Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 26 (2015) 391 – 396

www.elsevier.com/locate/procedia

12th Global Conference on Sustainable Manufacturing

Advancing Environmentally Conscious Machining

Yogie Rinaldy Ginting[a], Brian Boswell[a], Wahidul Biswas[b]* and Nazrul Islam[a]

[a]*Department of Mechanical Engineering, Curtin University, Australia*
[b]*Sustainable Engineering Group, Curtin University, Australia*

* Corresponding author. Tel.: +61-08-9266-4520; fax: +61-08-9266-4811. *E-mail address:* w.biswas@curtin.edu.au

---

Abstract

Modern machine tools now consume far more energy than their predecessors, a contradiction in terms since manufacturing organisations expect machining to be carried out in the most sustainable and cost effective way. The goal for environmentally conscious manufacturing is to consume minimum energy and produce minimum atmospheric emissions, liquid and solid waste. Dry machining is obviously the most ecological form of metal cutting as there are no environmental issues for coolant use or disposal to consider. This research was implemented in an industrial situation in a local small to medium sized enterprise (SME) in Western Australia to determine the technical, economic and environmental benefits of the replacement of traditional flood cooling with Minimum Quantity Liquid (MQL). The use of MQL and air reduced the greenhouse gas emissions and eco-toxicity associated with the disposal of the contaminated liquid. It was found that this alternative cooling method increased the performance of the metal cutting operation.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: Minimum Quantity Liquid; waste, sustainability; LCA, Taguch method

---

1. Introduction

Machining notoriously creates waste, typically large volumes of coolant and contaminated metal chips. New environmental laws and costs are compelling companies to reduce their impact on the environment, necessitating putting in place appropriate waste disposal measures. A local manufacturing company in Perth has been experiencing liquid contamination of the work place ground due to liquid coolant escaping from the waste chip storage. The obvious answer to this environmental contamination of the ground is to remove the polluting source i.e. the liquid coolant. Dry machining is obviously the most ecological form of metal cutting as there are no environmental issues for coolant use or disposal to consider. However, in practice just removing the coolant could have ramifications on the cutting parameters. An examination to determine the effects of changing to a MQL cooling method, such as cutting force, feed rate, depth of cut, cutting power, surface finish and tool life [1] was organized. For this reason a machining test was carried out by dry cutting [2] and by flood cutting to establish the two extreme conditions. Machining parameters when using MQL need to be optimal in order to obtain high quality products with the lowest environmental impact, at the minimum cost. The challenge that industry faces is how to find the optimum combination of cutting conditions in order to sustainably produce parts at a reasonable cost to manufacture. To help achieve this goal the use of the Taguchi Method was used to establish the optimum cutting parameters to machine 4043 Steel bolts. This method allows the effect of many different machining parameters to be robustly tested on their machining performance. A two level L8 orthogonal array was selected where 0 and 1 represent the different levels of the two control parameters, cutting speed, and depth of cut as shown in Table 1. This analysis of the machining process identifies the best reduction of waste achieved from the metal cutting process.

Organizations need to embrace the sustainable philosophy to reduce their carbon footprint, allowing them to meet ever increasing government registration. The total CO_2 produced by machining consists of electrical power used by the machine tool [3], metal chips, tool tips and coolant costs if used. The technique used for assessing the environmental aspect and potential impact associated with machining is performed in accordance with the Environmental Management [4] Life

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
doi:10.1016/j.procir.2014.07.087

Cycle Assessment Principles and Framework ISO 14040-44 standard [5]. This analysis of the machining process identified that the best reduction in greenhouse gasses would be achieved from refining the metal cutting aspect of the process.

