Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 29 (2015) 645 – 650
www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Investigation into alternative cooling methods for achieving environmentally friendly machining process

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Abstract

The machining of metals has traditionally involved the use of large quantities of water and oils for dissipating the cutting tool temperature, improving the surface finish of parts and increasing tool life. Invariably, the cutting fluid has become contaminated with use, has required being environmentally disposed and has accounted for approximately 17% of the total production cost of parts.

A Streamline Life Cycle Assessment (SLCA) of machining of parts has been carried out to investigate the environmental and energy saving benefits associated with the replacement of traditional cooling method, with Minimum Quantities of Liquid (MQL) combined with cold compressed air.

Keywords: Tool life; Cutting fluid; Minimum Quantity of Liquid; Cold Air; Environmental; Energy saving; Life Cycle Assessment.

1. Introduction

Environmental predictions of global warming due to greenhouse emissions have highlighted the need for sustainable manufacturing. This has led to governments throughout the world introducing legislation for industry to reduce waste in all its forms. The net economic cost of damage from climate change across the globe has an estimated average value of US$12 per tonne of CO_2 [1] Published evidence has indicated that the net damage cost for climate change is projected to be significant, and carbon emissions will continue to increase if changes are not forthcoming. Manufacturers need to take responsibility to minimise waste in an effort to ensure a sustainable future.

Metal cutting notoriously creates waste impacting on the environment, therefore appropriate waste disposal measures need to be in place. Toyota found that coolant contributed 31.8 % of energy usage in their machining centre system [2]. They identified that an alternative cooling method is a promising area in reducing the energy requirements of machining.

A small to medium enterprise (SME) company Donhad in Perth has become aware of the environmental contamination to the surrounding ground due to waste liquid coolant escaping from the machining process. The picture below Figure 1 shows the extent of the contamination due to the coolant escaping from the metal skip waste bin. The clean-up of the contamination was estimate to have cost the company $40k. The company's immediate action was to contain the chip bin inside a secondary sealed bin in order to retain escaping coolant. More challenging and a better solution for the company are to eliminate liquid coolant from its machining operation.

Fig. 1. Donhad polluted waste bin site

At present there are three main greener cooling fluids used in reducing the amount of traditional cutting fluid used. They are:

doi:10.1016/j.procir.2015.02.184

- cryogenic cooling using liquid nitrogen [3, 4]
- compressed air
- minimum quantities of liquid using vegetable oil

Each fluid is presented to the cutting zone reducing the tool interface temperature. Selection of which green fluid to use depends on three main factors:

- workpiece material
- cost of producing the green fluid
- applying the fluid to the cutting zone

Research has shown that MQL [5-8] or cold air machining [9, 10] would be the best green fluids used to replace flood cooling in this workplace, with respect to the above factors. To assist the company to achieve its objective a series of machining tests using the exact same machining parameters with MQL and cold air (CA) were evaluated. Findings from these tests proved that the company could implement MQL and cold air with increased cutting speed improving its productivity. These environmental pollution prevention strategies are known as Cleaner Production strategies as these initiatives also result in economic benefits. The current research will assess as to whether the application of innovative cutting methods in Western Australian Small and Medium sized enterprises would help achieve cleaner production benefits.

Life cycle assessment (LCA) has so far been considered for assessing environmental implications of the use of different cutting fluids, machining operations and machine tools. Clarens *et al.* [11] carried out a comparative life cycle assessment of water and gas based systems to show as to whether is environmentally friendlier to deliver lubricants in air rather than water. Narita and Fujimoto [12] and Ismet [13], while Li *et al.* [14] utilised LCA for estimating carbon emissions from the use of a CNC machine. At this time there is only limited published literature that applied LCA to compare the environmental performance of conventional fluid with MQL and compressed air within an industrial situation.

