Table 4.2: $N_{break}\ [\,RPM\,] = \dfrac{11414}{\left(\dfrac{F_v \pi D_{avg}}{60\times 1000}+1.78\right)}$

a_p [mm]	4.00	1441	1130	943	816	724	653	X	X	X
	3.75	1512	1189	994	861	764	690	631	X	X
	3.50	1590	1254	1051	912	810	732	669	618	X
	3.25	1677	1328	1115	969	862	779	713	659	X
	3.00	1774	1412	1188	1035	922	834	764	707	658
	2.75	1885	1507	1272	1110	990	897	823	761	710
	2.50	1929	1616	1370	1198	1070	971	892	826	771
	2.25	1941	1663	1484	1301	1165	1059	973	903	843
	2.00	1956	1676	1502	1380	1279	1165	1072	996	931
	1.75	1974	1691	1516	1392	1299	1225	1164	1111	1040
	1.50	1995	1709	1532	1407	1313	1238	1177	1125	1081
	1.25	2021	1732	1552	1426	1330	1254	1192	1140	1095
	1.00	2055	1761	1579	1450	1353	1276	1212	1159	1114
	0.75	2102	1801	1614	1483	1383	1304	1240	1185	1139
	0.50	2171	1860	1667	1531	1429	1347	1280	1224	1176
	0.25	2298	1970	1765	1621	1513	1426	1356	1296	1245
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.3: Original $N_{opt}\ [\,RPM\,] = \dfrac{V_c \times 1000}{\pi \times D_{avg}}$

a_p [mm]	4.00	1881	1612	1445	1327	1238	1167	X	X	X
	3.75	1887	1617	1449	1331	1242	1171	1113	X	X
	3.50	1893	1622	1454	1335	1246	1175	1117	1068	X
	3.25	1900	1628	1459	1340	1251	1179	1121	1072	X
	3.00	1908	1635	1466	1346	1256	1184	1126	1076	1034
	2.75	1918	1643	1473	1353	1262	1190	1131	1082	1039
	2.50	1929	1653	1481	1361	1269	1197	1138	1088	1045
	2.25	1941	1663	1491	1369	1278	1205	1145	1095	1052
	2.00	1956	1676	1502	1380	1287	1214	1154	1103	1060
	1.75	1974	1691	1516	1392	1299	1225	1164	1113	1069
	1.50	1995	1709	1532	1407	1313	1238	1177	1125	1081
	1.25	2021	1732	1552	1426	1330	1254	1192	1140	1095
	1.00	2055	1761	1579	1450	1353	1276	1212	1159	1114
	0.75	2102	1801	1614	1483	1383	1304	1240	1185	1139
	0.50	2171	1860	1667	1531	1429	1347	1280	1224	1176
	0.25	2298	1970	1765	1621	1513	1426	1356	1296	1245
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

