Reduction and avoidance of lubricant mist demands an integrated assessment approach†

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A case study to identify major factors for lubricant mist exposure covered 15 metal machining sites. The investigation included milling, turning, drilling and grinding applications. Systematic analysis considered all relevant data concerning the machine tool, the lubricant and the suction plant. The efficiency of the implemented maintenance program at the installed filter systems was checked by concentration measurements immediately before and after service. All performed measurements of lubricant aerosol and vapor loads upstream and downstream of the installed filter systems were carried out according to VDI 2066 and BIA 3110, respectively. The selection criteria for the sites to be investigated, the systematic nature of the data acquisition and the procedure of the analysis are demonstrated in detail by performing comparisons between selected applications using emulsions and those employing straight oil for lubrication. The results of the study identify recirculation of ventilated air as the major source of workplace exposure to airborne lubricant emissions. More than 60% of the demisters investigated emit air at total lubricant loads (aerosols and vapor) above the limit of 20 mg m^{-3} at any time of operation; which also means immediately after service. A common reason for exceeded aerosol loads in recirculated air is *e.g.* the fact that the type of filter system applied is often not suitable for the separation problem. Loads of lubricant vapor are usually higher at the processes which use water emulsions as lubricant. In a quarter of the cases the limits were exceeded solely due to high vapor loads even immediately after service. The exposure can be reduced by replacing the lubricant, installation of a vapor separation plant or avoiding air recirculation. Maintenance time of the demisting system and aerosol separation efficiency of state-of-the-art demisting systems can be expanded by implementation of enhanced preliminary filter stages. This study confirms that appropriate service measures lower both aerosol emissions and lubricant vapor concentrations due to the reduction of exposed oil-wetted surfaces. The performed measurements show no significant relationship between loads of airborne lubricants and the type of machining process. Therefore, investigations at a much more detailed level have to be performed. However, the individual assessment of any workplace due to the complex situation remains essential.

Introduction

Metal working fluids (MWFs) are necessary to secure high quality surfaces and to extend tool life in metal cutting applications. In thermal treatment processes lubricants guarantee defined cooling rates. Extreme process conditions cause airborne emissions of MWFs into the workspace. Aerosols are generated due to high peripheral speeds of workpieces and cutting tools. Evaporation of MWFs due to hot surfaces and re-condensation as well as combustion of components causes very fine particles with diameters down to 0.1 μm. Vapor emissions occur due to the (semi-) volatility of MWF components. Airborne emissions of cutting fluids are expected to have a serious health impact on exposed employees.[1–5] Condensed oilfilms in the work environment are potential sources of accidents due to slippery surfaces and increase the risk of fire. Micro-organisms growing in organic compounds cause hygiene problems. Furthermore, environmental pollution as well as machine failures and elevated cleaning costs are relevant. In 1982 in the USA approximately 1.2 million employees were potentially exposed to MWFs.[3] In Austria in 1996 approximately 190 000 people were employed in the metal industry.[6] The four metal working sites included in this study employed 3380 people. Approximately 45% of these employees were exposed to lubricant emissions. The annual consumption of MWF concentrates and oils of the companies investigated is 650 tons.

Exposure data reported in ref. 2 provide results of several studies performed during the period 1950–96 in the USA. The collected data represent aerosol concentrations of MWFs measured in the ambience of different types of metal cutting processes. Measurement results of lubricant aerosols and vapor at 13 different types of metal working processes in Germany during 1988 and 1994 were published in ref. 1. Three-quarters of the samples were taken at milling, turning, drilling and grinding sites. Further investigations covered measurements at 28 mist separation plants. The recorded data set contains upstream and downstream loads of airborne MWFs drawn by isokinetic sampling according to VDI 2066 and BIA 3110 as well as particle size distributions at the investigated site. The data set is related to area measurements using a sampling system relying on the German standard TRGS 402.