1.1. Cutting and cooling test methods

The workpiece (bolt) cutting tests consisted of machining the same spec of steel as the bolts on a Geoturning 250 MA CNC lathe (as being typically the lathe type used by Donhad), and a Yokogawa CW140 clamp on power analyser to measure the cutting power. An Airtx vortex tube (Model 20008) with an inlet pressure of 85psi supplied chilled air at a temperature of -15°C. The compressed air used was supplied from the workshop airline. The MQL was delivered from a Uni-max cutting tool lubrication system which distributed atomised Coolube 2210 metalwork lubricant to the cutting zone. This system operates on the same principle as a Serv-O-Spray allowing the lubricant to be sprayed from a single air source, which allows adjustment to the amount of lubricant delivered to the cutting zone. Rocol ultra cut fluid was used for the wet test machining which is suitable for ferrous materials. The cutting tool selected for all of the tests was a Sandvik tool holder with a coated tungsten carbide insert (WNMG 080408 - TF IC8150 5507835). All cooling nozzles used during the tests were kept at approximately 25mm from the tool during all tests. The cutting power was established for non-machining of the workpiece to establish the lathes controller and axillary equipment for use when analysing the cutting power. Fig. 2 shows the machines power used when idling and available power for metal cutting.

Fig. 2. Idle power of the CNC lathe

Cutting tests were carried out dry, flood, MQL and combine cooled air with MQL. Typical machining practices were used to machine the face ensuring that the tool tip was constantly removing material. The cutting power was measured for each machined workpiece. The cutting parameters selected reflected typical Donhad working conditions. This being the pertinent aspect of how the energy used in cutting would be the same. Sensitivity analysis for individual machines would provide the efficiency for the cutting motor used for the same cutting parameters used for each machine. This would normally involve a minimum amount of energy difference between machines. More substantial energy differences are related to different size of motors used for individual machines, and axillary equipment the machine may have.

1.2. Strategies and methods

Van Berkel [15] highlighted the following cleaner production (CP) strategies for processes products, and service efficiencies reducing the negative human impact on the environment. There are five (CP) strategies:

- input substitution
- product modification
- technological modification
- good housekeeping
- and on-site recycling

for achieving both economic environmental benefits. The replacement of Traditional Flood Cooling (TFC) with Minimum Quantity Liquid (MQL) and Cold Air (CA) as cutting fluid in machining operations for producing bolts falls under both product modification and technological modification CP strategies. A LCA and an economic analysis has been carried out to determine the environmental and economic benefits associated with the application of these cleaner production strategies. This LCA analysis has been regarded as a streamlined life cycle assessment 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 [16].

The goal is to assess the environmental benefits associated with the replacement of a TFC system with the MQL and CA cooling systems. The functional unit is the machining of one bolt which forms the basis of developing a life cycle inventory (LCI).

The machining parameters are as follows:

- depth of cut = 1mm
- cutting speed = 170m/minute and
- cutting time = 4 minutes

These cutting parameters remain constant for all machining tests. 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 company Donhad. The coolant consumption for TFC and MQL cutting methods were 12 litres per minute 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 0.98g/ml and 0.89g/ml, respectively. Using this information, the amount of coolant for TFC and MQL systems have been calculated as 1.97g and 0.15g, respectively. There was no coolant used for CA cutting method.

Cutting tools: Up to 60 bolts can be machined with one cutting tool when both TFC and CA systems 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 9.2g. 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. Recorded readings of 0.323kWh, 0.295kWh and 0.223kWh of energy was required for machining one bolt when cooling with TFC, MQL and CA respectively.

Pumping energy: the energy required for pumping coolant for the TFC system 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.

$$E_{Pump} = gmHt/(3.6 * 10^3) \tag{1}$$

where, E_{Pump} = Energy for pumping coolant (Wh), g = gravity (9.8m/s^2), 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 coolant, therefore, pumping energy for coolant was not considered.

Compressor energy: Energy consumption for compressed air flow for both MQL and CCA systems have been calculated using following formula [17]:

$$\text{Com power (HP)} = \frac{\text{Pressure (PSI)x Flow (gallon per minute)}}{1714} \tag{2}$$

All input and output data of the LCI were added to 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* [14].