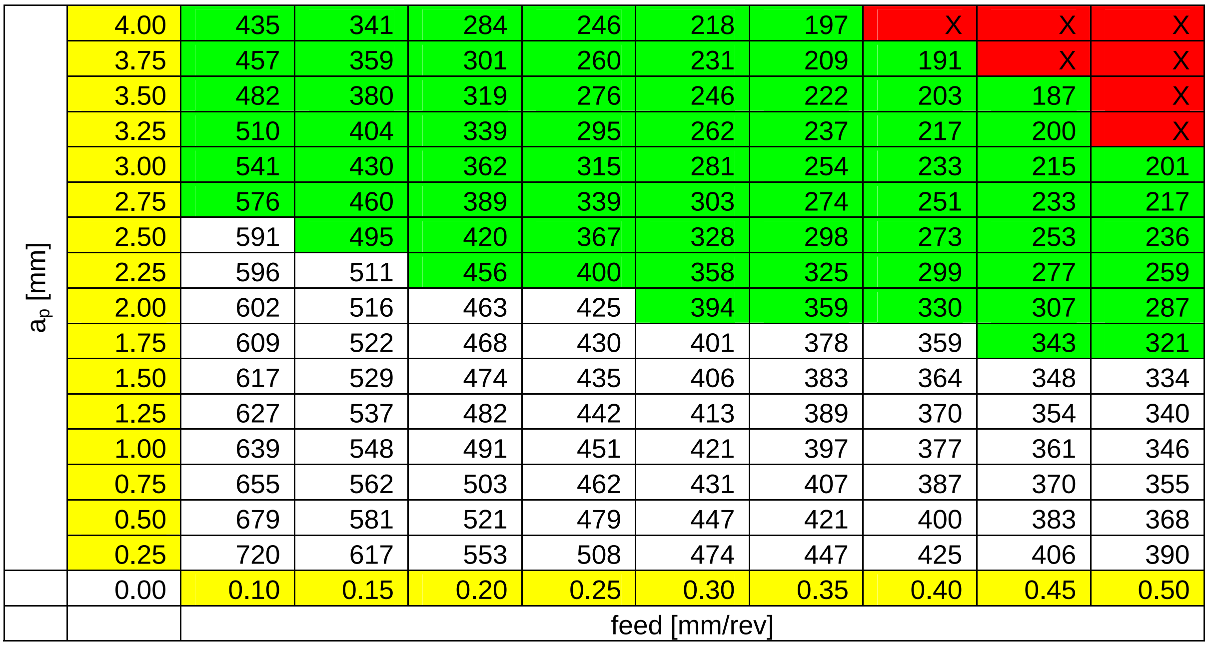
Table 4.4: The modified *N* considering P_{max} of 11.4 kW:



a_p [mm]	4.00	1441	1130	943	816	724	653	X	X	X
	3.75	1512	1189	994	861	764	690	631	X	X
	3.50	1590	1254	1051	912	810	732	669	618	X
	3.25	1677	1328	1115	969	862	779	713	659	X
	3.00	1774	1412	1188	1035	922	834	764	707	658
	2.75	1885	1507	1272	1110	990	897	823	761	710
	2.50	1929	1616	1370	1198	1070	971	892	826	771
	2.25	1941	1663	1484	1301	1165	1059	973	903	843
	2.00	1956	1676	1502	1380	1279	1165	1072	996	931
	1.75	1974	1691	1516	1392	1299	1225	1164	1111	1040
	1.50	1995	1709	1532	1407	1313	1238	1177	1125	1081
	1.25	2021	1732	1552	1426	1330	1254	1192	1140	1095
	1.00	2055	1761	1579	1450	1353	1276	1212	1159	1114
	0.75	2102	1801	1614	1483	1383	1304	1240	1185	1139
	0.50	2171	1860	1667	1531	1429	1347	1280	1224	1176
	0.25	2298	1970	1765	1621	1513	1426	1356	1296	1245
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

The new V_c based on modified N was shown in **Table 4.5**. V_c which have values above or below the recommended range (i.e. minimum V_c = 335 m/min and maximum V_c = 555 m/min) based on tool supplier recommendation was coloured in blue text. The speeds were not applicable in machining processes.

Table 4.5: The new cutting speed [m/min]; $V_c = \frac{\pi D_{avg} N}{1000}$



a_p [mm]	4.00	435	341	284	246	218	197	X	X	X
	3.75	457	359	301	260	231	209	191	X	X
	3.50	482	380	319	276	246	222	203	187	X
	3.25	510	404	339	295	262	237	217	200	X
	3.00	541	430	362	315	281	254	233	215	201
	2.75	576	460	389	339	303	274	251	233	217
	2.50	591	495	420	367	328	298	273	253	236
	2.25	596	511	456	400	358	325	299	277	259
	2.00	602	516	463	425	394	359	330	307	287
	1.75	609	522	468	430	401	378	359	343	321
	1.50	617	529	474	435	406	383	364	348	334
	1.25	627	537	482	442	413	389	370	354	340
	1.00	639	548	491	451	421	397	377	361	346
	0.75	655	562	503	462	431	407	387	370	355
	0.50	679	581	521	479	447	421	400	383	368
	0.25	720	617	553	508	474	447	425	406	390
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

