The International JOURNAL of ENVIRONMENTAL, CULTURAL, ECONOMIC & SOCIAL SUSTAINABILITY

Volume 5, Number 4

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THE INTERNATIONAL JOURNAL OF ENVIRONMENTAL, CULTURAL, ECONOMIC AND SOCIAL SUSTAINABILITY
http://www.Sustainability-Journal.com

First published in 2009 in Melbourne, Australia by Common Ground Publishing Pty Ltd
www.CommonGroundPublishing.com.

ISSN: 1832-2077
Publisher Site: http://www.Sustainability-Journal.com

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Typeset in Common Ground Markup Language using CGCreator multichannel typesetting system
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An Experimental Approach to Show that High Cutting Speeds Can Reduce the CO2 Emissions during Machining

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Abstract: It is essential that the CO2 emissions produced by metal cutting manufacturing are reduced due to global warming. Metal cutting is an essential aspect of modern manufacturing, and accounts for approximately 70 percent of world metal manufacturing. Reductions of CO2 can be shown to be possible when machining at high cutting speed, when using tungsten coated tool tips. The addition of air-cooled with the addition of a small amount of vegetable oil, also allows high cutting speeds to be used. In addition to the cutting speed the tool paths and depth of cut are examined to determine their effect in reducing the CO2 emissions. A machining conditions model, reducing the environmental burden for machining operation is proposed based on this research. Two Numerical Control (NC) programs that produce a simple shape are evaluated, to show the feasibility of the proposed operating conditions model.

Keywords: Cutting Speed, Air-Cooling, CO2 Emissions, Environmental Burden

Introduction

MANUFACTURING NOTORIOUSLY CREATES pollution. As more international and government environmental protection legislation is introduced, manufacturing companies will be compelled to reduce their impact on the environment and prove that appropriate waste disposal measures are in place. This will be essential to allow companies to operate. In addition to the obvious waste that is produced during manufacturing is the amount of green house gas produced, particularly CO_2, from the electrical power used by the machine tool. Dry machining is obviously more ecologically desirable for metal cutting as there are no environmental issues or disposal costs for the coolant. Researchers have found that air-cooling prolongs tool life when dry machining and it is now becoming more common in the manufacturing industry. However, there is a cost to the environment that researchers commonly neglect, this being the amount of energy involved in providing the cooling effect. In this research the environmental cost of providing the cold air to the tool tip will be contrasted against that of traditional wet coolant.

The need for optimum machining parameters has always been of great concern to the manufacturing industry, where the economy of the machining process plays the key role in the competitiveness of the product. This largely depends on selecting the best machining parameters for the machine. However, manufacturers now have the additional challenge of

The International Journal of Environmental, Cultural, Economic and Social Sustainability
Volume 5, Number 4, 2009, http://www.Sustainability-Journal.com, ISSN 1832-2077

being environmentally friendly in their production, while still being cost effective. This requires that the best machining practices are used in an effort to reduce the total amount of green house gas produced during machining. In practice, many cutting parameters need to be considered, such as cutting force, feed rate, depth of cut, tool path, cutting power, surface finish and tool life. The machining parameters in accordance to the rules for optimisation were selected as used by J. Wang [1], the objective being to minimise the production cost with least effect on the environment.

Lian-yi Chen *et. al.* [2] developed a prediction system for the environmental burden of machine tool operation based on life cycle analysis (LCA). This model enables the evaluation of the equivalent CO_2 emission during machining. The CO_2 emission is calculated from the electrical consumption of the machine tool components, cutting tool status, coolant used, lubricant oil quantity and metal chip quantity. Two programs are used to compare cutting at different speeds and widths of cut. It was shown that when coolant is used the environmental burden increased due to the additional power drawn by the coolant pump or compressor if air is being used. The Hirohisa model [3] proved to be successful in predicting the environmental burden for various machining operations, allowing a comparison of the two tool paths and different coolant used. In this current work all inputs were calculated in terms of carbon dioxide emission to allow the evaluation and comparison of the total impact on the environment. Lohdia [4] compared the environmental performance of conventional wet machining using uncoated carbide tools and dry machining.

An important factor in any machining operation is the economics, and this research proves that economical dry milling with vortex air cooling is superior to machining with cutting fluid. Additionally, the disposal of scrap chips from dry milling is more profitable and environmentally friendly than chips contaminated with coolant from wet cutting. In this paper the use of cooled air and environmental cutting conditions are shown to reduce the effect of producing green house gas. The use of environmental cutting conditions will indeed be essential in the future to offset companies carbon costs, as governments throughout the world introduce legislation to reduce green house gases.

