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Application of Life cycle assessment in sustainable machining of aluminium 6061 alloy under different lubricating conditions

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Abstract : Aluminium is considered more precious than gold, most commonly used for different aerospace, automotive, and shipping industries. Boring is a critical machining method in assembly operations. This paper investigates the machining performance in machining 6061 aluminum alloy under different cutting conditions through a specially designed mixing nozzle for mist and flood lubrication. Experiments were performed with twenty-seven runs selected from Taguchi robust design, cutting parameters selected from the manufacturer's recommendation. Results revealed an improved machining characteristic while machining the component with near dry machining compared to dry and flood lubrication. Life cycle assessment of selected functional unit to investigate the ecological impact using CML baseline method. LCA analysis concluded that dry machining is a more sustainable approach than near dry and flood machining approaches.

Keywords: Machining time, metal removal rate, functional unit, life cycle assessment.

Acronyms and Abbreviations list

v_c	Cutting speed
f_n	Feed rate
a_p	Depth of cut
FL	Flood lubrication
C_s	Cutting time (sec.)
S_t	Standby time (sec.)
T_r	Tool return time (sec.)
T_t	Total time (sec.)
MQL	Minimum quantity lubrication
LCA	Life cycle assessment

FU	Functional unit
AD	Abiotic depletion
ADFF	Abiotic depletion (fossil fuels)
GW	Global warming (GWP100a)
ODP	Ozone layer depletion
HT	Human toxicity
FWAE	Fresh water aquatic ecotoxicity
MAE	Marine aquatic ecotoxicity
TE	Terrestrial ecotoxicity
PO	Photochemical oxidation
AF	Acidification
EU	Eutrophication

1. Introduction

Machining productivity increases with the usage of lubricants and coolants by reducing wear and surface roughness. Lubricating fluids contain harmful chemical ingredients that cause environmental pollution. Persistent exposure while machining may lead to respiratory drawbacks in the operator’s health. Disposal of cutting fluids is also a significant concern in flood lubrication. The high temperature established at the contact surface in internal turning operations is due to increased hardness, poor thermal conductivity. Traditional cooling has frequently been used to tackle heat production and development effectiveness issues, with extensive use of lubricants. It seems a viable elucidation to prominent levels of heat up, but it poses a severe health risk, endangering green production and long-term sustainability [1]. In the modern industrial sector, sustainable manufacturing is the most recent notion. Sustainable manufacturing, which includes three functional elements: sustainable products, processes, and systems, is a comparatively lesser-known but crucial component of sustainable development [2]. Mist lubrication systems reached a milestone in reducing the allergic effects of non-degradable lubricants on workshop floors [3]. The MQL approach decreases the concentration of lubricant without sacrificing the project's effectiveness.

Consequently, this technique can be acknowledged as a credible alternative for addressing non - degradable lubricant issues. Mist [4] lubrication utilizes aerosol through various channel systems, offering a reduction in environmental pollution. Fluids should be biodegradable and offer stability for a more extended period due to less quantity usage. Near dry machining [5] is superior to dry and wet machining while turning AISI4340 steel with an uncoated carbide insert to analyze the effect of MQL on flank wear and surface roughness. Cutting forces increase prominently in dry conditions and decrease in flood lubrication [6]. Cutting enactment with MQL is far better than the dry turning process as it offers lower temperature reduction [7]. Machining with MQL proved to be better than dry and wet cooling, increasing cutting performance by reducing tool wear, cutting temperature, and forces between chip-tool interactions [8]. A bulk of reports focusing on how to make machining operations more sustainable are focused on dry or MQL machining [9].

This work investigates the effect of three different cutting conditions (dry, flood and minimum quantity lubrication on cutting time, rate of metal removal and various environmental impact indictors.

2. Material and Methods

Boring trials were executed on 200mm long aluminum alloy 6061 (Internal diameter -69mm, Outer diameter-75mm, and wall thickness-3mm) as shown in figure 1 with carbide insert Kennametal through-hole boring bar on a conventional lathe at different cutting parameters under different cutting environments to evaluate the extensive machinability features as shown in figure 2. The experimental details are given in Table 2.