According to the tool supplier, the maximum V_c is 555 m/min and the minimum V_c is 335 m/min. Referring to **Table 4.5**, values that is outside the recommended V_c is not feasible and hence indicated by ‘X’. The cutting parameters based on minimum energy consideration with machine spindle load criterion were determined by the least value of total energy per volume removed. The calculated value in determining these parameters was shown in **Table 4.6, to 4.11**.

Table 4.6: Material removal rate (considering spindle load) [mm^3/s],

$$MRR = \frac{V_c a_p f_n \times 1000}{60}$$

a_p [mm]	4.00	2898	3408	X	X	X	X	X	X	X
	3.75	2857	3370	X	X	X	X	X	X	X
	3.50	2811	3328	X	X	X	X	X	X	X
	3.25	2761	3280	3672	X	X	X	X	X	X
	3.00	2703	3226	3622	X	X	X	X	X	X
	2.75	X	3165	3563	3887	X	X	X	X	X
	2.50	X	3094	3496	3822	X	X	X	X	X
	2.25	X	2874	3417	3747	4026	X	X	X	X
	2.00	X	2580	3083	3540	3938	4184	X	X	X
	1.75	X	2284	2729	3134	3508	3859	4192	4501	X
	1.50	X	1984	2371	2722	3047	3352	3641	3917	X
	1.25	X	1679	2007	2304	2579	2838	3082	3316	3539
	1.00	X	1369	1636	1879	2104	2314	2514	2704	2886
	0.75	X	X	1258	1445	1617	1779	1933	2079	2219
	0.50	X	X	869	997	1116	1228	1334	1435	1532
	0.25	X	X	461	529	593	652	708	762	813
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.7: Cutting time (considering spindle load) [min] = $\frac{l}{f_n N_{opt}}$

a_p [mm]	4.00	0.34	0.29	X	X	X	X	X	X	X
	3.75	0.32	0.27	X	X	X	X	X	X	X
	3.50	0.31	0.26	X	X	X	X	X	X	X
	3.25	0.29	0.25	0.22	X	X	X	X	X	X
	3.00	0.28	0.23	0.21	X	X	X	X	X	X
	2.75	X	0.22	0.19	0.18	X	X	X	X	X
	2.50	X	0.20	0.18	0.16	X	X	X	X	X
	2.25	X	0.20	0.17	0.15	0.14	X	X	X	X
	2.00	X	0.19	0.16	0.14	0.13	0.12	X	X	X
	1.75	X	0.19	0.16	0.14	0.13	0.11	0.11	0.10	X
	1.50	X	0.19	0.16	0.14	0.12	0.11	0.10	0.10	X
	1.25	X	0.19	0.16	0.14	0.12	0.11	0.10	0.10	0.09
	1.00	X	0.19	0.16	0.14	0.12	0.11	0.10	0.09	0.09
	0.75	X	X	0.15	0.13	0.12	0.11	0.10	0.09	0.09
	0.50	X	X	0.15	0.13	0.11	0.10	0.10	0.09	0.08
	0.25	X	X	0.14	0.12	0.11	0.10	0.09	0.08	0.08
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.8: Tool life (considering spindle load):
Referring to **Table 4.4**, if N is equal to N_{opt} then, T_{opt} = 16.3 min (i.e. from optimum tool life with minimum cost equation)

otherwise, if N is equal to N_{break} then, $T_{sub-opt} = \frac{3.43\times10^{8}}{V_c^{3.02} f^{1.15} a_p^{0.26}}$ [min] (shaded in green)