In contrast to earlier investigations, the aim of the work within this field study was to identify major sources of lubricant mist exposure at metal working sites by applying an integrated assessment approach. In addition to systematic measurements

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the investigation should include relevant aspects of the machine tool, physical and chemical properties of the MWF used as well as details about the suction plant installed. An assessment of the effectiveness of currently applied maintenance programs at the filter systems by concentration measurements immediately before and after service is the innovative aspect of this study. The goal was to check whether recirculation of ventilated air into the workroom was permissible or not. The collected data should provide a basis to optimise maintenance procedures and to propose effective measures to reduce and avoid emissions.

Description of the experimental procedures

The approach aimed to enable comparisons of data collected at different types of metal cutting processes and data derived from different companies. Therefore, systematic measurements of aerosol and vapor loads had to be related to technical data of the configuration system investigated which includes the machine tool, the lubrication and the suction plant system. The capability of the integrated assessment approach applied within this study should be validated.

The selection of the sites investigated was determined by the following criteria: The study should cover investigations (i) at the four most important metal cutting processes (occurring in regional metal industries); (ii) in different companies; (iii) at applications which employ emulsions for lubrication and straight oils at the same type of metal cutting process; and (iv) at sites which were expected to generate relevant emissions (visual inspection).

Criteria of minor priority covered technical details such as requirements for putting up measurement equipment and production schedule at the plant.

The goals of the study, to identify major factors for exposure to airborne lubricant emissions and to propose effective measures for reduction and avoidance, required detailed analyses of configuration and process parameters at the site. The type of metal cutting process, the type of lubricant employed, the phase of operation (*e.g.* smooth/rough work), the temperature of the ventilated air, the integrity of the machine tool housing and the type of suction plant (centralised/decentralised) were considered as relevant for upstream concentrations of the demisting equipment installed. The filter system was characterised by the main effect, part or stage utilised for demisting although most of the state-of-the-art filter systems combine different mechanisms or effects (*e.g.* several fiber filter stages for pre-separation of large droplets and an electrostatic force filter stage to collect the finest particles such as smoke and combustion residues). In addition to upstream and downstream parameters of the ventilated air and details about the maintenance program employed the number of working shifts at the machine tool was recorded.

Air samples drawn for measuring lubricant loads upstream and downstream of the demisting system installed were taken by isokinetic sampling according to VDI 2066. Loads of lubricant aerosols and vapor were measured separately by using a sampling system recommended by the German BIA (BIA 3110).[7] The sampling system relies on collecting the particle phase on a glass-fiber filter and adsorbing the vapor phase on Amberlite® XAD-2 adsorbent resin. The analysis of the sample was performed by eluting the charged filter and adsorbent resin with 1,1,2-trichlorotrifluoroethane (quality valid for IR spectroscopy, Merck, Darmstadt, Germany) and quantitative FTIR spectroscopy (PE Spectrum 1000, Perkin-Elmer, Norwalk, CT, USA) in the spectral region between 2800 and 3000 cm^{-1}. Spectra of standard concentrations were prepared with cutting fluid samples drawn from the machine at the site investigated. According to ref. 7 the limit of determination of the method is $0.25\ \mathrm{mg\ m}^{-3}$ for aerosols and $0.5\ \mathrm{mg\ m}^{-3}$ for vapor at a sampled air volume of $5.6\ \mathrm{m}^3$.

Depending on the aerosol concentration of the sampled air the measurement time was 15, 30, 60, 90 or 120 min in order to avoid overloading the sampling filter. Upstream of the demisting system the measurement time never exceeded 30 min due to high concentration of aerosol. An important requirement of the performed measurement was to ensure that one pair of samples, upstream and downstream of the filter system, was drawn during machining the same workpiece at the machine tool to ensure equal upstream concentration when the downstream sample was drawn.