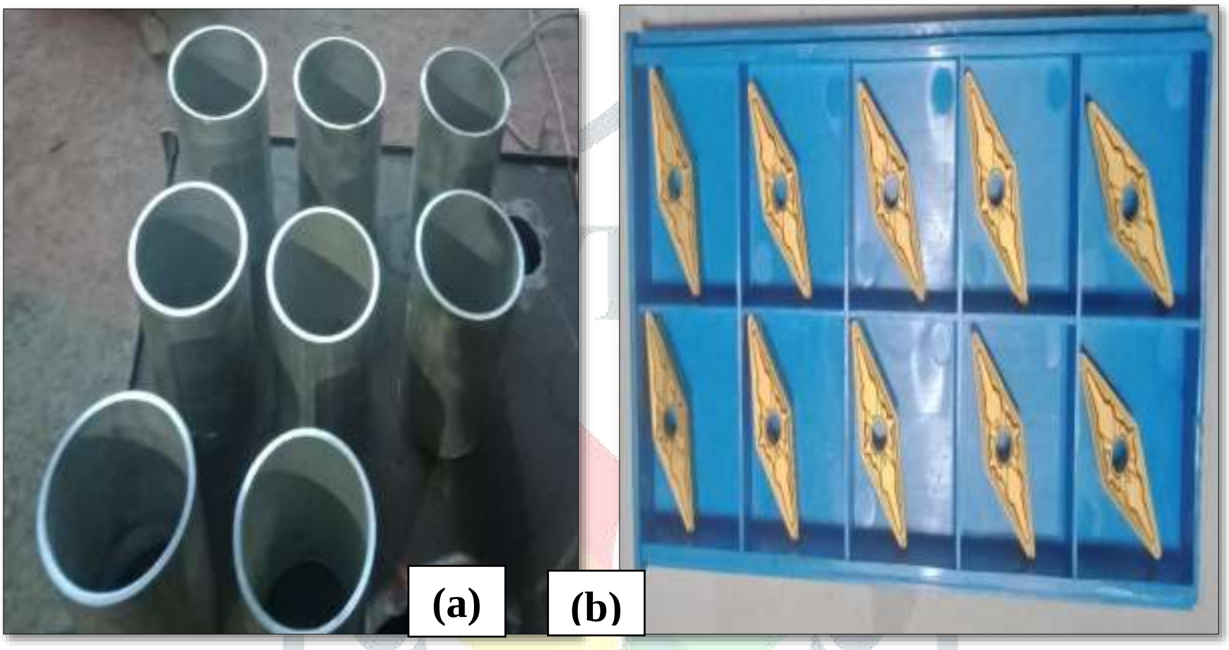

Figure 1 (a) Aluminium alloy stocks (b) Carbide inserts

Table 1: Aluminium alloy 6061 chemical compositions [10]

Element	Mg	Si	Fe	Cu	Cr	Z	Ti	Mn	Al
Amount (wt%)	0.8-1.2	0.4-0.8	0.7	0.15-0.4	0.04-0.035	0.25	0.15	0.15	96.85

Table 2: Experimental conditions

Machine Tool	Manual Lathe Machine 6ft 14 x 12, HMT 6, 2 HP
Work material	6061 aluminium alloy (⌀75mmX 3mm thickness)
Boring Bar Specifications	Kennametal A16T-SVUBR3NH2, Diameter: 30mm, Length: 305mm, L/D ratio:10mm, Through hole type
Cutting insert geometry	VNMG160408-QM wintechcarbide, L:16.6mm, D: 9.525, S: 4.76, d_1: 3.81, R: 0.8, Positive rake
Process parameters	v_c: 185, 215, 245 mm/min, f_n: 0.15,0.20,0.25 mm/rev, a_p: 0.3,0.5,0.7mm
Cutting Condition	Dry, Flood and MQL
Air Pressure & Lubricant Flow rate	6 bars, Dry: 0ml/h, Flood: 120,000ml/h, MQL: 100ml/h though internal nozzle in boring bar