2. Method and materials

2.1. Taguchi Method

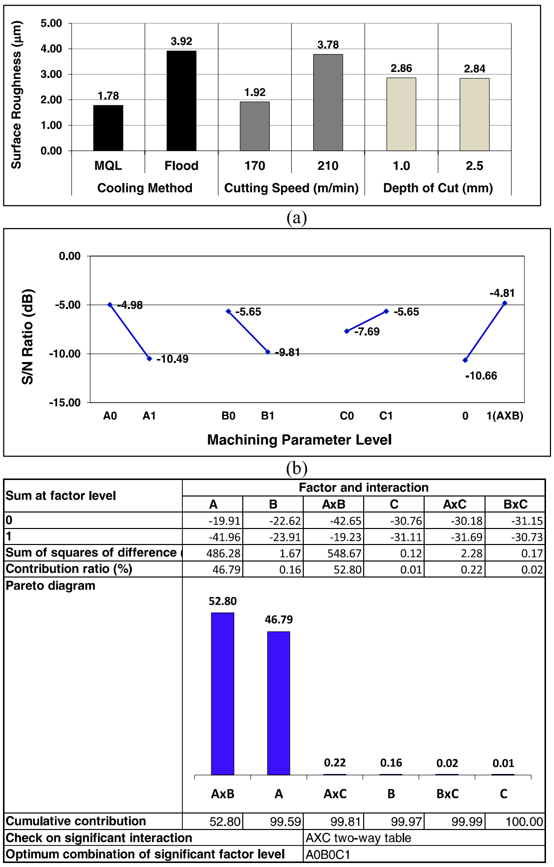
Analysis of the machining tests provided the deviation and nominal values of the two quality measurements used to determine the optimum sustainable machining parameters (tool life and surface roughness). Further analysis implemented the use of signal-to-noise ratios to differentiate the mean value of the experimental and nominal data of these quality measurements. A viable measure of detectability of a flaw is its signal-to-noise ratio (S/N). Signal-to-noise ratio measures how the signal from the defect compares to other background noise. To help analyse the contribution of each variable and their interactions in terms of quality the Pareto ANOVA analysis is implemented. The Pareto ANOVA analysis [6] was completed for each of the quality measures for tool life and surface roughness. The Pareto ANOVA analysis identified which control parameter affected the quality of the machined bolt (Figure 1). By using the Pareto principle only 20% of the total machining configuration is required to generate 80% of the benefit of completing all machining test configurations. This method separates the total variation of the S/N ratios (Figure 2). Each of the measured quality characteristics - tool life, and surface roughness, has its own S/N values for each of the 8 different tests as shown in Table 2. In order to obtain accurate results the S/N values are derived from an average value of 3 readings for each of the quality measurements.

Table 1 Machining parameters

Input parameter	Symbol	Levels	
		Level 0	Level 1
Cooling method	A	MQL (2.4 mL/min, 50 Psi)	Flood (12.3L/min)
Cutting speed (m/min)	B	170	210
Depth of Cut (mm)	C	1	2.5
Feedrate (mm/rev)		0.25	0.25

Table 2 Experimental Design with 8 Runs

No	Cooling method	Cutting speed (m/min)	Depth of Cut (mm)	Machine Power (kW)	R_a1 (μm)	R_a2 (μm)	R_a3 (μm)
1	A0	B0	C0	4.43	1.86	1.88	2.04
2	A0	B0	C1	7.44	2.00	2.00	1.95
3	A0	B1	C0	5.27	1.54	1.55	1.55
4	A0	B1	C1	9.56	1.66	1.67	1.69
5	A1	B0	C0	4.84	1.93	1.86	1.94
6	A1	B0	C1	7.96	1.88	1.83	1.84
7	A1	B1	C0	5.63	6.09	6.07	6.02
8	A1	B1	C1	9.65	5.85	5.86	5.85



Sum at factor level	Factor and interaction					
	A	B	AxB	C	AxC	BxC
0	-19.91	-22.62	-42.65	-30.76	-30.18	-31.15
1	-41.96	-23.91	-19.23	-31.11	-31.69	-30.73
Sum of squares of difference (	486.28	1.67	548.67	0.12	2.28	0.17
Contribution ratio (%)	46.79	0.16	52.80	0.01	0.22	0.02
Pareto diagram						
	AxB	A	AxC	B	BxC	C
Cumulative contribution	52.80	99.59	99.81	99.97	99.99	100.00
Check on significant interaction	AXC two-way table					
Optimum combination of significant factor level	A0B0C1					

Fig 1. Surface roughness measurement: (a) Traditional Analysis (Based on Average Response only), (b) Taguchi Method (Based on S/N Ratio) and (c) Pareto ANOVA

