International Journal of Robotics and Mechatronics

Characterization and Optimization of Machinability and Environmental Impact of Machining of Ti-6Al-4V with Minimum Quantity Lubrication

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Abstract— Minimum quantity lubrication has gained recent importance in high speed machining. However, more understanding and optimization of the MQL parameters remains a challenge to improve its performance. The main objective of this paper is to study the environmental impact and the machining performance of Minimum Quantity Lubrication (MQL) in milling of Ti-6Al-4V. In this paper, the effect of MQL parameters; namely oil and air flow rate, nozzle orientation and nozzle distance on the machining performance was investigated and compared to flood and dry milling of titanium alloys. The machining performance was evaluated in terms of cutting forces, surface roughness and tool temperature. It was found that better machining performance and environmental impact was obtained using an optimized MQL jet.

Keywords—Minimum Quantity Lubrication, environmental impact, milling of Ti-6Al-4V.

DOI: 10.21535/ijrm.v4i1.971

I. Introduction

New manufacturing paradigms involve more dependence on green manufacturing techniques. The assessment of the environmental performance of machining processes has become an essential aspect of process characterization and optimization [1]. Carbon and greenhouse gas emissions are serious concerns for today's manufacturers due to the increasing requirements of emissions reduction worldwide. Metal cutting processes are among the highest category of energy consumption in manufacturing processes [2]. Therefore, new machining techniques have emerged to respond to the industrial needs of improved productivity and part quality, and reduced cost while effectively contributing to emissions reduction.

Minimum Quantity Lubrication (MQL) of machining processes has gained significant interest, as an emerging technology to replace the conventional flood cooling in conventional and high speed machining of metallic and composite components automotive, aerospace and die and mold industries [3-11]. The use of this technique results in considerable reductions in the quantity of lubricant used, reducing manufacturing costs, as well as the impact of the process on the environment [12].

The technology appears to have a niche of applications, where it would prove beneficial in terms of quality and savings, in addition to the environmental benefits [13]. Several work has focused on the application of MQL in machining operations, such as milling [14-19], turning [20-25] and drilling operations [3-11, 26-30]. However, the application of MQL in machining processes requires special considerations of the jet characteristics to ensure that the cutting fluid adequately covers and penetrate to the cutting zone area, mainly, the tool–chip and tool–work interfaces. This require the droplet size of the spray to be small enough to penetrate the cutting zone [3, 30], but greater than 5-10 µm, otherwise they become airborne fluid particles that cause health problems if inhaled [31].

In the machining process, the particle size and velocity characteristics of the MQL spray strongly influence the cutting temperature. Heat generation due to friction at the tool-chip interface in machining can increase tool wear. It affects the plastic deformation process in the primary and secondary shear zones during cutting [32]. In addition, it creates residual stresses in the machined surface and results in thermal deformation of the cutting tool [8].

A good understanding of the lubrication and cooling effects at the cutting zone will lead to efficient and economic machining [32]. However, there is limited knowledge of the flow regimes through which MQL functions, and the effect of different MQL parameters on its machining performance. Additionally, the machining of difficult-to-cut materials; e.g., Titanium and Inconel MQL did not have its fair share of investigation. Therefore, the main objective of this work is to study the effect of different MQL parameters, namely, the air flow rate (AFR) and oil flow rate (OFR), nozzle distance and nozzle orientation on its machining performance in order to select the optimum MQL jet. The machining performance was evaluated in terms of the surface roughness, the cutting forces and the tool temperature. The optimum MQL configuration was

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This paper was submitted on April 1, 2017; revised on May 9, 2017; and accepted on August 31, 2017.

selected for further comparison with dry and flood machining in terms of machining and environmental performance. Life cycle analysis was conducted using the Eco-indicator method to quantify the environmental impact of each process.