a_p [mm]	4.00	36.4	47.7	X	X	X	X	X	X	X
	3.75	31.8	41.3	X	X	X	X	X	X	X
	3.50	27.6	35.4	X	X	X	X	X	X	X
	3.25	23.8	30.2	36.7	X	X	X	X	X	X
	3.00	20.3	25.4	30.7	X	X	X	X	X	X
	2.75	X	21.2	25.4	29.6	X	X	X	X	X
	2.50	X	17.4	20.7	23.9	X	X	X	X	X
	2.25	X	16.3	16.5	19.0	21.5	X	X	X	X
	2.00	X	16.3	16.3	16.3	16.6	18.5	X	X	X
	1.75	X	16.3	16.3	16.3	16.3	16.3	16.3	16.4	X
	1.50	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3	X
	1.25	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
	1.00	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
	0.75	X	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3
	0.50	X	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3
	0.25	X	X	16.3	16.3	16.3	16.3	16.3	16.3	16.3
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.9 : Total energy [kWs]:

$$E = \left(P_o 60t_1 + \left(P_o + k\dot{v}\right)60t_2 + P_o 60t_3\left(\frac{60t_2}{60T}\right) + y\left(\frac{60t_2}{60T}\right)\right) \div 1000$$

where : $P_0 = 3594$ W ; $t_1 = 2$ min; $t_3 = 2.9$ min ; $k = 4.3$ Ws/mm^3 and

$$y = \frac{5.3\ MJ}{4} = 1325 \times 10^3\ J$$

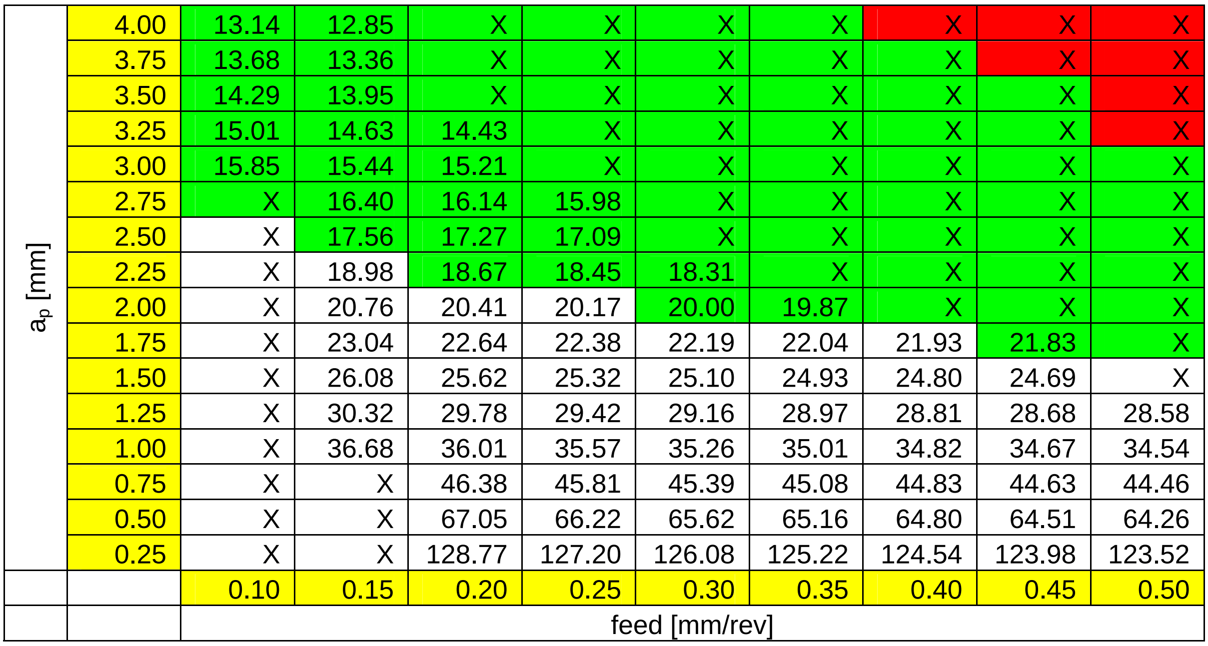
a_p [mm]	4.00	777	760	X	X	X	X	X	X	X
	3.75	760	742	X	X	X	X	X	X	X
	3.50	743	725	X	X	X	X	X	X	X
	3.25	726	708	698	X	X	X	X	X	X
	3.00	710	692	681	X	X	X	X	X	X
	2.75	X	675	665	658	X	X	X	X	X
	2.50	X	659	648	641	X	X	X	X	X
	2.25	X	643	632	625	620	X	X	X	X
	2.00	X	626	616	609	604	600	X	X	X
	1.75	X	610	599	592	587	583	580	578	X
	1.50	X	593	583	576	571	567	564	562	X
	1.25	X	576	566	559	554	550	547	545	543
	1.00	X	559	549	542	537	534	531	528	526
	0.75	X	X	531	525	520	517	514	511	509
	0.50	X	X	513	507	503	499	496	494	492
	0.25	X	X	494	488	484	481	478	476	474
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.10: Volume removed in single pass [mm^3] = $\pi \times l \times \left(r_i^2 - \left(r_i - a_p\right)^2\right)$