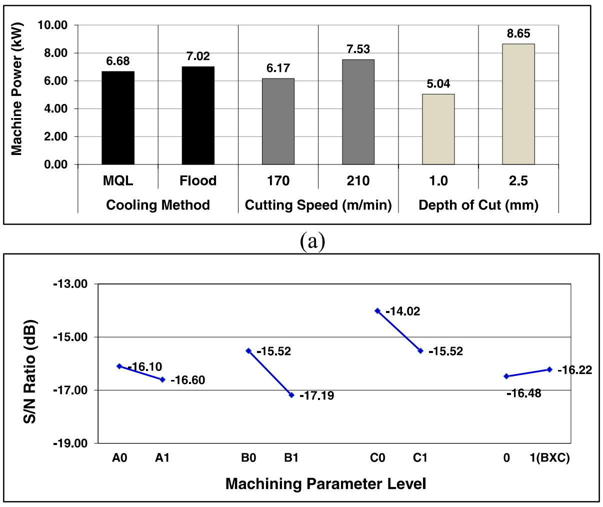


Fig 2. Machine power measurement: (a) Traditional Analysis (Based on Average Response only) and (b) Taguchi Method (Based on S/N Ratio)

2.2. Testing procedure

Two cooling methods were tested; the first was traditional flood and the second the new condition MQL. The nominal size of each construction bolt was 200 mm length and 42 mm diameter the material composition is listed in Table 3. The experiment was carried out on a CNC lathe holding the workpiece (laboratory cutting test bolt) in a three-jaw chuck supported by a dead centre was employed. Triangle-shaped inserts with enriched cobalt coating (WNMG 080408 - TF IC8150 5507835) were used as the cutting tools. The inserts were mounted on a standard DWLNR 2525M 08 tool holder. A new cutting tip was used for machining each work piece to avoid any tool wear effect. Details of cutting conditions used —cutting speed, feed rate, and depth of cut—are given in Table 1. The range of depth of cut was chosen as per the companies production requirements for cutting operations.

Table 3 Workpiece (bolt) Composition[7]

Work piece composition	AISI 4043 (C= 0.38–0.43%, Mn= 0.60–0.80% Mn= 0.60–0.80%, P= 0.035%, S= 0.040%, Si= 0.15–0.35%, Ni= 1.65–2.00%, Cr= 0.70–0.90%, Mo= 0.20–0.30%)

In this research the machine performance between the two cooling methods were compared, TFC and MQL. The machining power data was measured by Yokogawa CW140 clamp type power analyzer and the surface finish was obtained by using Mitutoyo SJ-201 Surface Roughness Tester. The tool wear was examined using a Pro MicroScan 5908 microscope. Important physical and chemical properties of coolant are listed in Tables 4.

Table 4 Coolant Physical and Chemical Properties

Properties	MQL	TFC
Physical state	Low viscous oil	Low viscous liquid
Viscosity	10 mm^2/s (cSt) at 40°C	350 cSt at 21°C
Colour	Yellowish fluid	Clear brown concentrate
Odor	Slight sulphur smell	Mild
Flash point (Open Cup)	>200 °C, >400F(COC)	>150 °C
Pourability	-12 to -20 °C	Not available
Vapor pressure	Negligible under normal conditions	Not available
Density (20°C)	Approx. 890 kg/m^3	950 kg/m^3
Solubility in water	Insoluble	Soluble
Solubility in organic solvents	Soluble	Not available

2.3. Environmental and economic analysis

There are five cleaner production (CP) strategies that consist of input substitution, product modification, technological modification, good housekeeping and on-site recycling, for achieving both economic and environmental benefits. The replacement of traditional flood cooling (TFC) with Minimum Quantity Liquid (MQL) in machining operations for producing bolts falls under both product modification and technological modification CP strategies. Life cycle assessment has been carried out to determine the environmental benefits associated with the application of these cleaner production strategies. This LCA analysis has been regarded as a streamlined LCA (SLCA) as this analysis does not take into account the emissions associated with the mining and production of bolt material and also the emissions associated with the use and disposal of bolts. This SLCA only takes into accounts all inputs and outputs associated with the machining operation. The four steps of ISO 14040-44(2006): goal and scope, life cycle inventory, impact assessment and interpretation, have been followed to perform this SLCA analysis [8].