II. MQL MILLING OF TITANIUM ALLOYS

Partial immersion milling tests of Ti-6Al-4V alloy were performed to study the effect of air flow rate (AFR) and oil flow rates (OFR), nozzle distance (d) to the cutting area, and the nozzle orientation ( ) with respect to the feed direction, on the machining performance of MQL to select the optimum combination of MQL parameters. The latter is evaluated in terms of the cutting forces, tool temperature and surface roughness. Additionally, the performance of optimized MQL combination was compared to dry and flood cutting (6 l/min).

Table 1 – Test matrix for the tested MQL parameters

MQL Parameters	Levels
Air flow rate (AFR)	25 and 31 l/min
Oil Flow rate (OFR)	10 and 17.5 ml/min
Nozzle distance (d)	40 and 80 mm
Nozzle orientation (θ)	20°, 45°, 90° and 135°

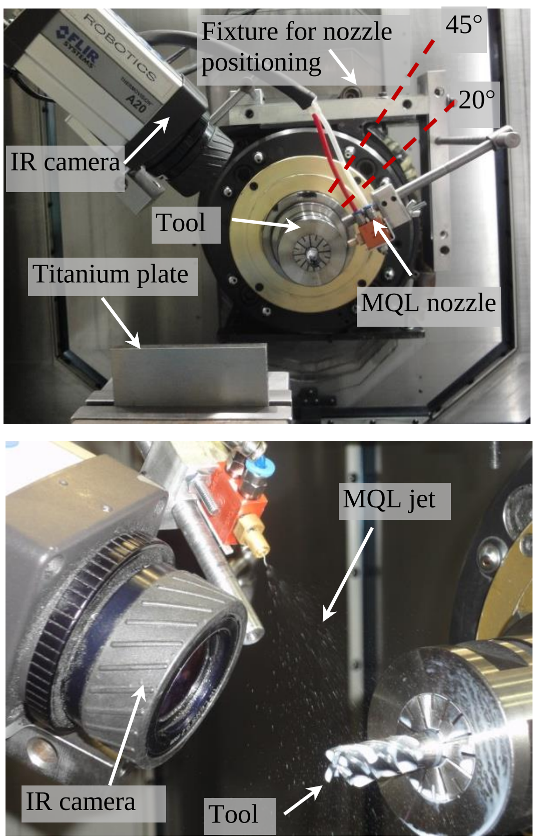

Figure 1 (a) Machining setup and (b) close up on the MQL jet

TABLE 1 shows the test matrix of the tested parameters. The milling tests were performed at a speed of 70 m/min with 2 mm radial depth of cut 'rd' and 6.35 mm axial depth of cut 'ad' using a 12 mm diameter SECO milling cutter "JHP770120E2 R040.0Z4ASIRA". The MQL nozzle was attached to a specially designed fixture to control the position and the orientation of the nozzle with respect to the cutting zone. The cutting forces were measured using a three- component Kistler dynamometer (Kistler 9255B). A portable Taylor Hobson surtronic, with 0.8 mm cut off and 0.02 mm resolution was used to measure the roughness of the machined surfaces. All the experimental tests were performed at the Aerospace Manufacturing, Structures, Materials and Manufacturing (SMM) Laboratory, National research Council Canada. The vegetable based "Mecagreen 550" oil was used to form a 5% concentration emulsion for the MQL tests. The "TRIM VHP E210" oil was used for 5% emulsion for flood coolant.

Figure 1 shows (a) the set up used in the machining tests, and (b) an example of the aerosol coming out of the MQL nozzle. The figure shows positions of the MQL nozel with the Thermovision A20 infrared (IR) camera, which was used to measure the temperature field near the cutting zone during the MQL and dry milling tests. Temperature measurements during flood machining could not be measured at the cutting area while flooded with the cutting coolant.