Concentration limits for airborne lubricant emissions

In Germany threshold limit values for airborne lubricant concentrations at the workplace were issued in 1996 for aerosols and for the sum of aerosols and vapor (Table 1). The Austrian limit values for loads of airborne MWFs at the workplace are of the quality of recommended standards. Furthermore, the Austrian approach differs from the German standard in qualifying the toxic potential of the vapor phase. In contrast to the German approach the Austrian legislation does not limit airborne lubricant emissions of recirculated air. In Germany recirculation is permissible if the sum of aerosols and vapor does not exceed 20% of the threshold limit value (ZH 1/248 and VDI 2261 Bl. 3) at the workplace (Table 1). Recirculation of ventilated air is forbidden in Austria as well as in Germany if the lubricant contains substances that are expected to cause cancer.

In this paper, exceedence of the limit value is deemed to have occurred if the Austrian limits at the workplace, which are given as $1\ \mathrm{mg\ m}^{-3}$ for aerosols and $20\ \mathrm{mg\ m}^{-3}$ for the sum of aerosols and vapor, are exceeded.

Results

The performed study covered systematic analysis and measurements at 15 metal machining sites. Table 2 provides information about numbers of different system configurations. The investigation included milling, drilling, turning and grinding processes. Drilling was either performed together with milling or turning work. One-third of the machine tools were equipped with full-integrated housing. The MWFs employed divided into two different sorts of straight oil and five qualities of water emulsion (3–6%). All decentralised suction plants were equipped with compact filter devices and recirculated ventilated air into the workroom. Centralised plants drew off air after separation.

At processes where straight oil was used for lubrication, smoke appeared frequently during operation (*e.g.* rough work). These applications were either equipped with electrostatic filters or fiber filters enhanced by using a HEPA (high efficiency particulate air filter, according to EN 1822) filter stage for separation of particularly fine aerosols. Sinter plate element filters occurred only together with milling/drilling applications. All centrifugal force filters were more than 10 years old. At one single milling/drilling site, lubricant vapor separation was performed by utilising activated charcoal.

All four different types of demisting systems installed at the sites investigated are listed in Table 3. As mentioned above they are characterised by the main effect, part or stage utilised for separation, despite the fact that most of the devices combine several different types of demisting stages. Table 4 gives details of applied maintenance programs and rates. Maintenance rates depended mainly on the type of filter system, upstream concentrations of aerosolised lubricants, loads of chips and dust, the number of working shifts at the machine tool, and also on specific properties of the lubricant

Table 1 Threshold limit values of airborne lubricant emissions at the workplace and for recirculation of exhaust air after mist separation. All values in mg m^{-3}

	Austria		Germany	
	Limit at the workplace	Limit for air recirculation	Limit at the workplace	Limit for air recirculation
Aerosols	1	—	—	—
Sum of aerosols and vapor	20	—	10	2

Table 2 Number of system configurations investigated (machine tools, lubrication and suction plant including demisting)

Machine tool[a]			Lubrication		Suction plant[b]							
	Housing				Type		Demisting system[c]				Ventilated air	
Process	FI	PI	Emulsion (3–6%)	Straight oil	C	D	EF	SPE	FF	CFF	R	O
Milling/drilling	3	4	6	1	3	4	3	4	2	—	4	3
Turning/drilling	5	—	4	1	—	5	1	—	2	2	5	—
Grinding	2	1	1	2	—	3	1	—	4	2	3	—

[a] Machine tool housing: FI, full integrated housing; PI, partial integrated housing. [b] Suction plant: C, central suction plant; D, decentralised suction plant; R, air recirculated to workroom; O, outgoing air. [c] Demisting system: EF, electrostatic filter; SPE, sinter plate element filter; FF, fiber filter; CFF, centrifugal force filter.