The goal is to assess the environmental benefits associated with the replacement of a TFC system with the MQL cooling system. The functional unit is the machining of one bolt which forms the basis of developing a life cycle inventory (LCI). The LCI took into account the following inputs: coolant, cutting tools and energy for this machining operation. Most of the following information on this machining operation for developing the LCI was obtained from a local SME in Western Australia

Cutting fluid: The data was directly collected from a local industry Donhad in Bessendean, Western Australia. The coolant consumption for TFC and MQL cutting methods were 12 litres per month and 20 cc per 8 hours, respectively. The number of bolts machined per day is 300 and the factory operates 5 days a week for 20 hours a day. The densities of coolants used for TFC and MQL are 0.985gram/ml and 0.89 gram/ml, respectively. Using these information, the amount of coolant for TFC and MQL systems have been calculated as 1.97 gram and 0.15 gram, respectively.

Cutting tools: Up to 60 bolts can be machined with one cutting tool when both TFC system are used and this tool's use life was increased to up to 67 bolts when the MQL cooling system was introduced. The weight of the cutting tool is 9.2 gram. Using this information, the amount of material used for cutting tool has been allocated to the machining of one bolt to help simplify the analysis.

Cutting energy: Since there is no provision for measuring cutting energy in the work place, a similar machining operation was conducted at Curtin University's machine laboratory. About 0.323 kWh, and 0.295 kWh of energy was required for machining one bolt for TFC, and MQL systems, respectively.

Pumping energy: The energy required for pumping coolant was determined by obtaining the information on the amount of coolant pumped for machining one bolt, time of cutting (i.e. 4 minutes/bolt) and the head of the pump (1 meter) using the following equation.

[illegible] (1)

where, E_{Pump} = Energy for pumping coolant (Wh), g = gravity (9.81 m/s2), m = coolant flow rate (kg/hour/bolt), H = head (m) and t = cutting time (hour/bolt)

MQL system used pressure of compressed air to dispense a shot of coolant, therefore, pumping energy for coolant was not considered for this system.

Compressor energy: Energy consumption for compressed air flow for MQL system has been calculated using following formula:

Compressor power (HP)= Pressure (PSI)x Flow (gallon per minute)/1714 (2)

Once the LCI has been developed using the above information (Table 5), the input and output data in the LCI were put into the Simapro 7.3.3 software to determine the greenhouse emissions and other related environmental impacts associated with this machining operation. The recorded units of input and output data from the life cycle inventory depended on the prescribed units of the relevant materials in Simapro or its emission databases. The emission factors of the Western Australian energy mix had been used for determining environmental impacts of energy for machining. Since the Simapro software does not have emission databases for coolant and cutting tool production, separate databases were developed following Li et al [9].

Table 5 Life cycle inventory for machining one bolt for traditional flooding and MQL cooling systems

Inputs	units	TFC	MQL
Cutting energy	kWh	0.323	0.295
Pumping energy	kWh	5.124E-05	0
Compressor energy	kWh		0.051
Coolant	gm	1.97	0.15
Cutting tools	gm	0.15	0.14
Disposal	gm	1.97	0.15

The cost saving associated with these cleaner production strategies has been estimated by working out the amount of coolant, cutting tool material, energy for machining and disposal costs avoided. No additional cost has been involved for switching to MQL cooling system, because the industry is using the existing compressor for compressing air and the same coolant pump being used for both traditional flood cooling and MQL cooling systems. The cost (Australian Dollar or A$) related information which were obtained from the industry are listed below

Cost of coolant = $21/litre
Cost of cutting tool = $12 per piece
Cost of disposal = $40,000 pa (30% of which is used coolant)
Electricity price = A$0.12/kWh

3. Results and discussions

3.1. Technical analysis

The power required by the MQL cooling method is lower than that of TFC. Cutting 1 mm and 2.5 mm depth of cut the power analyzer recorded 4.43 kW and 7.44 kW respectively, with the TFC recording 4.84 kW and 7.96 kW for each depth of cut. It was found that a significant reduction in power requirement when using MQL for each cutting process. MQL proved to be reliable in maintaining tool life during the cutting of bolt material. For this reason using tool wear to compare the cutting performance was found to be difficult as there was no appreciable wear to observe or catastrophic breakdown of the tips as shown in figure 3. It was found to be more expedient to use the bolt surface finish in determining tool life.