Nomenclature

A	**chip cross-sectional area**	**mm** ^{2}
ACE	number of actual cutting edges	
ATC	electrical consumption of automatic tool change	kWh
a	axial depth of cut	mm
a_{rad}	radial depth of cut	mm
C_c	environmental carbon cost	\$/kg
C_e	environmental burden of coolant	\$/kg
C_u	unit cost	\$

C_{uv}	environmental unit cost	$/min
c_{mat}	cost of material per part	$
c_1, c_0	labour cost, overhead cost	$/min
CD_e	environmental burden of coolant disposal	kg-CO_2/l
C_{Mc}	cooling burden on air	
CP_e	environmental burden of coolant production	kg-CO_2/l
CS	cutting fluid discharge	l/s
CUT	coolant usage time	s
E_e	electrical consumption of machine tool	kWh
FC	fanuc controller	kWh
F_x	tooth X direction instantaneous cutting force	N
F_y	tooth Y direction instantaneous cutting force	N
F_z	tooth Z direction instantaneous cutting force	N
F_{ra}	average radial force per tooth	N
F_{ta}	average tangential force per tooth	N
F_{za}	average force for the number of teeth	N
f	feed rate	mm/tooth
f_{xt}	X direction average cutting force on teeth	N
f_{yt}	Y direction average cutting force on teeth	N
f_{zt}	Z direction average cutting force on teeth	N
Ψ	instantaneous cutting angle of the cutter	
g	exponent of slenderness ratio	
K	machining factor for milling different materials	

K_i (i=1-3)	coefficients carrying constant values	
k	CO_2 emission intensity of electricity	$kg\text{-}CO_2/kWh$
MRR	material removal rate	cm^3/min
MT	machine time	s
m	number of operations to produce part	
n	tool life exponent	
P_{mil}	cutting power	kW
P_r	total profit rate	$/min
r	a machine exponent for different materials	
S	peripheral speed of cutter	sfm
S_p	sale price of part	$
SME	electrical consumption of servo motors	kWh
SPE	electrical consumption of spindle motor	kWh
T	average number of teeth in contact with the material	
T_e	cutting tool	
T_u	time for unit part	min
t_s, t_{tci}	set-up time, tool change time	min
TD_e	emission intensity of cutting tool disposal	$kg\text{-}CO_2/kg$
TL	tool life	s
TP_e	emission intensity of cutting tool production	$kg\text{-}CO_2/kg$
TW	tool weight	kg
V	cutting speed	m/min
w	exponent of chip cross-section area	
U	specific cutting energy	J/m^3
Z_c	number of teeth cutting simultaneously	

Implications of Tool Cooling

Previous research on the viability of air-cooling was restricted to qualitative experimental results [5] in order to determine the feasibility of dry machining with air-cooling. Li [6] conducted a study to develop a methodology to analyse the performance in metal turning under near-dry conditions compared with flooded and dry cutting. It was found that under wet-cooling cutting conditions the cutting forces, cutting temperature and power consumption were reduced by as much as 40 percent when compared with the values obtained when dry cutting. A comparison between dry and wet machining has shown that higher cutting temperatures and forces exist during machining. Dhar *et. al.* [7] investigated the influence of dry lubrication and minimum quality lubrication on cutting temperature, chip formation and dimensional accuracy when turning AISI 1040 steel. The depth of cut was maintained at a constant 1.0 mm. Cutting velocity and feed rate were varied from 64 – 130 m/min and 0.1 – 0.2 mm/rev respectively. From these machining tests it was concluded that the cutting performance of Minimum Quantity Liquid (MQL) machining is better than that of conventional machining with flood cutting fluid, and MQL provides the benefits mainly by reducing cutting temperature.

There has been a substantial amount of research carried out showing how MQL is an extremely useful method of prolonging tool life. However, there has not been the same body of evidence to show that benefits can be obtained by applying MQL - for example to end milling application. Some of the questions arising are:

- are the cutting forces reduced?
- is there less power being used?
- has the tool lasted as long?