Table 3 Service programs of industrial demisting systems

	Maintenance program	
Demisting system	Rate/months	Work
Electrostatic filter	1–1.5	Cleaning/replacement of wiremesh or synthetic preliminary demister stages; cleaning the collector of the electrostatic stage
Sinter plate element filter	1.5	Backsweeping and washing of the sinter plate elements; replacement of broken parts
Fiber filter	1–6 (18)	Cleaning/replacement of wiremesh or synthetic demister stages; replacement of HEPA elements
Centrifugal force filter	3–6	Cleaning and/or replacement of wiremesh and/or fiber filter stages used as preliminary and/or fine filter stages

Table 4 Airborne lubricant emissions of industrial demisters measured immediately before and after service (average and range, containing all measured exhaust air loads at milling, turning, drilling and grinding processes)

Load of lubricant aerosols			Total lubricant load (sum of aerosol and vapor load)/mg m^{-3}		
	Before service	After service		Before service	After service
Minimum	0.3	0.1	Minimum	1.2	0.9
Average	1.7	1.2	Average	20	18
Maximum	6.1	3.5	Maximum	63	48

and organisational demands. Sinter plate element filters and some fiber filter systems utilise the pressure drop at the system for indicating service demand.

In conformity with the results published in ref. 1, aerosol and vapor loads upstream and downstream of the demisting system were scattered over a wide range and were not significant for the type of metal cutting process. Vapor loads were usually higher at sites where emulsions were used. Table 4 provides the range and average of aerosol loads and total lubricant loads (sum of aerosols and vapor) measured in ventilated air after demisting immediately before and after service. As indicated by the values of Table 4 the average aerosol load at all the sites investigated exceeded the defined limit value of 1 mg m^{-3} in both cases, immediately before and after maintenance. The mean value of the total loads of airborne lubricants (aerosols and vapor) in the ventilated air was at the limit at service time and slightly underneath immediately afterwards.

Fig. 1 gives the percentage of sites investigated where the preliminary defined limit loads for recirculation of ventilated air were exceeded immediately before and after service. The results show that immediately before service 70% of the cases recirculate exhaust air into the workroom at inadmissible loads of airborne lubricants. Immediately after maintenance the measurements indicate that total lubricant loads are still exceeded at 60% of the sites. Regarding the aerosols solely, 54% of the measured downstream concentrations exceeded the limit of 1 mg m^{-3}. Before service 30% of downstream samples exceeded the total limit value solely due to vapor loads. The applied service program reduced the exceeded concentrations due to high vapor loads to a quarter of the sites checked.

In the following, the systematic nature of the assessment

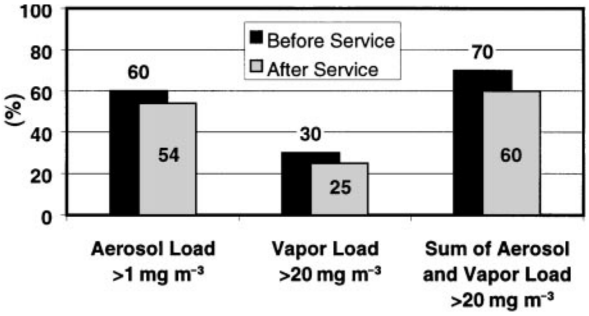

Fig. 1 Analysis of lubricant loads exceeding the limit values immediately before and after service.

approach applied within this field study and the results achievable are demonstrated in detail by presenting some selected examples of the sites investigated. In addition to the results of the measurements performed, Table 5 provides relevant background information about the configuration of the machine tool, the lubrication and the demisting system at the selected processes. For each type of process an example site employing emulsion and an application for using straight oil is listed.

Discussion and conclusion

In the following, the integrated assessment approach applied within this study will be demonstrated by performing detailed analysis and comparison of the measurement results given in Table 5. Its capability to identify major sources of airborne lubricant emission and to formulate effective measures will be verified.