III. RESULTS AND DISCUSSIONS

A. *Effect of MQL Parameters on Machining Performance*

In this section, the effect of different MQL parameters on the machining performance is studied. **Figure 2** shows the main cutting force for different combinations of AFR and OFR applied at different orientations (θ) and for two nozzle distances from the cutting zone, 40 and 80 mm respectively. From the force results, it can be shown that the main cutting force decreases with the decrease of nozzle distance, i.e. 40 mm. This can be attributed to the fact that the closer the nozzle, the better penetration of the MQL jet to the cutting area. Additionally, better MQL penetration was achieved at high OFR/high AFR (17.5 ml/min and 31 l/min) combination. This is demonstrated by the 15% decrease in the cutting force as compared to other MQL combinations. This can be attributed to the jet characteristics associated with this MQL parameters that can give small droplets of oil at high velocity, which is recommended for machining due to better penetration and accessibility and hence, better lubrication and cooling effect [33]. As an effect of the nozzle orientation, lower cutting force can be observed with the 45° nozzle orientation. This can be due to the better accessibility of the jet to the cutting area at this angle, especially the area with the maximum chip load.

The effect of the tested MQL parameters on the surface finish is shown in **Figure 3**. It can be noticed that the surface roughness decreases with the decrease of the nozzle distance from 80 mm to 40 mm. This can be attributed to the better atomization the jet applied, and hence its penetration at closer distance to the cutting area, which is in agreement with visualization results in literature. Lower surface roughness can be observed with the 45° nozzle orientation. This can be demonstrated by the decrease of surface roughness by up to 37% as compared to other nozzle orientations for all the MQL OFR/AFR combinations. This is mainly due to the better accesibility of the jet to the cutting area, which improves the lubrication capacity of the jet and hence, the surface quality. Additionally, better surface finish is achieved with MQL jet at high OFR/high AFR (17.5 ml/min and 31 l/min) combination. This is demonstrated by the decrease in the surface roughness by up to 60% as compared to other MQL combintations. This can be attirbuted to the high velocity of the small droplets of oil associated with this MQL parameters. This jet characteristics enhances the penetration to the cutting zone and hence, improves the machining performance [33].

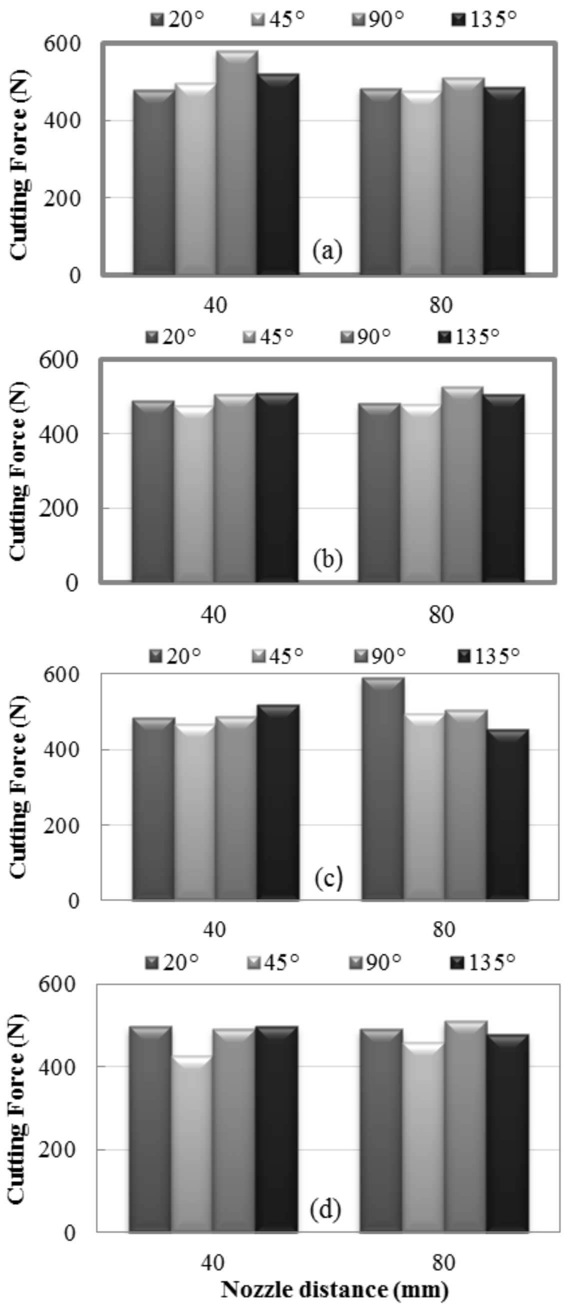

Figure 2 Cutting forces for different MQL parameters, a) OFR = 10 ml/min, AFR = 25 l/min, b) OFR = 10 ml/min, AFR = 31 l/min, c) OFR = 17.5 ml/min, AFR = 25 l/min and d) OFR = 17.5 ml/min, AFR = 31 l/min