These are only some of the unanswered questions. Conventional wisdom for milling states that flooding with a continuous, copious flow is recommended, and milling dry is preferred to milling with minimum fluid. Mist spray application of the cutting fluid is sometimes seen as beneficial, which may be considered to be close to the MQL application. Also, conventional wisdom implies that the use of cutting fluid has little effect on force and power at high cutting speeds. Although a good cutting fluid reduces power consumption at intermediate to low cutting speeds.

This research will consider two cooling strategies, the first being traditional flood coolant using water-miscible cutting fluid, and the second uses cooled air directed at the tool tip. It is anticipated that the addition of a small amount of cutting fluid (MQL) in conjunction with cold air applied to the tool tip will decrease the forces, power and temperature close to that of wet machining.

Each cooling method will have its environmental contribution examined, as well as examining the effectiveness of the machining process. As the liquid discharge is the main factor when considering the liquid coolant, then the environmental burden cost can be obtained from Equation (1), and the emission intensities can be obtained from Table 1.

$$C_e = \frac{CUTxCS}{3600x1000}(CP_e + CD_e) \qquad (1)$$

For air-cooling the main factor to consider is the volume of air being passed over the tool - tip. Therefore the electrical energy used for cooling can be calculated from Equation (2).

$$C_e = CUTxCS(CP_e + C_{Mc}) \qquad (2)$$

The CO_2 emission intensities used to calculate the environmental burden during machining operations are cited from environmental reports, technical reports, homepages and industrial tables. Examples of these values are given in Table 1 and it should be noted that the CO_2 value for producing electricity is the TEPCO 2010 emission voluntary target [8]. For analysis of the coolant, the dilution factor of the amount of water required must be included. This data can be obtained from a user information guide of the machine tool coolant used.

Table 1: Typical Values of CO_2 Emission Intensities

CO_2 Emission Intensities	
Electricity kg-CO_2/kWh	0.304
Cutting fluid production kg-CO_2/l	0.9776
Cutting fluid disposal kg-CO_2/l	0.0029
Dilution of water kg-CO_2/l	0.189
Tool tip production kg-CO_2/kg	34
Tool tip disposal kg-CO_2/kg	0.0184
Other Parameters Relating to Evaluation Factors	
Initial cutting fluid quantity (l)	
Additional supplements of cutting fluid (l)	
Initial dilution fluid quantity (l)	
Additional supplement of dilution fluid (l)	
Mean interval between replacement of coolant	
Tool life (s)	
Number of tip changes	
Cutting tool density (tip) g/cm^3	
Workpiece density g/cm^3	
Coolant tank capacity (l)	

Equipment

The machine tool path tests were carried out on a 30 Leadwell machining centre, and the tool forces were measured by using a Kistler type 9257 dynamometer secured to the machine bed with the data being recorded with Dynoware Type 2825A-02 software. The workpiece was made from AISI 1040 steel bar having a 50 mm square section, with a test length of 100 mm. A 16 mm diameter end mill having two tungsten tip inserts consisting of TiN TiCN

A1203 TiN was used to machine the workpiece. The cold air was provided by a vortex tube supplied with compressed air at a pressure of 500 kN/m^2. The manufacturer's software, Dynoware, reads the end mill cutting forces F_x (red), F_y (blue) and F_z (pink) forces in real time, and displays force-time graphs for each of the axes as shown in Figure 1.

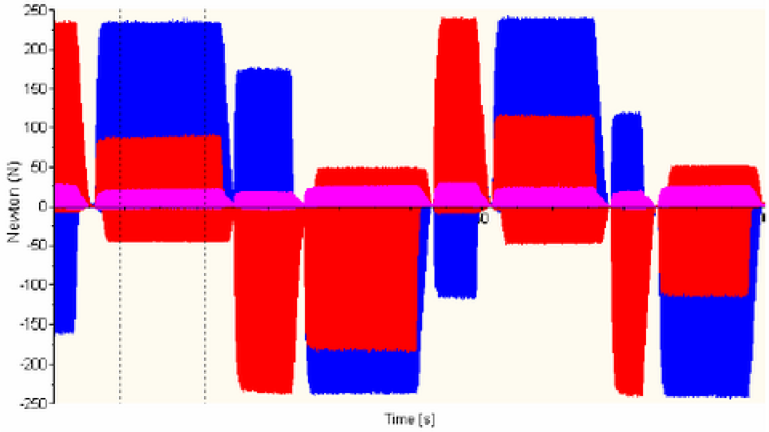


Figure 1: 2288 rpm end Mill Cutting Force Test

Cutting Energy

The total energy per cut is defined as the cutting power multiplied by the cutting time. This parameter is useful as it determines the total amount of energy required to remove a certain amount of material, allowing the electrical cost to be calculated.