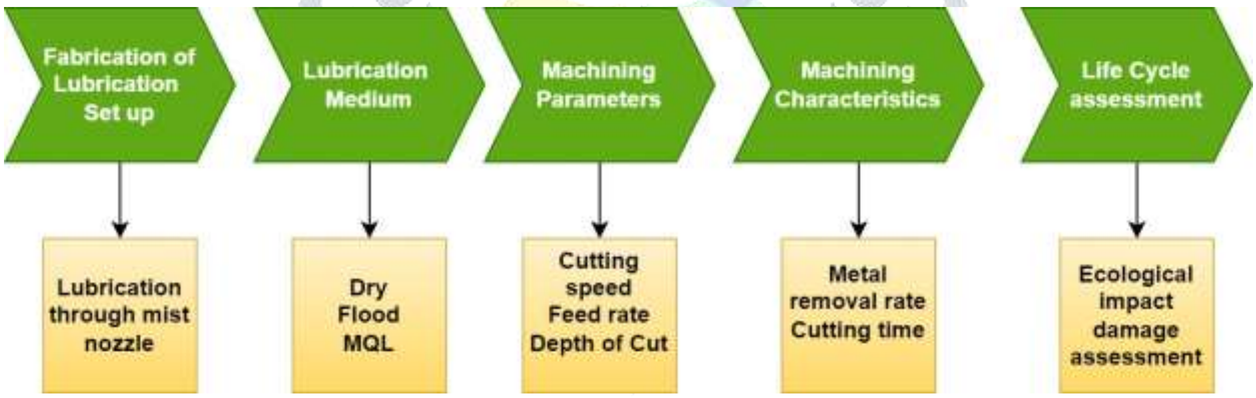

Figure 2. Adopted research methodology

3. Results & discussion

The efficacy, efficiency, and total cutting cost with specific inserts are primarily determined by the tool–work material machinability at required conditions. Under different cutting conditions,

Table 3: Experimental results

Lubrication Type	C_s	f	D_c	MRR	C_s (sec)	S_t (sec)	T_R (sec)	T_t (sec)
Dry	185	0.15	0.30	8.35	18.00	37.00	4.50	59.50
Dry	185	0.20	0.50	18.50	20.00	47.00	5.00	72.00
Dry	185	0.25	0.70	32.37	34.00	59.00	8.50	101.50
Dry	215	0.15	0.50	16.13	36.00	64.00	9.00	109.00
Dry	215	0.20	0.70	30.19	28.00	56.00	7.00	91.00
Dry	215	0.25	0.30	16.12	25.00	48.00	6.20	79.20
Dry	245	0.15	0.70	25.72	19.00	37.00	4.70	60.70
Dry	245	0.20	0.30	14.70	17.00	35.00	4.20	56.20
Dry	245	0.25	0.50	30.62	16.40	32.50	3.90	52.80
Flood	185	0.15	0.50	13.88	17.70	45.40	4.40	67.50
Flood	185	0.20	0.70	25.90	18.00	51.00	4.70	73.70
Flood	185	0.25	0.30	13.87	33.20	57.00	8.10	98.30
Flood	215	0.15	0.70	22.57	34.80	52.00	8.20	95.00
Flood	215	0.20	0.30	12.90	24.70	54.00	5.90	84.60
Flood	215	0.25	0.50	26.87	22.40	56.00	5.60	84.00
Flood	245	0.15	0.30	11.02	17.20	51.00	4.40	72.60
Flood	245	0.20	0.50	24.50	15.60	49.00	3.80	68.40
Flood	245	0.25	0.70	42.87	14.90	46.00	3.70	64.60
MQL	185	0.15	0.70	19.42	15.00	32.00	3.75	50.75
MQL	185	0.20	0.30	11.10	14.70	31.00	3.90	49.60
MQL	185	0.25	0.50	23.12	11.40	33.00	2.80	47.20
MQL	215	0.15	0.30	9.68	13.20	28.00	3.30	44.50
MQL	215	0.20	0.50	21.50	14.10	29.00	3.50	46.60
MQL	215	0.25	0.70	37.62	10.00	32.00	2.50	44.50
MQL	245	0.15	0.50	18.38	6.80	28.00	1.70	36.50
MQL	245	0.20	0.70	34.30	8.70	31.00	2.20	41.90
MQL	245	0.25	0.30	18.38	9.20	30.00	2.30	41.50