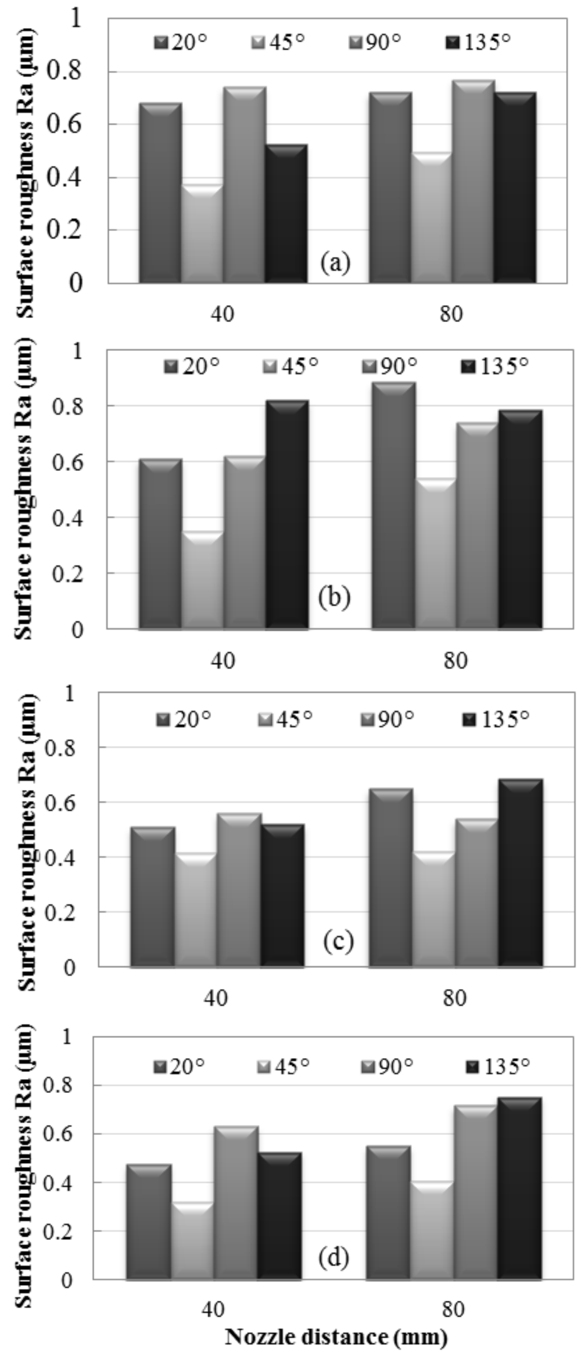

Figure 3 Surface roughness for different MQL parameters, a) OFR = 10 ml/min, AFR = 25 l/min, b) OFR = 10 ml/min, AFR = 31 l/min, c) OFR = 17.5 ml/min, AFR = 25 l/min and d) OFR = 17.5 ml/min, AFR = 31 l/min

Figure 4 shows the results of the tool temperature measurements for different MQL parameters, nozzle distance and orientations. Similar to the forces and surfance roughness, it can be noticed that lower tool temperature was achieved with the application of MQL with 17.5 ml/min oil flow rate and 31 l/min air flow rate, as compared to the remaining MQL combinations, by up to 48% reduction in the tool temperature. This is mainly attributed to the jet characteristics (droplet size and axial velocity) associated with the OFR and AFR.