Changes in the quality of capturing generated emissions at the site are dominated by the decrease of ventilated air during maintenance time due to the elevated pressure drop of a clogged filter system. For example, the filter at the machine tool Ecocut 1 (milling/drilling, checkpoint No. F2/F3) was operated at approximately 50% of the nominal air flow of the electrostatic demister installed. The intended expansion of residence time for the charged air in the demister system results in extremely low downstream loads of lubricant aerosols as attested by the measurement results provided (checkpoint No. F2/F3). The measured loads of lubricant vapor are extremely high at Ecocut 1, even immediately after service. Forty-two days after service downstream loads of aerosols are still less than 1 mg m^{-3}. The appropriate measure at this site is to check the vapor pressure of the lubricant in order to avoid high loads of gaseous phase. The volume of ventilated air at the fiber filter, which is part of the suction plant at Gildemeister (turning/drilling, checkpoint No. D5/D6), decreased by approximately 25% within less than 25 d. Even worse is the situation at Karstens (grinding, checkpoint No. S1/S2) where the HEPA filter stage of the fiber filter system installed was completely clogged. This example demonstrates the consequences of belated service drastically: Exposure to hazardous emissions is caused due to the reduction of ventilated air and by re-emission of lubricants from dirty filters (checkpoint No. S1/S2). The centrifugal force filter installed at the Oerlikon Boehringer (turning/drilling, checkpoint No. D1) was not serviced within 6 months. The difference of the vapor load measured upstream and downstream of the filter system indicates a measurement error due to an overloaded sampling filter (turning/drilling, checkpoint No. D1).

Sinter plate element filters cause a high pressure drop due to the fine pores necessary for highly efficient aerosol separation. The measured loads at Hüller Hille 11/12 (milling/drilling, checkpoint No. F4/F5) indicate a certain transformation of lubricant aerosols into vapor caused by the filter system itself. The phase shift induced by the high-pressure drop at the filter system results in zero separation efficiency for aerosol loads at the end of the service time. A comparison between applications using water emulsion for lubrication and those which employ straight oil indicates significantly that vapor loads were less when straight oil was used for lubrication.

In addition to the fact that high vapor loads are usually associated with high concentrations of aerosols, high temperatures in the machine housing as well as the physical properties of the lubricant employed also determine the load of gaseous phase. This is significantly demonstrated if vapor loads at Ecocut 1 (milling/drilling, checkpoint No. F2/F3) and Hüller Hille 11/12 (milling/drilling, checkpoint No. F4/F5) are compared.

For sampling volatile particles (liquid and also solid materials) on fiber filters several points have to be considered in order to avoid measurement errors or to assess the reliability of the results obtained. For sampling aerosolised MWFs, there is the risk that some of the collected liquid adhering to the sampling filter will be stripped off during sampling if the gaseous phase is not saturated with MWF vapor. Evaporative losses of sampled aerosols result in an underestimation of the liquid phase. However, quantification of evaporative losses is complex. The amount of losses depends mainly on the vapor pressure of the sampled MWF aerosols, the degree of saturation of the sampled gas, the gas velocity penetrating the sampling filter and the sampling time.

The saturation rate of the air in the suction plant depends on the retention time in the connecting pipes between the machine tool and the filter system. Hence, upstream of filter systems in central suction plants the ventilated air can be regarded as saturated. Ventilated air upstream of filter systems installed in decentralised suction plants often remains unsaturated. Further relevant factors determining the conditions of the ventilated air are the integrity of the machine tool housing, the vapor pressure of the MWF employed and the temperature of the ventilated air. Unsaturated conditions may also be present during phases of operation where workpieces are changed.

Ideal isokinetic sampling of volatile particles requires equal filtration velocities at the sampling filter, which means the same by-pass flow rate, respectively. Differences in the velocities of the sampling air flow penetrating the sampling filter cause different amounts of evaporative losses of the collected lubricant. In reality it is impossible to ensure equal flow rates if isokinetic sampling is performed. The velocity in the pipe of the suction plant and the selected diameter of the nozzle at the sampling probe determine the rate of the by-pass flow during isokinetic sampling. Realising a constant flow rate would require continuous adjustable nozzles at the sampling probe.