where : l = 49 mm , $r_i = 50$ mm

a_p [mm]	4.00	59112	59112	59112	59112	59112	59112	59112	59112	59112
	3.75	55562	55562	55562	55562	55562	55562	55562	55562	55562
	3.50	51993	51993	51993	51993	51993	51993	51993	51993	51993
	3.25	48404	48404	48404	48404	48404	48404	48404	48404	48404
	3.00	44796	44796	44796	44796	44796	44796	44796	44796	44796
	2.75	41169	41169	41169	41169	41169	41169	41169	41169	41169
	2.50	37522	37522	37522	37522	37522	37522	37522	37522	37522
	2.25	33857	33857	33857	33857	33857	33857	33857	33857	33857
	2.00	30172	30172	30172	30172	30172	30172	30172	30172	30172
	1.75	26468	26468	26468	26468	26468	26468	26468	26468	26468
	1.50	22744	22744	22744	22744	22744	22744	22744	22744	22744
	1.25	19002	19002	19002	19002	19002	19002	19002	19002	19002
	1.00	15240	15240	15240	15240	15240	15240	15240	15240	15240
	0.75	11459	11459	11459	11459	11459	11459	11459	11459	11459
	0.50	7658	7658	7658	7658	7658	7658	7658	7658	7658
	0.25	3839	3839	3839	3839	3839	3839	3839	3839	3839
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.11: Total energy per mm^3 [Ws/mm^3] = $\dfrac{E \times 1000}{volume\ removed}$



a_p [mm]	4.00	13.14	12.85	X	X	X	X	X	X	X
	3.75	13.68	13.36	X	X	X	X	X	X	X
	3.50	14.29	13.95	X	X	X	X	X	X	X
	3.25	15.01	14.63	14.43	X	X	X	X	X	X
	3.00	15.85	15.44	15.21	X	X	X	X	X	X
	2.75	X	16.40	16.14	15.98	X	X	X	X	X
	2.50	X	17.56	17.27	17.09	X	X	X	X	X
	2.25	X	18.98	18.67	18.45	18.31	X	X	X	X
	2.00	X	20.76	20.41	20.17	20.00	19.87	X	X	X
	1.75	X	23.04	22.64	22.38	22.19	22.04	21.93	21.83	X
	1.50	X	26.08	25.62	25.32	25.10	24.93	24.80	24.69	X
	1.25	X	30.32	29.78	29.42	29.16	28.97	28.81	28.68	28.58
	1.00	X	36.68	36.01	35.57	35.26	35.01	34.82	34.67	34.54
	0.75	X	X	46.38	45.81	45.39	45.08	44.83	44.63	44.46
	0.50	X	X	67.05	66.22	65.62	65.16	64.80	64.51	64.26
	0.25	X	X	128.77	127.20	126.08	125.22	124.54	123.98	123.52
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