Metal removal rate, and machining time are addressed in this study to compare machinability characteristics in different machining techniques. Due to the presence of lubricating layer and less heat generation during machining, less cutting time observed in near dry machining, figure 3.

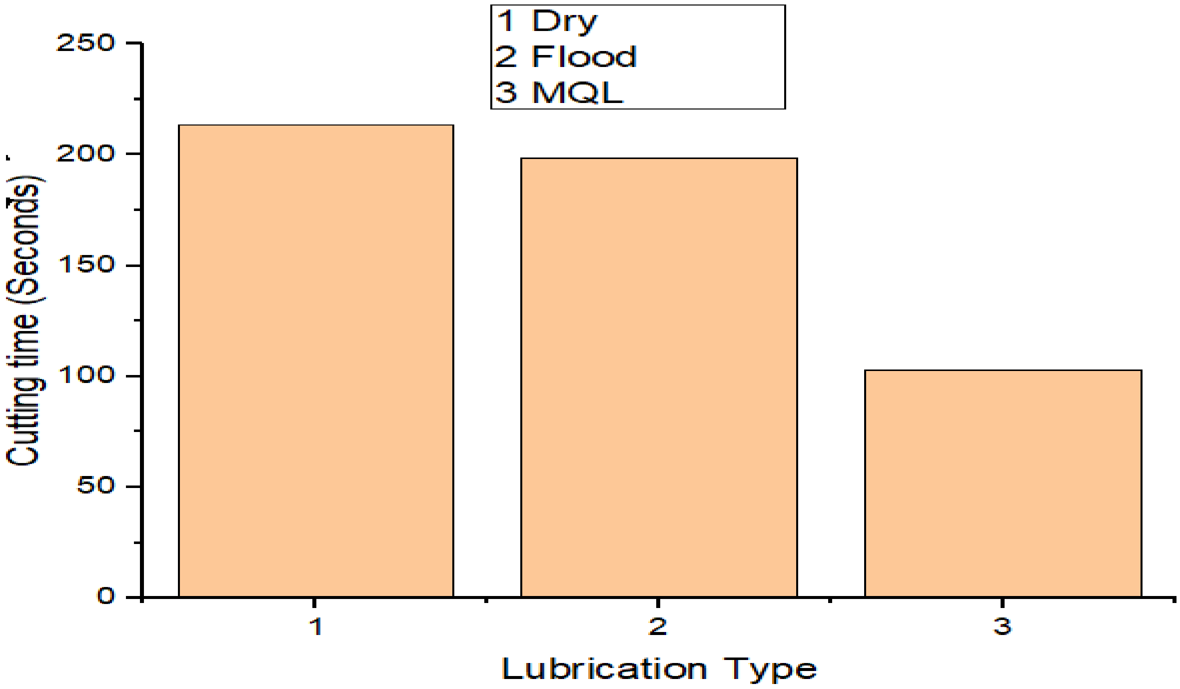

Figure 3. Cutting time comparison in different cutting conditions

3. Life Cycle assessment

LCA (Life Cycle Assessment) is a useful tool for estimating the potential environmental implications of products, processes, or services in order to help with product selection. Technical requirements must be assessed with environmental and economic factors in order to create more sustainable process designs [11]. The goal of this research is to compare the environmental implications of three different cutting procedures for the internal turning of aluminium alloy: dry, flood, and MQL. LCA analysis was carried out using the CML Baseline LCIA methodology by ISO 14040:2006 and ISO 14044:2006 standards [12]. as mentioned in table 4.