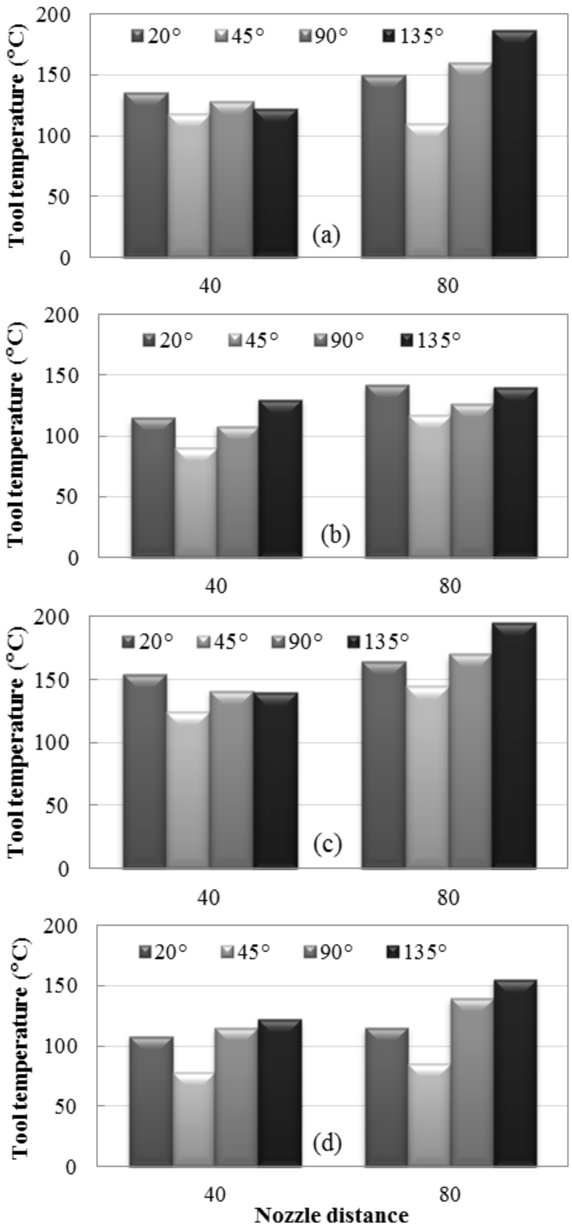

Figure 4 Tool temperature for different MQL parameters, a) OFR = 10 ml/min, AFR = 25 l/min, b) OFR = 10 ml/min, AFR = 31 l/min, c) OFR = 17.5 ml/min, AFR = 25 l/min and d) OFR = 17.5 ml/min, AFR = 31 l/min

This condition leads to better atomization and penetration of the MQL jet, and hence improved cooling capacity of the jet in addition to the better lubrication obtained with higher oil flow rate. Additionally, an increase in the tool temperature, by up to 16%, can be noticed with the increase of the nozzle distance from 40 mm to 80 mm. This trend is in agreement with the effect of nozzle distance on the cutting force and surfcae roughness, which is related to the poor atomization and hence, penetration of the jet with the increase of the distance between the nozzle and the zone of application. Lower tool temperature can be observed with the 45° nozzle orientation as compared to other tested angles (by up to 40% reduction in the tool temperature). This can be attributed to the better accesibility of the jet to the cutting area, specially to the area with the maximum chip load. Therefore, it was shown that better machining performance was achieved using MQL jet at high OFR/AFR (17.5 ml/min and 31 l/min) applied at 40 mm from the cutting area with the nozzle positioned at 45° with repsect to the feed direction.