4.3 Optimisation procedure: Direct search method based on minimum energy criterion for high machine capability.

Section 7.3 discussed in detail the optimisation procedure for machine that has process constraints. If machine which do not have these constrain (i.e. powerful machine), the same procedure can be applied. Consider a machine that has maximum spindle speed power of 18.6 kW and cutting EN8 steel using CNMG120408 insert, the optimum cutting parameters based on minimum energy criterion can be calculated as follow:

Table 4.12: Power , P [kW] = $\dfrac{F_v V_c}{60 \times 1000}$

a_p [mm]	4.00	11.1	12.9	14.4	15.6	16.7	17.7	18.6	19.4	20.1
	3.75	10.5	12.2	13.5	14.7	15.7	16.6	17.5	18.3	19.0
	3.50	9.8	11.4	12.7	13.8	14.8	15.6	16.4	17.2	17.8
	3.25	9.2	10.7	11.9	12.9	13.8	14.6	15.3	16.0	16.7
	3.00	8.5	9.9	11.0	12.0	12.8	13.6	14.3	14.9	15.5
	2.75	7.9	9.2	10.2	11.1	11.8	12.5	13.2	13.8	14.3
	2.50	7.2	8.4	9.3	10.2	10.9	11.5	12.1	12.6	13.1
	2.25	6.6	7.6	8.5	9.2	9.9	10.4	11.0	11.5	11.9
	2.00	5.9	6.9	7.6	8.3	8.9	9.4	9.8	10.3	10.7
	1.75	5.2	6.1	6.7	7.3	7.8	8.3	8.7	9.1	9.5
	1.50	4.5	5.3	5.9	6.4	6.8	7.2	7.6	7.9	8.2
	1.25	3.8	4.5	5.0	5.4	5.8	6.1	6.4	6.7	7.0
	1.00	3.1	3.6	4.0	4.4	4.7	5.0	5.2	5.5	5.7
	0.75	2.4	2.8	3.1	3.4	3.6	3.8	4.0	4.2	4.4
	0.50	1.7	1.9	2.1	2.3	2.5	2.6	2.8	2.9	3.0
	0.25	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.13: Cutting speed [m/min]; $V_c = \sqrt[3.02]{\frac{3.43\times10^8}{T_{opt} f^{1.15} a_p^{0.26}}}$; where T_{opt} = 18.3 min

a_p [mm]	4.00	546	468	420	385	360	339	323	296	273
	3.75	549	471	422	388	362	341	324	315	291
	3.50	553	474	424	390	364	343	326	312	312
	3.25	556	477	427	392	366	345	328	314	336
	3.00	560	480	430	395	369	348	330	316	303
	2.75	564	483	433	398	371	350	333	318	306
	2.50	569	487	437	401	374	353	336	321	308
	2.25	574	492	441	405	378	356	339	324	311
	2.00	580	497	445	409	382	360	342	327	314
	1.75	587	503	451	414	386	364	346	331	318
	1.50	594	509	457	419	391	369	351	335	322
	1.25	604	517	464	426	397	375	356	341	327
	1.00	616	527	473	434	405	382	363	347	333
	0.75	631	541	485	445	415	392	372	356	342
	0.50	653	560	502	461	430	406	385	368	354
	0.25	694	594	533	489	456	430	409	391	376
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.14: Spindle speed, N [RPM] = $\frac{V_c \times 1000}{\pi D_{avg}}$; where initial diameter, D = 100 mm