The following process has been excluded while doing the inventory analysis for life cycle assessment:

a) The elements required to make the Al 6061 alloy and cutting tool and the manufacturing of workpiece which is used for three different cutting conditions.

b) Manufacturing of coated carbide bit and its inability to enumerate the exact environmental impact of a coated carbide insert is inadequate due to a lack of appropriate datasets. This has an impact on the study's absoluteness and highlights the necessity for machining-specific datasets. This omission, however, has no significant impact on the outcomes of this study. According to a recent study, a thorough evaluation may still be done by factoring in power and coolant usage, which are important aspects of the life cycle assessment [13].

c) Transportation and its cost, cutting inserts, coolant, air compressor, and workpiece.

d) Carbon dioxide emission while machining the Al stock particularly in flood and mist lubrication. Due to the lack of adequate recorded data during experimentation, this parameter was also kept out of the assessment approach.

e) To conduct the inventory analysis, detailing of all three cutting conditions has been streamlined on similar aspects. Because the cutting parameters are having different subsets at all instances, the amount of material removed is different, and the finished product has variable material removal volume. As a result of the streamlining, the metal portion, the generated chips, and the finished product, all of which are made of Aluminium alloy, are excluded from LCA calculations.

Regardless of the cutting fluid used, the machined part is expected to be used for the same purpose. As a result, the assessment does not include the use phase, end-of-life processing, or disposal.

3.1 Inventory handling

Experimental data recorded during experimentation recorded on electricity consumption, lubricant quantity, and air compressor capacity. Total material removed from the machining trials in distinct cutting environments forms the calculation of impact assessment on hired method and damage assessment. Data sets used for analysis given in Table 4, acquired from the Ecoinvent database:

Table 4: Background process details for impact assessment

System input	Units	Description
Electricity	KWh	Electricity, high voltage {IN-Northern grid}| market for electricity, high voltage | Cut-off, U
Lubricants	Kg	Lubricating oil {RoW}| production | Cut-off, U
Compressed air	m^3	Compressed air, 600 kPa gauge {GLO}| market for | Cut-off, U

Table 5: Results of process inventories for ecological impact assessment

Impact Category	Dry Machining	Flood Machining	MQL Machining
AD	7.16E-05	1.15E-04	1.09E-04
ADFF	7.81E+01	2.65E+02	1.74E+02
GW	8.26E+00	1.41E+01	1.34E+01
ODP	2.37E-06	1.96E-06	9.25E-07
HT	4.84E+00	7.99E+00	7.62E+00
FWAE	1.43E+01	1.85E+01	2.03E+01
MAE	3.40E+04	4.57E+04	4.93E+04
TE	2.38E-02	3.60E-02	3.59E-02
PO	2.62E-03	4.59E-03	4.19E-03