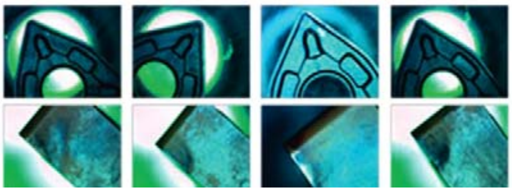


Fig 3 Tool tips from cutting test

A deeper depth of cut of 2.5 mm increased the cutting temperature but no significant tool wear was observed. It can be clearly seen from the colour of chips produced from both depths of cut value. For a traditional flood machining, the SME organisation uses 170 m/min cutting speed and 0.25 mm/rev feedrate. The same values were used to start with however the test suggested a higher cutting speed would be possible.

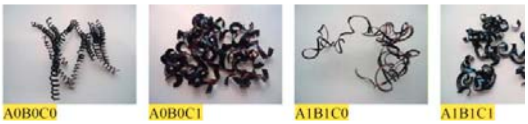


Fig 4 Chips of Cutting Test

MQL has been proven to provide a better than traditional flood cooling method in machining the bolts. When using TFC, the company using 1 mm depth of cut. After using MQL, the depth of cut was found to be able to be increased to 2.5 mm, without reducing the quality of the bolt. Increasing depth of cut means higher metal removal rate and shorter effective time of machining. With the reduction of the effective time of the machining, even though time required to load and unload a part is fixed, the total machining time can be reduced significantly.

Under TFC environment, surface roughness greatly increased (up to 6.09 μm) when the cutting speed increased from 170 m/min to 210 m/min. Meanwhile, under MQL environment surface roughness stay in the same range when similar increase in cutting speed was applied. Surface roughness under MQL cooling ranged from 1.54 μm to 2.04 μm.

Without coolant, bolts and chips are cleaner and easier to handle. Clean bolts and chips accelerate the packing process of bolt and chips collection become more sustainable. The use of MQL has eliminated the drawbacks of traditional flood system used within the company by producing clean chips and cleaner machines. Clean bolts and chips accelerate the packing process of bolt and chips collection become faster. Cleaner machines reduce maintenance time and lower maintenance costs. Non-contaminated chips can be sold as scrap metal with a higher price figure 4. Normally chips weight deducted up to 30% to account for the coolant.

Technical benefits of the use of MQL by the SME have been summaries below:

i. The cost of a machining process can be reduced when using MQL systems because it needs lower power consumption and makes machining time shorter.
ii. MQL is more environmentally friendly because this system reduces liquid waste significantly by removing coolant from machining process.
iii. Deeper depth of cut (2.5 mm) and higher cutting speed (210 m/min) with similar or even better surface finish under MQL environment will increase productivity.
iv. Improved productivity.

3.2. Environmental and economic analysis

Table 6 shows the most relevant environmental impacts, including global warming, euthrophication, cumulative energy and human toxicity, associated with this machining operation for two different cooling systems. The global warming, cumulative energy, euthrophication, and human toxicity can be avoided by 21%, 32%, 81% and 87%, respectively due to replacement of the traditional flood cooling (TFC) system with the MQL cooling system. Global warming appears to be the most dominant environmental impact than other impacts Table 6. This may be because of the major share of coal and natural gas in the electricity generation mix in Western Australia and the emissions associated with the manufacturing materials such as cutting tools.