$$U = \frac{P_{mil}}{MRR} \qquad (3)$$

The specific cutting energy is the energy required to deform a chip from a volume of material during cutting, and can be calculated by Equation (3). The specific cutting energy can be used to calculate the total cost of the energy required to remove a certain amount of material from the workpiece. The cost is directly proportional to the specific cutting energy. Operating parameters that influence milling are so numerous that it makes it extremely difficult to predict results reliably. These variables include the size and shape of the workpiece, the material from which it is made, the kind of milling operation, physical properties and conditions, and these are only a few examples of the parameters that have a profound effect on the milling operation. Even with all these parameters that can effect the milling operation it is still worthwhile to establish at least initial parameters for the milling operation. These parameters include power and force requirements, cutting speed and feed rate, and depth of cut used. Two power requirements exist for any milling operation: the first is the power to rotate the tool spindle when cutting, and the second lesser value is the power required to feed the workpiece into the cutter. Equation (4) may be used to calculate the power required at the machine spindle for milling [9].

$$SME = K \times S \times T[0.0041(1000A)^{r}] \qquad (4)$$

A more accurate method of determining the cutting power is to have the power monitored on the machine when cutting.

Environmental Parameters Model

End-milling is a cutting process that removes material by feeding the workpiece past a rotating cutter, as shown in Figure 2, and this can generate a flat surface with a shoulder. Together the depths of cut, feed rate, and cutting speed have the greatest effect on the performance of the machining operation. Normally the depth of cut is predetermined by the workpiece geometry and machining sequence. To keep costs as low as possible it is recommended, if practical, to machine the workpiece in one pass, keeping the machining time to a minimum. Therefore the challenge of determining the machining parameters is reduced to selecting the proper cutting speed and feed rate. Tolouei-Rad *et al.* [10] was one of the first researchers to investigate the parameters that affect the efficiency of the milling operations which are now considered. The unit cost has traditionally been the sum of four cost terms: raw materials, set-up costs, machining costs and tool change costs as calculated from Equation (8). However, this research has shown that there is now a fifth item that needs to be included: namely the environmental factor.

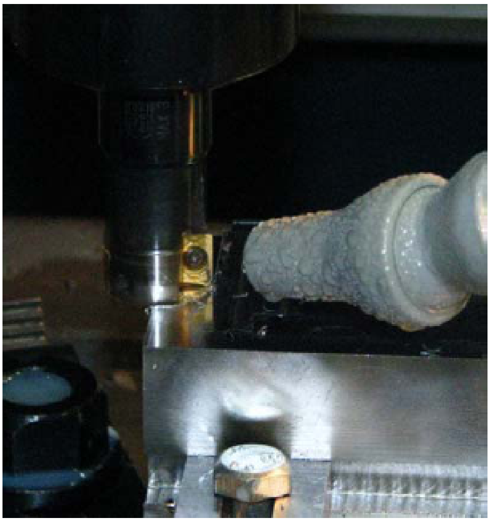


Figure 2: End-mill being used to Create a Flat Surface

The environmental cost per unit can be represented by:

C_c = Carbon added to the environment

The cost of cutting has traditionally been measured in terms of economic factors only: a cost for the environmental impact is now included. The economics of cutting operations have been analysed countless times as it is believed to be a very important aspect of viable machining operations. The environmental burden is measured in terms of CO_2 generation, which is a good indicator of impact on global warming. The machining process includes the cost to make the tool tips as well as the power required to machine the workpiece. Cutting tool tips are costed from the aspect of tool life. Therefore, tool life is compared with machining time to calculate the environmental burden for the tool tip as given by Equation (5).

$$T_e = \frac{MT}{TL \times ACE}(TP_e + TD_e)TW \qquad (5)$$

The major environmental burden during machining can be contributed to the power needed for the operation of the machine tool: this can be calculated by Equation (6). Servo motors and spindle motors can vary dynamically during the operation of the cutting process, making it necessary to estimate the consumption of electrical power for these motors [3]. Other machine tools may have additional auxiliary equipment which need to be included in the value of machine tool power consumption *E e* .