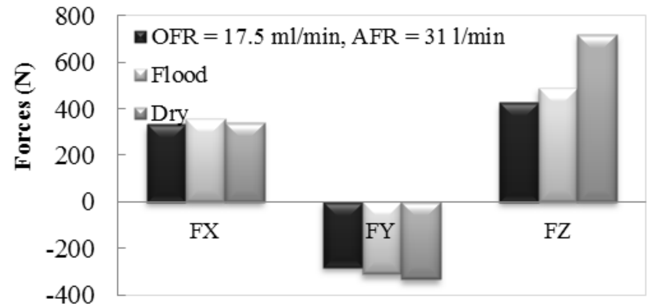

Figure 5 Cutting forces for MQL, flood and dry cutting

B. MQL vs Flood and Dry Milling

The machining performance of the optimum MQL jet (with optimum OFR/AFR, 40 mm distance and 45° orientation) was compared to flood and dry cutting. **Figure 5** shows the cutting forces for MQL vs flood and dry. It can be noticed that for the optimum MQL jet, the cutting forces are slightly lower to the force level obtained using flood coolant (up to 13% decrease). On the other hand, a remarkable improvement in the machining performance can be noticed when using MQL as compared to dry cutting. This is demonstrated by a decrease in the main cutting force by up to 36%. Therefore, the optimum selection of MQL parameters can lead to a coherent MQL jet with small droplets, with improved atomization and penetration to the tool-chip interface, which reduces the cutting forces and can be translated into enhanced productivity.

The measured roughness of the machined surface for the optimum MQL jet, as well as, for dry and flood coolant is shown in **Figure 6**. It can be noticed that similar surface finish was obtained with flood coolant and MQL. This result promotes the application of MQL in industry given its environmental and economic impact as compared to flood. A remarkable improvement in the surface finish can be noticed by using MQL as compared to dry cutting. This is demonstrated by the 55% reduction in the surface roughness when the MQL is applied.

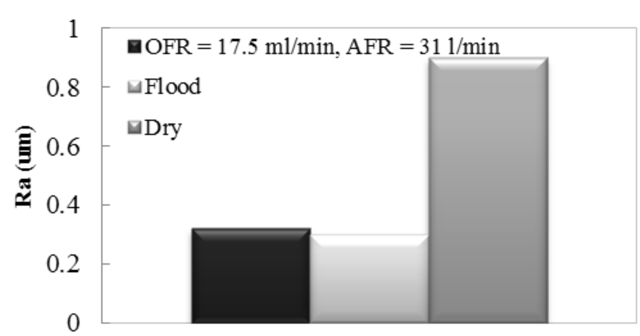

Figure 6 Surface roughness for MQL, flood and dry cutting

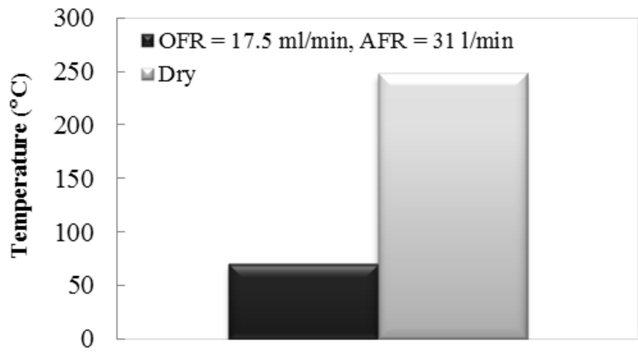

Figure 7 Tool temperature for MQL, flood and dry cutting

Figure 7 shows the results of the tool temperature measurements for MQL jet as compared to dry cutting. The temperature in case of flood coolant was not measured due to the difficulty of using the IR camera with wet conditions. A significant decrease in the tool temperature can be noticed by using MQL as compared to dry cutting. This is demonstrated by the 60% reduction in the tool temperature when the MQL is applied with the optimum parameters (i.e. OFR = 17.5 ml/min, AFR = 31 l/min and at 40 mm at 45°).

