Supplementary material

Resource efficiency analysis of lubricating strategies for machining processes using Life Cycle Assessment methodology

Alessio Campitelli[1],*, Jorge Cristóbal[1], Julia Fischer[1], Beatrix Becker[1], Liselotte Schebek[1]
[1] Technical University of Darmstadt, Institute IWAR, Department of Material Flow Management and Resource Economy, Franziska-Braun-Straße 7, 64287 Darmstadt, Germany
* Corresponding author: Email: a.campitelli@iwar.tu-darmstadt.de; Phone: +49 6151 16 – 20729

1. Process parameters

Table SM1 Process parameters for the investigated drilling and milling processes

Drilling process parameters						
Process - Drilling (PD)	**Tool diameter**	**Processed metal alloy**	**cutting speed**	**Feed per revolution**	**Drilling depth**	**Machining time**
	D [mm]		v_c [m/min]	F [mm]	t_b [mm]	sec
PD1	8.5	aluminium (AlSi7MgCu0)	70	0.13	42.5	44
PD2		steel (42CrMo4)	70	0.13	42.5	58
PD3		cast iron (GJL250)	70	0.13	42.5	61

Milling process parameters								
Process - Milling (PM)	**Tool diameter**	**No. cutting edges**	**Processed metal alloy**	**cutting speed**	**feedrate**	**Infeed**		**Machining time**
						axial	**radial**	
	D [mm]	z		v_c [m/min]	f_z [mm]	a_p [mm]	a_e [mm]	sec
PM1	80	10	aluminium (AlSi7MgCu0)	1500	0,013	0,2	70	65
PM2	63	5	steel (42CrMo4)	210	0,2	0,2	31	70
PM3		5	cast iron (GJL250)	225	0,2	0,2	31	61

2. Foreground data generation

Table SM2 Generation of foreground data for relevant parameters

Parameter	Data generated by	Measurement / calculation
Electricity	own measurements	To investigate the needed electricity of the reference processes the power at the main connector of the machine, the high pressure pump and the MQL mobile device are recorded. A measuring system from National Instruments (NI 9227) in combination with the current measuring clamps of the company Chauvin Arnaux (type MN 21 and Mini 02) are used.
Compressed air	own measurements	By means of a flow sensor of the company Hontsch (type TA-Di / U10a), the flow rate of the used compressed air is measured. In order to measure the total consumption during a cutting process, the measuring system is installed in front of the machine tool as well as the MQL mobile device.
Use of FL-oil	own measurements/ calculations	The amount of used FL is calculated using the FL mass balance (see Figure SM1).
Use of MQL-oil	own measurements	To measure the consumption of MQL oil a silencer is used. This silencer is used according to the manufacturer's instructions for the cleaning of compressed air. The weight of the silencer before and after running the MQL program for 5 minutes is used to determine the flow rate of the MQL oil.
Filter fleece	Documents	The quantity of filter fleece required is determined using purchasing documents. It is important that the filter fleece quantity is assigned to the reference quantity of the investigated process per time.
Tool wear	expert interviews	The percentage of a hole over the entire service life is calculated from the service life of the tool and the drilling depth or the milling distance of the respective reference process, which are stated in meters. The service life of a tool is ascertained by the tool manufacturer.
Waste and wastewater	own calculations	The generated waste and wastewater results from the input (as shown in Figure SM1), due to the existing linear relationship between input and output streams.

3. Life Cycle Inventories

Table SM3 Input and Output data for the investigated drilling processes (PD1 – PD3) (Schebek et al., 2016)

		PD1 (Aluminium)		**PD2 (Steel)**		**PD3 (Cast iron)**	
Parameter	**unit**	**PD1-FL**	**PD1-MQL**	**PD2-FL**	**PD2-MQL**	**PD3-FL**	**PD3-MQL**
Electricity (CNC machine)*	kWh	0.055	0.045	0.066	0.057	0.141	0.114
Compressed air	Nm^3	0.17	0.32	0.26	0.35	0.30	0.40
FL-oil	g	14.5	-	193.7	-	11.6	-
MQL-oil	g	-	0.039	-	0.052	-	0.056
Filter fleece	g	0.008	-	0.022	-	0.027	-
Drilling tool	item	0.00008	0.00008	0.0006	0.0006	0.00009	0.0003
Hazardous waste „used filter fleece“	g	0.008	-	0.022	-	0.027	-
Hazardous waste “used emulsion”	g	12.9	-	172.4	-	10.3	-

of which discharge over chips	g	8	-	107	-	6.4	-
*Depending on the lubrication Strategy the FL high-pressure pump or the MMS device are also included in the energy consumption of the CNC machine.							