$$E_e = k(SME + SPE + ATC + FC) \qquad (6)$$

The above Equation (6) only considered the electrical consumption of peripheral devices actually used by the Leadwell machining centre. Appendix A gives the expanded equations used to calculate the terms in Equation (6). The total cost of the electrical consumption producing the environmental burden for the machining process can be calculated from Equation (7).

$$C_c = C_e + T_e + E_e \qquad (7)$$

The traditional unit cost can be calculated by [10]:

$$C_u = c_{mat} + (c_1 + c_0)t_s + \sum_{i=1}^{m}(c_1 + c_0)K_{1i}V_i^{-1}f_i^{-1} + \sum_{i=1}^{m}c_{ti}K_{3i}V_i^{1/n-1}f_i^{[(u+g)/n]-1} + \sum_{i=1}^{m}(c_1 + c_0)t_{tci} \qquad (8)$$

The unit time to produce a part by a multi-tool milling operation can be represented by equation (9) as shown by Hirohisa Narita *et. al.* [3]:

$$T_u = t_s + \sum_{i=1}^{m} K_{1i}V_i^{-1}f_i^{-1} + \sum_{i=1}^{m} t_{tci} \qquad (9)$$

The environmental unit cost can be represented by equation (10).

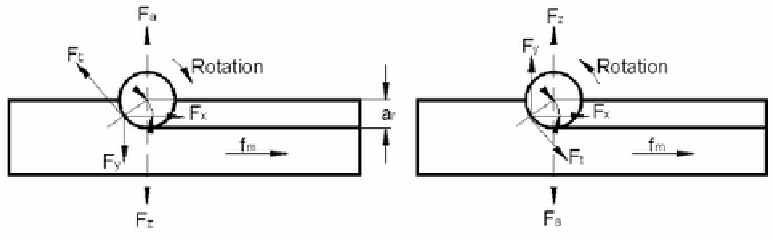
$$C_{uv} = C_u + C_c \qquad (10)$$

It must be noted the cutting speed *V* and feed rate *f* used in Equations (8) and (9) to calculate the unit cost *C u*, and unit time *T u,* must be the appropriate environmental cutting speed and feed rate. The goal of metal cutting operations is to maximise the total profit rate per unit, taking into account the environmental burden costs that may be imposed on the industry. The environmental total profit rate can be represented by:

$$P_r = \frac{S_p - C_{uv}}{T_u} \qquad (11)$$

End Mill Case Study

End milling is one of the most widely used metal removal operations for generating surfaces on the vertical numerically controlled milling machine. There are many choices of machining parameters to consider in order to achieve the most effective machining of the workpiece. Typically the tool forces are a major factor in the cutting of the workpiece, and vary over the cut of the tooth, as shown by Figure 1. The cutting force components acting on one tooth are shown in Figure 3. The maximum cutting forces recoded during machining tests are given in Table 2. As previously discussed, the machining cost to the environment needs to be included. To that end the most environmental tool path should also be used in the challenge to obtain the most environmentally machined part.



Up milling Down milling

Figure 3: Cutting Forces Acting on One Tooth of an end Mill

Figure 3 shows the instantaneous cutting force on an individual tooth per cut in the X, Y and Z direction at the instantaneous tooth cutter angle *ψ,* with Z_c being the number of simultaneously cutting teeth. The helix angle can be neglected if the depth of cut is kept small during the tests. Since the forces are shown to vary over the cut it is reasonable to use the average cutting forces on the tooth, with the end mill total cutting force taking account of all the teeth cutting the workpiece as shown by M. Alauddin *et.al.* [11].

Table 2: Recorded Tool Forces, and Cutting Parameters

Cut No.	**Cutting Speed (m/min)**	**Up Milling**	**Down Milling**	**Half Immersion**	**Full Immersion**	**Type of cooling**	**Force F_x (N)**	**Force F_y (N)**	**Force F_z (N)**
1	105	Y	-	Y	-	wet	206	156	29
2	105	-	Y	Y	-	wet	119	337	43
3	105	Y	-	-	Y	wet	308	347	39
4	105	Y	-	Y	-	air	196	148	10
5	105	Y	-	-	Y	air	278	314	32
6	115	Y	-	Y	-	wet	134	326	47
7	115	-	Y	Y	-	wet	239	91	22
8	115	Y	-	-	Y	wet	244	262	33
9	115	Y	-	Y	-	air	229	82	23
10	115	Y	-	-	Y	air	228	233	26
11	125	Y	-	Y	-	wet	128	316	48
12	125	-	Y	Y	-	wet	272	120	29
13	125	Y	-	-	Y	wet	249	261	59
14	125	Y	-	-	Y	air	209	215	31