IV. ENVIRONMENTAL IMPACT OF FLOOD, MQL AND DRY MILLING OF TITANIUM ALLOYS

The Eco-indicator 99 method for life cycle analysis (LCA) was used to identify and compare the environmental impact of the different lubrication modes (i.e. dry, MQL and flood) using the single score indicator. **Figure 8** shows the stages of the LCA performed using SimaPro software to calculate the Eco-indicator single scores of the machining processes performed in this research work to compare the dry, MQL and flood lubrication modes. The materials and energy consumed are the main inputs to the LCA model of the machining process, which outputs desired products, waste materials and emissions. Selecting the appropriate waste treatment methods (e.g. material recycling and/or parts reuse) and waste scenarios can significantly improve the environmental performance of the life cycle of the process or product under study. However, the waste treatment process has its own emissions associated with the power consumption or chemical reactions that can occur during waste transformation. The impact of the emissions is determined on the environmental categories (human health, ecosystem quality and resources). The final score is calculated based on the normalized and weighted impacts of the performed activities and used materials on the mentioned environmental categories. This is performed with respect to the European continental system as the reference for the LCA model parameters (e.g. land area, area fraction of water and number of inhabitants). The database in the Eco-indicator 99_Annex Report [34] was used to provide information on the reference system and the emissions of different activities and their environmental impact.

TABLE 2 shows the main LCA model inputs to the process for the flood, MQL and dry milling processes. All the inputs indicated in **TABLE 2** are equivalent to 1 hour of milling of Ti6Al4V. This corresponds to removing 2.06 kg of Ti6Al4V at the cutting conditions of the comparative study (speed = 70 m/min, feed-rate = 610 mm/min, a_d = 6.35 mm and r_d = 2 mm). The boundaries of the LCA model include the activities of MQL and flood oils production from vegetable and inorganic oils, respectively, as specified by each oil supplier. The machining power indicated in **TABLE 2** for each lubrication mode was calculated from the resultant cutting forces measured from the cutting tests performed in this research work. The average powers of lubricant pumping and air compression were also included for the flood and the MQL types, respectively. The transportation of the MQL and flood oils was included in t.km units which reflect the product of the distance travelled by the vehicle in 'km' and the mass of the transported material in 'metric tons'. The environmental impacts of the extraction and production processes of the Ti6Al4V workpiece stock, the removed chip and the solid carbide tool have been excluded from the LCA model since they have a common effect in all lubricant types.

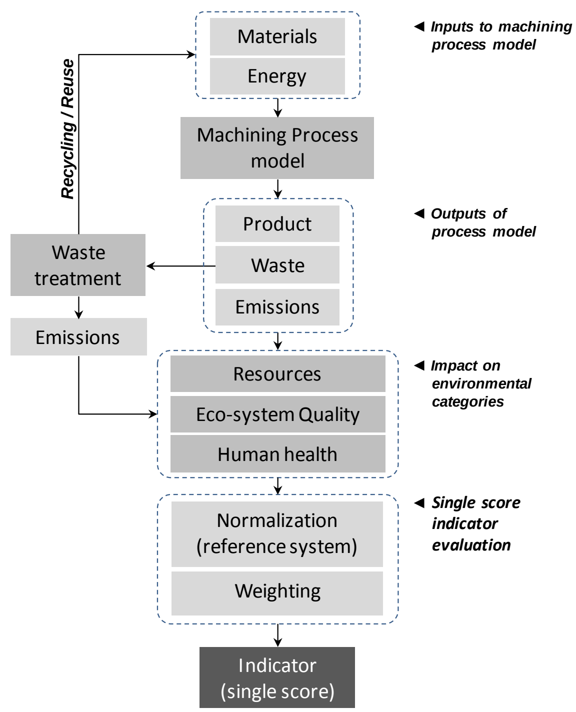

Figure 8 Single score indicator evaluation method

TABLE 2 LCA MODEL INPUTS TO FLOOD, MQL AND DRY MACHINING PROCESSES

Type	Activity	Process inputs		
		Item	Amount	Unit
Flood	Flood oil production	Oil	16.90	kg
		Water	320.80	kg
		Cargo van	1.69	t.km
		Electricity	196.55	kWh
	Machining	Electricity	5.00	kWh
	Pumping	Electricity	2.00	kWh
MQL	MQL oil production	MQL oil	1.00	kg
		Cargo van	0.10	t.km
	Compressed air	Electricity	1.00	kWh
	Machining	Electricity	4.46	kWh
Dry	Machining	Electricity	6.33	kWh

For the flood type, the full machine tool tank capacity was 3000 kg of cutting fluid, 5% of which is oil and 95% water. For the 1 hour machining process considered in this model, the flow rate of 6 l/min required 337 kg of cutting fluid of a 938 kg/m^3 density. Therefore, the effective amount of oil for the considered process was 16.9 kg based on the 5% oil ratio. The transport share of this oil amount was 1.69 t.km using a 1 ton cargo van for a distance of 100 km from the supplier to the manufacturing facility. The electrical energy required to produce this type of oil is 11.6 kWh/kg [35], which led to a total energy of 196.6 kWh to produce the specified oil amount.