a_p [mm]	4.00	1811	1552	1391	1278	1192	1124	X	X	X
	3.75	1817	1557	1395	1282	1196	1127	X	X	X
	3.50	1823	1562	1400	1286	1200	1131	X	X	X
	3.25	X	1568	1405	1291	1204	1136	X	X	X
	3.00	X	1575	1411	1296	1209	1140	X	X	X
	2.75	X	1582	1418	1303	1215	1146	X	X	X
	2.50	X	1591	1426	1310	1222	1153	1095	X	X
	2.25	X	1602	1436	1319	1230	1160	1103	X	X
	2.00	X	1614	1447	1329	1240	1169	1111	X	X
	1.75	X	1629	1460	1341	1251	1179	1121	X	X
	1.50	X	1646	1475	1355	1264	1192	1133	1083	X
	1.25	X	1668	1495	1373	1281	1208	1148	1098	X
	1.00	X	1696	1520	1396	1303	1228	1167	1116	X
	0.75	X	1734	1554	1428	1332	1256	1194	1141	1096
	0.50	X	X	1605	1475	1376	1297	1233	1179	1132
	0.25	X	X	1700	1561	1457	1374	1305	1248	1199
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.15: Cutting time, t_2 [min] = $\frac{l}{fN}$; where l = 49 mm

a_p [mm]	4.00	0.27	0.21	0.18	0.15	0.14	0.12	X	X	X
	3.75	0.27	0.21	0.18	0.15	0.14	0.12	X	X	X
	3.50	0.27	0.21	0.18	0.15	0.14	0.12	X	X	X
	3.25	X	0.21	0.17	0.15	0.14	0.12	X	X	X
	3.00	X	0.21	0.17	0.15	0.14	0.12	X	X	X
	2.75	X	0.21	0.17	0.15	0.13	0.12	X	X	X
	2.50	X	0.21	0.17	0.15	0.13	0.12	0.11	X	X
	2.25	X	0.20	0.17	0.15	0.13	0.12	0.11	X	X
	2.00	X	0.20	0.17	0.15	0.13	0.12	0.11	X	X
	1.75	X	0.20	0.17	0.15	0.13	0.12	0.11	X	X
	1.50	X	0.20	0.17	0.14	0.13	0.12	0.11	0.10	X
	1.25	X	0.20	0.16	0.14	0.13	0.12	0.11	0.10	X
	1.00	X	0.19	0.16	0.14	0.13	0.11	0.10	0.10	X
	0.75	X	0.19	0.16	0.14	0.12	0.11	0.10	0.10	0.09
	0.50	X	X	0.15	0.13	0.12	0.11	0.10	0.09	0.09
	0.25	X	X	0.14	0.13	0.11	0.10	0.09	0.09	0.08
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.16: Material removal rate , [mm^3/s] = $\frac{V_c a_p f \times 1000}{60}$

a_p [mm]	4.00	3642	4681	5594	6423	7191	7911	X	X	X
	3.75	3433	4413	5274	6055	6779	7458	X	X	X
	3.50	3224	4144	4951	5685	6365	7002	X	X	X
	3.25	X	3872	4627	5313	5948	6543	X	X	X
	3.00	X	3599	4301	4938	5528	6082	X	X	X
	2.75	X	3324	3972	4561	5106	5617	X	X	X
	2.50	X	3047	3641	4180	4680	5148	5592	X	X
	2.25	X	2767	3306	3796	4250	4676	5079	X	X
	2.00	X	2485	2969	3409	3816	4199	4561	X	X
	1.75	X	2199	2628	3017	3378	3716	4037	X	X
	1.50	X	1910	2283	2621	2934	3228	3506	3771	X
	1.25	X	1617	1932	2219	2484	2733	2968	3193	X
	1.00	X	1319	1576	1809	2026	2228	2420	2604	X
	0.75	X	1014	1211	1391	1557	1713	1861	2002	2137
	0.50	X	X	836	960	1075	1183	1285	1382	1475
	0.25	X	X	444	510	571	628	682	733	783
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.17: T_{opt} [min] = $(3.02-1)\left(\frac{60P_0t_3+y}{P_0}\right)\div 60$; where P_0 = 3594 W ; t_3 = 2.9 min ; y = 1325000 J