Table SM4 Input and Output data for the investigated milling processes (PM1 – PM3) (Schebek et al., 2016)

		PM1 (Aluminium)		PM2 (Steel)		PM3 (Cast iron)	
Parameter	**unit**	**PM1-FL**	**PM1-MQL**	**PM2-FL**	**PM2-MQL**	**PM3-FL**	**PM3-MQL**
Electricity (CNC machine)*	kWh	0.103	0.081	0.072	0.065	0.062	0.058
Compressed air	Nm³	0.31	0.40	0.20	0.23	0.23	0.40
FL-oil	g	130.3	-	59.5		60.3	-
MQL-oil	g	-	0.074	-	0.083	-	0.064
Filter fleece	g	0.011	-	0.003	-	0.003	-
Milling tool	item	0.0003	0.0003	0.0001	0.0001	0.0001	0.0003
Hazardous waste „used filter fleece“	g	0.011	-	0.003	-	0.003	-
Hazardous waste “used emulsion”	g	116	-	44.9	-	45.7	-
of which discharge over chips	g	72	-	0		0.8	-
*Depending on the lubrication Strategy the FL high-pressure pump or the MMS device are included in the energy consumption of the CNC machine.							

4. Mass balance of a flood lubrication system

The determination of FL consumption may prove to be very difficult depending on the type of operation, equipment or FL supply-system. However, the determination of measures for the reduction of FL consumption presupposes that the essential partial contributions of the FL-consumption are known.
These partial contributions are:

- the discharge through chips,
- the discharge through machining components,
- evaporation during processing and machine standstill,
- leaks,
- adhesion to the machine and the tank.

The relations between the inputs and outputs can be seen in Figure SM1. This mas balance is created using the data set up in the LernRess pilot project as an example for the reference process PM1 with FL (see also Table 2). The system boundary in this case is the machining centre. The amount of the FL emulsion is regarded as an incoming material stream (7% FL and 93% water). The FL emulsion is discharged through a plurality of material streams: the biggest material flow is frequently the FL discharge through the chips. But this can strongly depend on the machined material. A further loss factor is the exchange of the FL emulsion at the end of the service life, which is generally three months. Furthermore, parts of the emulsion are lost by evaporation.

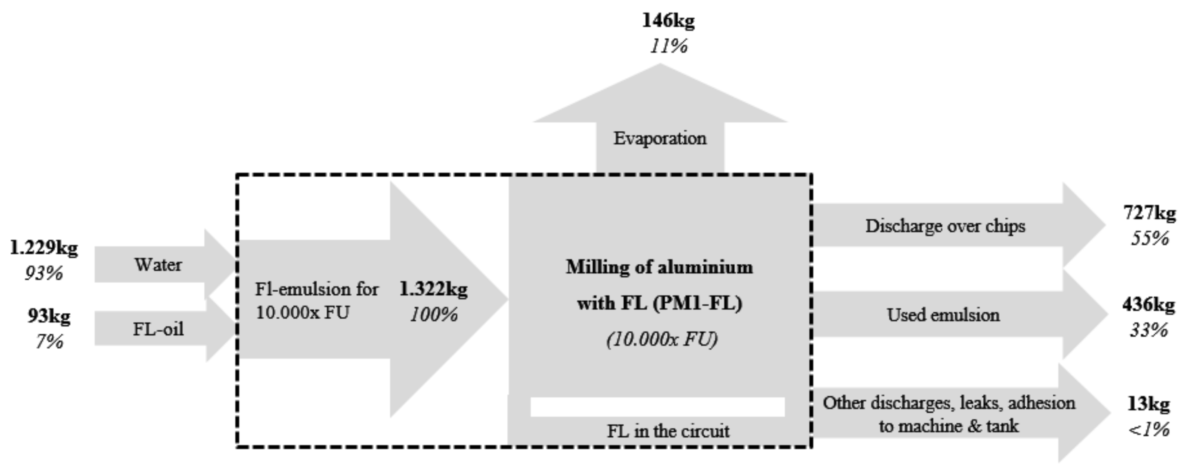

Figure SM1 Exemplary representation of a FL-mass balance for PM1-FL (Schebek et al., 2016)