For the MQL mode, only 1 Kg of vegetable based oil was used per 1 hour of machining. The MQL oil is sprayed with the pressurized air and does not recirculate into the MQL system. The transportation required for the MQL oil was 0.10 t.km using a 1 ton capacity cargo van for 100 km from the supplier to the manufacturing facility. The inputs of the dry machining process include only the machining power of Ti-alloy for 1 hour of milling.

The waste treatment of the flood lubricant after 6 months of use included the transportation of the mass of the full lubricant tank (3000 kg) to the waste oil treatment facility, where the oil and water emulsion could be separated. The waste scenario for the separated used oil was 50% recycling and 50% landfilling, and water treatment was applied to the waste water. The effect of flushing the flood and MQL oil traces suspended on the surface of the recycled formed chips was neglected compared to the effect of the amount of waste emulsion from the emptied machine tank.

TABLE 3 shows the calculated Eco-indicator single scores of the activities and processes involved in the modeled machining processes to compare the dry, MQL and flood lubrication modes. The flood machining had the highest total score, which indicates it had the highest impact on environment and hence is the least sustainable. The MQL machining had the lowest total score, which indicates it had the least environmental impact compared to flood and dry machining. The MQL single score was significantly lower than the flood machining and slightly (7%) less than the dry machining.

TABLE 3 SINGLE SCORE INDICATOR OF FLOOD, MQL AND DRY MACHINING PROCESS

Activity/process	Flood	MQL	Dry
Lubricant production	5.28	0.01	0.00
Machining of Ti-alloy	0.15	0.12	0.14
Lubricant waste treatment	1.72	0.00	0.00
50% Recycled oil product	-2.61	0.00	0.00
Total single score	4.54	0.13	0.14

The table shows that the lubricant production process contributes the most to the high score of the flood machining process score. This is mainly due to the relatively high power consumption of the oil production process as well as the oil transportation emissions. In the flood process, the waste treatment contributed to increasing the total score of the process. This is mainly due to the emissions of the water treatment process and the required transportation of the used lubricant. The negative score associated with the produced recycled oil indicates that it can be used to reduce the score of the newly produced oil.

V. CONCLUSION

Minimum Quantity Lubrication (MQL) is a promising alternative to conventional dry and flood coolant machining, for its economic and environmental advantages, as well as improved machinability. Milling tests were carried out to study the effect of different MQL parameters, such as oil flow rate/air flow rate combination, nozzle distance and orientation to define the best MQL parameters that produce the best machining performance. It was found that lower cutting forces, better surface roughness and lower tool temperature were achieved with higher AFR and OFR. Additionally, better machining performance were achieved when the nozzle was closer to the cutting area (i.e. 40 mm) with an angle of 45° with respect to the feed direction the parameters were selected to provide better atomization and better penetration of the jet into the cutting zone, which improves the cooling and lubrication capacity of MQL and hence, improves its machining performance. The optimum MQL jet was compared to flood and dry milling of Ti-4Al-6V. It was found that optimized MQL is comparable to machining under flood conditions. Additionally, optimum MQL jet showed better machining performance as compared to dry cutting, with 36% reduction in the cutting forces, 50% decrease in roughness and 60% decrease in tool temperature. The life cycle analysis of the flood, MQL and dry machining processes was conducted. The MQL machining had the lowest total score, which is significantly lower than the flood machining and slightly less than the dry machining. This indicates that MQL machining can provide a sustainable alternative to flood machining that can significantly improve the environmental and machining performance of the process.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Structures, Materials and Manufacturing Laboratory of the National Research Council of Canada, where all the experimental tests were conducted.

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