Constant machining parameters used in Tabe 2 are - 16 mm end mill having two tool tips, at constant feed rate of 305 mm/min, and 1 mm depth of cut. The selection of spindle speed and feed rate were determined from data suggested in Tool and Manufacturing Engineering Handbook chapter 10.

$$f_{xt} = \sum_{i=1}^{Z_c} \delta(i) \times F_{xi}(\varphi_i) \qquad (12)$$

$$f_{yt} = \sum_{i=1}^{Z_c} \delta(i) \times F_{yi}(\varphi_i) \qquad (13)$$

$$f_{zt} = \sum_{i=1}^{Z_c} \delta(i) \times F_{zi}(\varphi_i) \qquad (14)$$

$$\text{where } \delta(i) = 1 \qquad if \varphi_1 \le \varphi \le \varphi_2$$

$$\delta(i) = 0 \qquad \text{otherwise}$$

The entry angle of the tooth is given by ψ_1 with the exit angle of the tooth being ψ_2 for the Z_c number of teeth of the end mill. There is no need to round off to the nearest whole number of teeth cutting instantaneous, and can be calculated from equation (15) as used by M. Alauddin *et.al.* [11]:

$$Z_c = \frac{Z \times \varphi_s}{360} \qquad (15)$$

Therefore for an evenly pitched end mill the average cutting forces per tooth can be calculated from:

$$F_{xa} = \frac{f_{xt}}{Z_c} \qquad (16)$$

$$F_{ya} = \frac{f_{yt}}{Z_c} \qquad (17)$$

$$F_{za} = \frac{f_{zt}}{Z_c} \qquad (18)$$

For multi-tooth milling the average tangential force per tooth and average radial force per tooth can be calculated from:

$$F_{ta} = F_t \times Z_c \qquad (19)$$

$$F_{ra} = F_r \times Z_c \qquad (20)$$

The total cutting force *F c* applied to the cutting tool in a milling operation is a result of the tangential, feed and radial forces:

$$F_c = (F_{t^2} + F_{y^2} + F_{r^2})^{0.5} \qquad (21)$$

Two different machining paths are used to identify the most effective metal removal by the end mill by measuring the forces. Using the same tool paths the workpiece is machined with the spindle being reversed demonstrating the effect of up milling and down milling on the cutting action. Figure 4a and 4b show half immersion and full immersion by the end mill. To reduce the number of cutting tests carried out only the cutting speed parameter will be changed since this normally has the most effect on the performance on the end mills tool life. Half immersion to full immersion is also examined as this has an effect on the power requirements of the milling machine. In addition the tool tip cooling method was also examined with respect to effective power requirements. The tool forces measured over the range of cutting conditions are given in Table 2 showing which condition produced the smallest cutting force indicating a reduction of cutting power. There was no significant difference in cutting forces between wet and air machining indicating that the energy difference could only be contributed to the coolant process.