a_p [mm]	4.00	18.3	18.3	18.3	18.3	18.3	18.3	X	X	X
	3.75	18.3	18.3	18.3	18.3	18.3	18.3	X	X	X
	3.50	18.3	18.3	18.3	18.3	18.3	18.3	X	X	X
	3.25	X	18.3	18.3	18.3	18.3	18.3	X	X	X
	3.00	X	18.3	18.3	18.3	18.3	18.3	X	X	X
	2.75	X	18.3	18.3	18.3	18.3	18.3	X	X	X
	2.50	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	2.25	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	2.00	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	1.75	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	1.50	X	18.3	18.3	18.3	18.3	18.3	18.3	X	X
	1.25	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	X
	1.00	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	X
	0.75	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.50	X	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.25	X	X	18.3	18.3	18.3	18.3	18.3	18.3	18.3
	0.00	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.18: Total energy , [Ws]

$$: E = \left(P_o 60t_1 + (P_o + k\dot{v})60t_2 + P_o 60t_3 \left(\frac{60t_2}{60T} \right) + y \left(\frac{60t_2}{60T} \right) \right) \div 1000$$

where : P_0 = 3594 W ; t_1= 2 min; t_3 = 2.9 min ; k = 4.3 Ws/mm^3 and

$$y = \frac{5.3\ MJ}{4} = 1325 \times 10^3\ J$$

a_p [mm]	4.00	773	753	742	735	730	726	X	X	X
	3.75	757	738	727	720	714	710	X	X	X
	3.50	742	722	711	704	699	695	X	X	X
	3.25	X	707	696	688	683	679	X	X	X
	3.00	X	691	680	673	667	663	X	X	X
	2.75	X	675	664	657	652	648	X	X	X
	2.50	X	659	648	641	636	632	629	X	X
	2.25	X	643	632	625	620	616	613	X	X
	2.00	X	626	616	609	603	600	597	X	X
	1.75	X	610	599	592	587	583	580	X	X
	1.50	X	593	583	576	571	567	564	561	X
	1.25	X	576	566	559	554	550	547	545	X
	1.00	X	559	549	542	537	534	531	528	X
	0.75	X	541	531	525	520	516	514	511	509
	0.50	X	X	513	507	502	499	496	494	492
	0.25	X	X	494	488	484	481	478	476	474
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Table 4.19: Energy per volume removed [Ws/mm^3] = $\frac{E}{\pi\left(r_i^2 - r_f^2\right)l}$

a_p [mm]	4.00	13.07	12.74	12.56	12.43	12.34	12.28	X	X	X
	3.75	13.63	13.28	13.08	12.95	12.85	12.78	X	X	X
	3.50	14.26	13.89	13.68	13.54	13.44	13.36	X	X	X
	3.25	X	14.60	14.37	14.22	14.11	14.03	X	X	X
	3.00	X	15.42	15.18	15.02	14.90	14.81	X	X	X
	2.75	X	16.39	16.13	15.95	15.83	15.73	X	X	X
	2.50	X	17.56	17.27	17.08	16.94	16.84	16.75	X	X
	2.25	X	18.98	18.66	18.45	18.30	18.19	18.10	X	X
	2.00	X	20.76	20.40	20.17	20.00	19.87	19.77	X	X
	1.75	X	23.04	22.64	22.38	22.19	22.04	21.93	X	X
	1.50	X	26.08	25.62	25.31	25.09	24.93	24.79	24.69	X
	1.25	X	30.32	29.78	29.42	29.16	28.96	28.81	28.68	X
	1.00	X	36.67	36.01	35.57	35.25	35.01	34.82	34.66	X
	0.75	X	47.24	46.37	45.80	45.39	45.07	44.83	44.62	44.45
	0.50	X	X	67.04	66.21	65.61	65.16	64.80	64.50	64.26
	0.25	X	X	128.75	127.19	126.06	125.21	124.53	123.97	123.51
		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
		feed [mm/rev]								

Referring to **Table 4.19**, the minimum energy per volume removed is 12.28 Ws/mm^3. The cutting parameters for this criterion is V_c, f, a_p equal to 339 m/min , 0.35 mm/rev and 4 mm respectively.