Table 6 Environmental impacts of machining a bolt for traditional flood and MQL cooling systems

Impacts	TFC	MQL	Replacement of TFC with MQL	
			Saving	%
Global Warming (kg CO$_2$-eq)	0.38	0.30	0.08	21
Cumulative energy demand (MJ LHV)	4.93	3.35	1.58	32
Eutrophication (kg PO4- eq)	5.3E-04	1.01E-04	4.25E-04	81
human toxicity (DALY)	3.11E-08	4.06E-09	2.70E-08	87

Table 7 shows the breakdown of CO$_2$ emissions and costs in terms of inputs for TFC and MQL cooling systems. Coolant appears to offer more cost and carbon saving benefits compared to other inputs for this replacement. About 0.06 kg CO2 –e of global warming impact and machining cost of A$0.23 could be avoided for machining a bolt due to replacement of TFC system with a MQL cooling system. For a production rate of 300 bolts per day, it was estimated that about 4.7 tonnes of CO$_2$ –e emission can be mitigated and A$17,785 of operational cost can be avoided annually. The annual operation cost of the SME has been worked out as $0.5 million, which means that about 4% of this cost can be avoided by switching over to MQL system.

Table 7: Carbon and cost saving benefits associated with use of MQL cooling system

Inputs	GHG (kg CO$_2$-eq)		Cost (A$)	
	TFC	MQL	TFC	MQL
Cutting tool production	1.24E-04	1.84E-04	1.84	1.6477612
Coolant production	8.14E-02	1.36E-04	4.20E-02	3.50E-03
Pumping energy	4.53E-05		6.19E-06	
Compressor energy		4.35E-02		6.08E-03
Cutting energy	0.28	0.26	0.039	0.035
Coolant disposal	0.018	2.96E-05	3.03E-04	2.282E-05
Total	0.36	0.30	1.92	1.69

4. Conclusions

This research was undertaken to help eliminate the liquid waste problem resulting from the metal cutting process in a local manufacturing facility. It was established that the optimum solution would be to eliminate the use of liquid coolant used for machining, while still maintaining the same throughput of bolts. Research showed that using MQL was feasible as an alternative to flood as it provided some cooling and lubrication at the tool tip interface. Tool tips from the cutting process used in the company were examined and showed that the tips exhibited less wear when MQL was used. Similar results were obtained from the cutting test carried out in the laboratory, and can be seen from figure 1(a) as the surface finish improved.

The LCA analysis of traditional flood coolant when compared to MQL shows a substantial reduction of the carbon footprint. These savings were gained from a number of aspects of the process such as not using cutting fluid, carbon cost of manufacture and saving in disposal costs. The goals for this business were more than succeeded as productivity was increased, there was a reduced carbon footprint and elimination of the cutting fluid was met.

Finally, the replacement of TFC with MQL cooling system can help attain the three pillars of sustainability: economic, environmental, and social. Firstly, MQL can potentially significantly reduce the GHG emissions associated with the use of TFC system by 21%. Secondly, the MQL system is economically beneficial as it can help save 4% of the operational cost for the SME cheaper.

Acknowledgements

We acknowledge our industry partner Mr Gareth O'Neill, Forge Manufacturing Superintendent, Donhad, Bassendean, Western Australia for supporting us to conduct the measurement of machining operation and also for providing cost and production related data.

References

[1] Choudhury S K, Appa Rao I V K.. Optimization of cutting parameters for maximizing tool life. International Journal of Machine Tools and Manufacture 1999; 39: 343-353,.

[2] Sreejith P S, Ngoi B K A. Dry machining: machining of the future. Journal of Materials Processing Technology 2000; 101: 287-291,.

[3] Dietmair A, Verl A. A generic energy consumption model for decision making and energy efficiency optimisation in manufacturing. International Journal of Sustainable Engineering 2009; 2:123-133.

[4] Jeffrey T G G, Dahmus B. An Environmental Analysis of Machining. presented at the IMECE2004, Anaheim, California USA, 2004.

[5] Ekvall T, Finnveden G, Allocation in ISO 14041--a critical review. Journal of Cleaner Production vol. 2001; 9: 197-208,.

[6] Haughey D. Pareto Analysis Step by Step. 2013, Available: http://www.projectsmart.co.uk/pareto-analysis-step-by-step.html

[7] Committee A I H. Properties and selection: irons, steels, and high-performance alloys. 1990.

[8] ISO. Environmental management – life cycle assessment – principles and framework, ISO 14040/44. International Organization for Standardization (ISO), Geneva, 2006.

[9] Li C, Tang Y, Cui1 L, Yi Q. Quanitative analysis of carbon emissions of CNC-based machining systems. IEEE 2013; 869-884.