Table 1. Life cycle inventory for machining one bolt for traditional flooding and MQL cooling systems

		TFC	MQL	CA
Cutting energy	kWh	0.323	0.295	0.223
Pumping energy	kWh	5.124E-05	0	0
Compressor energy	kWh		0.051	0.072
Coolant	gm	1.97	0.15	0
Cutting tools	gm	0.15	0.14	0.15
Disposal	gm	1.97	0.15	0

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 and CA 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. The cost 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

2. Results and discussion

Table 2 shows the most relevant environmental impacts, including global warming, eutrophication, cumulative energy and human toxicity, associated with this machining operation for two different cooling systems. The global warming, cumulative energy, eutrophication and human toxicity can be avoided by 21%, 32%, 81% and 87%, respectively due to replacement of the traditional flood cooling system with the MQL cooling system. CA appears offer better environmental performance than MQL as 45%, 45%, 84% and 89% of the total global warming, cumulative energy, eutrophication and human toxicity, respectively can be avoided due to replacement of

TFC with compressed cold air. Global warming appears to be the most dominant environmental impact than other impacts (Table 2). 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 3 shows the breakdown of CO_2 emissions and costs in terms of inputs for TFC MQL and CA cooling systems. Reducing the cutting energy offer more carbon saving benefits compared to other inputs. About 0.06kg CO_2 –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. More GHG emissions can be avoided due to use of CA instead of MQL. The replacement of TFC with CA can save GHG emissions by 0.15 kg CO_2-eq for machining a bolt. For a production rate of 300 bolts per day, it was estimated that about 11.9 tonne CO_2 – emission can be mitigated due to replacement of TFC with CA and A$17,785 of operational cost can be avoided annually due to replacement of TFC with MQL. 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.

In general without coolant 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 and CA 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. Normally chips weight deducted up to 30% to account for the coolant.

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

1. Deeper depth of cut (2.5mm) and higher cutting speed (210 m/min) under MQL cooling system gave similar or even better surface finish.
2. The cost of a machining process can be reduced when using MQL systems since it needs lower power consumption and makes machining time shorter (deeper depth of cut and higher cutting speed)
3. Productivity under MQL cooling system is improved.
4. Liquid waste has been significantly reduced from machining process for both CA and MQL making them more environmentally friendly.

3. Conclusion

This research was undertaken to help eliminate the liquid waste problem resulting from coolant escaping into the ground at a local manufacturing facility. The demand for environmental sustainable manufacturing is the primary driving force to reduce the use of liquid coolant. However, determining the effectiveness of the alternative MQL and CA process cannot be judged simply by considering the cooling function only. As metal cutting is a very complex process, and a small change in cutting conditions can have major consequences. To determine the best cooling method it was only necessary to consider the energy factors needed for cooling as the machining aspects have been established. It was established that the optimum solution would still need to maintain the same throughput of workpieces. Research showed that using MQL and CA 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 as the surface finish improved.

The LCA analysis of traditional flood coolant when compared to MQL and CA 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 problems associated with the use of coolant can be completely avoided by using CA. In addition there are reductions of power required for metal removal when using MQL and CA, as power used for running the coolant pump is not required. 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 and CA cooling systems can help attain the three pillars of sustainability: economic, environmental, and social. Firstly, CA can potentially significantly reduce the GHG emissions associated with the use of TFC system by 45%. Secondly, the MQL system is economically beneficial as it can help save 4% of the operational cost for the SME cheaper.

Table 2. Environmental impacts of machining a bolt for traditional flood MQL cooling systems and CA

Impacts	Units	TFC	MQL	Cold air	Replacement of TFC with MQL		Replacement of TFC with MQL	
					Saving	%	Saving	%
Global Warming	kg CO_2-eq	0.38	0.30	0.21	0.08	21	0.17	45
Cumulative energy demand	MJ LHV	4.93	3.35	2.73	1.58	32	2.19	45
Eutrophication	kg PO_4- eq	5.26E-04	1.01E-04	8.23E-05	4.25E-04	81	4.44E-04	84
Human toxicity	DALY	3.11E-08	4.06E-09	3.28E-09	2.70E-08	87	2.78E-08	89

Table 3. Carbon and cost saving benefits associated with use of MQL cooling system

Inputs	GHG (kg CO_2-eq)			Cost (A$)		
	TFC	MQL	CA	TFC	MQL	CA
Cutting tool production	1.24E-04	1.84E-04	2.07E-04	1.84	1.6477612	1.84
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	1.57E-02		6.08E-03	8.60E-03
Cutting energy	0.28	0.26	0.194	0.039	0.035	0.027
Coolant disposal	0.018	2.96E-05		3.03E-04	2.282E-05	
Total	0.36	0.30	0.21	1.92	1.69	1.88

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