AF	4.14E-02	7.50E-02	6.80E-02
EU	1.54E-02	2.54E-02	2.47E-02

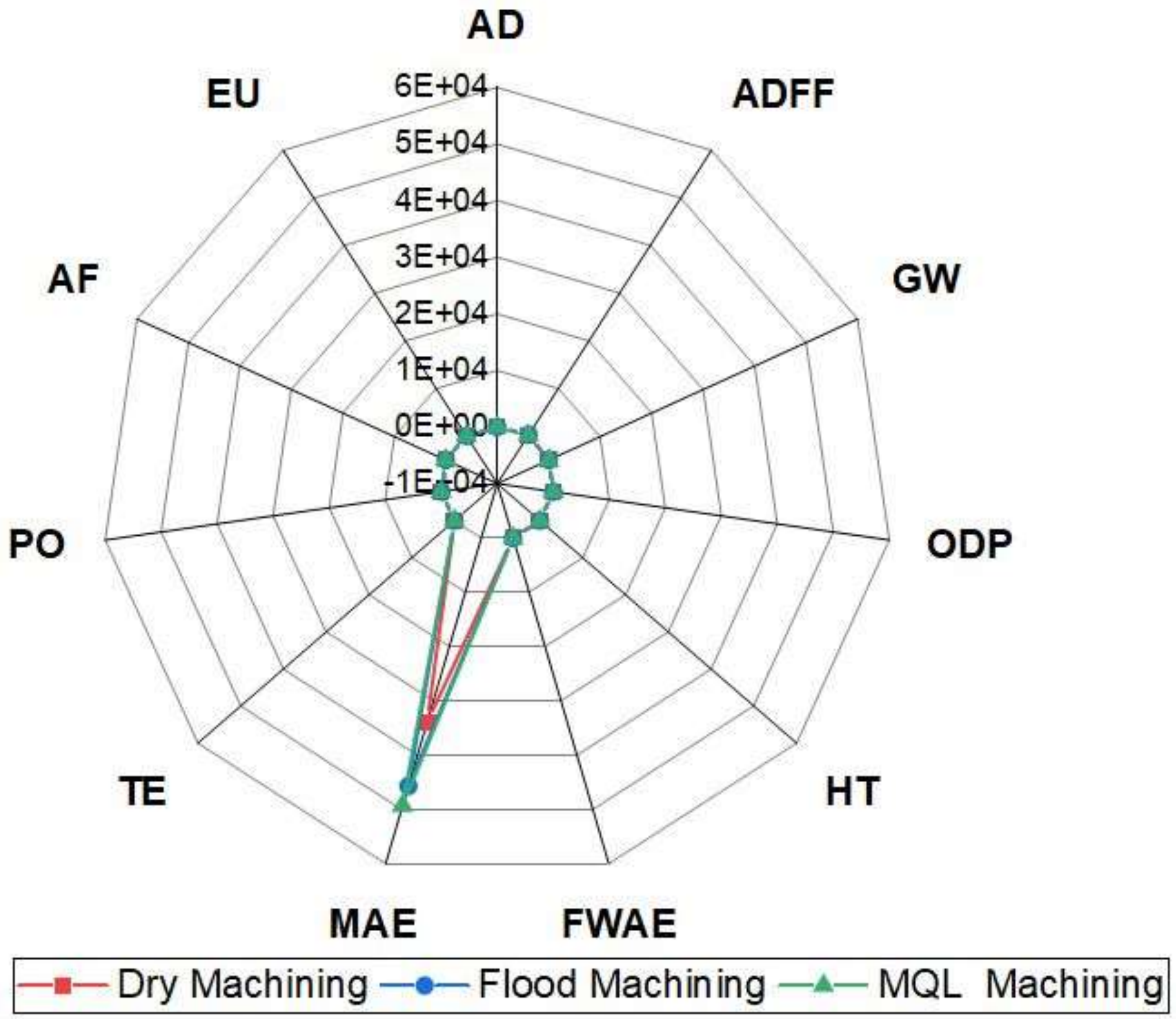

Figure 4. Comparison of the dry, flood and MQL machining on the values of damage categories

4. Conclusion

The outcome of lubrication conditions on metal removal rate in the boring of aluminium alloys 6061-T6 for various cutting speeds, feed rates, and depth of cut was investigated in this research study. Furthermore, life cycle assessment analysis indicates the ecological indications as per the given standard in the Ecoinvent database. Following conclusions can be drawn from the experimental studies:

- The mist produced by supplying aerosol internally through a boring bar proved an effective technique for better surface integrity than conventional and flood lubrication.
- MQL can be adopted as a permanent technique for boring operation, and it may be an economical approach compared to flood and dry machining.

- Cutting fluid with the least amount of lubrication reduces the negative aspects of cutting fluid during ecological aspects, such as friction reduction, cooling, and chip flushing.
- Human toxicity observed worst in case of flood machining due to abundant use of cutting fluid.

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