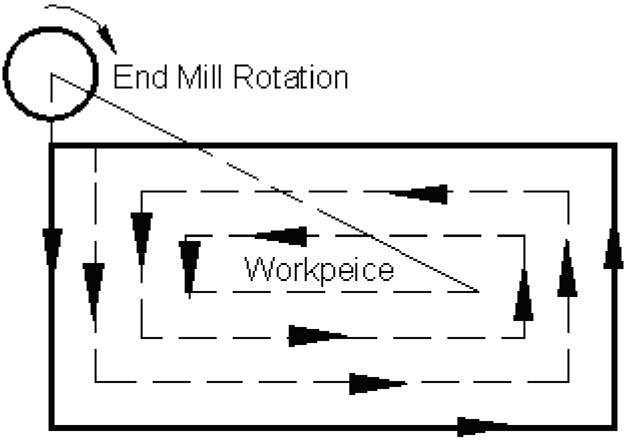


Figure 4a: Tool Path for Half Immersion

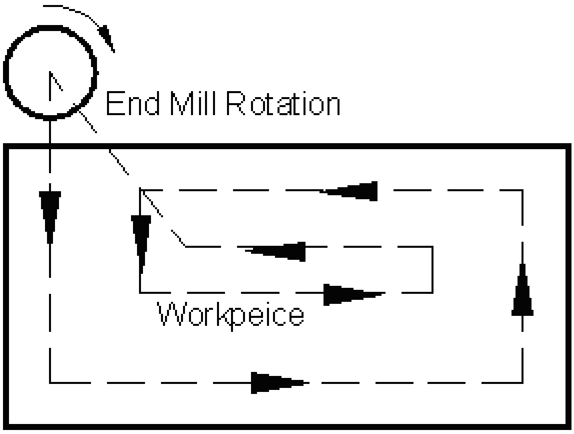


Figure 4b: Tool Path for Full Immersion of Cutter

Conclusions

Overall, dry machining is the more environmentally friendly machining method since there is no cooling of the tool cost. However, tool life is reduced making it necessary to use the most environmental method of cooling the tool during machining. Li [6] concluded that wet cutting generated the lowest cutting forces and temperatures. However, using the vortex tube air cooling the cutting forces were found to be less than that recorded for wet cutting which would result in less power being used. For finish turning Diniz [12] shows that it is possible to modify cutting parameter in dry cutting to obtain similar results to wet cutting, and similarly it can be concluded from the tests that modifying the cutting parameters with cold air can obtain similar results to wet cutting. The comprehensive study undertaken by Li [6] shows that is it possible to predict turning cutting forces and temperatures from theoretical analysis, with additional research in milling these tests have shown this to be possible for milling. Conventional wisdom for milling states that flooding with a continuous, copious flow is recommended, and milling dry is preferred to milling with minimum fluid [13]. Air cooling can only assist this conventional wisdom for milling as fundamentally it is a dry machining condition. Up-milling (conventional milling) is shown to have lower forces involved than down-milling, making it good machining practice for numerical control (NC) machines to cut metal by conventional milling to save power during machining. From earlier research carried out using a single point tool on a lathe it was found that the higher the cutting speed the more environmental efficient the machining process is. The results from the end mill tests also verify cutting at high speeds reduced the cutting forces. Therefore, for the best environmental machining conditions computer numerical control (CNC) part programs should use the highest cutting speed possible with cold air cooling when milling a flat surface. Equation (10) can be used to calculate the environmental unit cost for a machined part, the difficulty with this is the variety of machine tools in operation making it necessary for the equation to be customised for each machine. The challenges of reducing green house gas for machining companies will be an ongoing compromise between unit cost of the part and the environmental cost for the part.

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Appendix A

The electrical consumption of the spindle motor and servo motors can be calculated by giving an appropriate weighting factor for the machine table weight, friction coefficient of the ball screw, cutting force and torque. The electrical consumption of peripheral equipment such as automatic tool changer, machine controller and coolant pump are established from their running times. The load torques of servo motors are calculated from equation (22):

$$T_{L1} = T_U + T_M \qquad (22)$$

T_{L1} : servo motor torque (Nm)
T_u : axis friction torque (Nm) (is the torque due to rubber sealing and needs to be found experimentally)
T_m: ball screw torque (Nm) and can be calculated from Equation (23).

$$T_M = \frac{(\mu M \mp f)l\cos\theta \pm (M - f)l\sin\theta}{2\pi\eta} \qquad (23)$$

μ : friction coefficient of slides way
η : transmissibility of ball screw system
l: ball screw lead (m)
M : weight of workpiece and table (N)
f: cutting force in axis (N)
θ: gradient angle from horizontal plane (rad)
A typical two-stage, two-cylinder air compressor can provide 1050 SLPM at a maximum pressure of 1.2 KPa with a Motor load of 7.5 kW. From equation (24) the cost of compressed air can be calculated.

$$Air\_\cos t = \frac{(ML \times OH \times C \times T \times FL)}{ME} \qquad (24)$$

Where:

ML = Motor full load in kW
OH = Number of operating hours
C = Cost per kWh (0.16kWh)
T = % of time running at this operating level
FL = % of full-load at this operating level
ME = Motor efficiency at this level

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Mr Brian Boswell received his B.Sc.Eng degree with Honours in Mechanical Engineering from the University of Strathclyde, in Scotland and has just submitted his PhD in Manufacturing Engineering with respect to finding an effective environmental method of cooling tool tips during machining at Curtin University of Technology. Prior to lecturing and researching at Curtin University he has worked as a Design engineer and later as Head of School at James Watt College of Higher Education in Greenock. His current research interests are investigating metal cutting tools and modern manufacturing techniques. To date, he has published one referred journal papers and three international conference papers. He is a graduate member of the Institution of Mechanical Engineers.

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