Uncertainties resulting from differences in the sampling time have to be taken into account when measurements between upstream and downstream loads of MWF particles are compared. Upstream sampling time normally has to be kept short in order to avoid overloading the sampling filter. Measurements downstream of highly efficient filter systems may need to be performed for a prolonged period in order to reach the detection limit of the method. However, further research is required to quantify uncertainties in the field of sampling volatile particulate matter.

The described assessment approach identifies recirculation of ventilated air into the workroom as the major source of workplace exposure at metal working sites. More than half of the state-of-the-art filter equipment investigated, which was designed for aerosols separation only, was not able to ensure exhaust aerosol loads below the limit for workplace recirculation. For a high upstream load of aerosols, enhanced preliminary filter stages can be an efficient measure to elevate the

Table 5 Measurement results of selected sites investigated within the described field study

Machine tool		Lubrication		Demisting system: Technical information				Demisting system: Measurement results											
												Upstream load/ mg m^{-3}			Downstream load/ mg m^{-3}			Separation efficiency[h] (%)	
Name	Housing[a]	Type[b]	Manufacturer	Type[c]	Exhaust air[d]	Manufacturer, date	Nominal air flow/ $m^3 h^{-1}$	Checkpoint no.	Measured air flow/ $m^3 h^{-1}$	Time after service/d	Temperature/ °C	A[e]	V[f]	A+V[g]	A	V	A+V	A	A+V
Milling/drilling—																			
Ecocut 1	FI	WE	Aral Sarol 474 EP, Aral	EF	R	Ifs Industrie-filter-Service, IFE 5000 D, 1996	4.800	F2	2.209	15	24.5	2	55.2	57.2	0.1	44.9	45	94.2	21.4
								F3	1.997	42	27.5	8.4	61.6	70	0.6	62.4	63	92.5	9.9
Hüller Hille 11/12	PI	WE	Estramet S 33, Oemeta	SPE	O	Heimpel & Besler, Sinterstar 7,1, >10 years	5000	F4	7.901	6	23.5	4.3	7	11.3	1.3	7.1	8.4	69.7	25.7
								F5	7.558	135	30	3.7	5.2	8.9	0.5	8.5	9	86	(−1.1)
Liebherr LC 255	FI	SO	OMV CUT XU, OMV AG	EF	R	CZECH, EP 1000, 1998	1.700	F11	1.154	3	28	20.6	0.1	20.7	0.8	0.1	0.9	96	95.5
								F12	1.063	50	26	12.7	0.8	13.5	0.9	0.3	1.2	92.9	91.3
Turning/drilling—																			
Oerlikon Boehringer	FI	WE	BIO KS 3	CFF	R	Ing. G. Hoffmann, Type 12, >10 years	1.000	D1	846	6	6	35	33.8	68.8	3.5	19.3	22.8	90	66.8
R.N.F.90 Gilde-meister	FI	SO	OMV CUT XU	EF	R	CZECH, EP 1000, 1997	1.400	D5	1.459	3	27	14.5	5.6	21.1	0.6	4.7	5.3	95.9	73.9
								D6	1.086	25	30	9.7	8.9	18.6	0.4	5.5	5.9	96.1	68.3
Grinding—																			
Karstens	PI	WE	BIO KS 3, Quaker Chemical	FF	R	ISI-Industrie-Produkte, FIB 1800, 1992	1.800	S1	633	9	23.5	5.7	7.3	13	1.1	7.5	8.6	80.8	33.7
								S2	102	152	26	8.9	34.8	43.7	6.1	26.7	32.8	31.5	25
Gleason-Phoenix	FI	SO	Excelene 416, D. A. Stuart	FF	R	Hoffmann Filter, DLT 40 R, 1991	No info	S5	471	4	31	1.5	1.2	2.7	1.8	1.3	3.1	(−20)	(−14.8)

[a] According to Table 2. [b] WE = water emulsion; SO = straight oil. [c,d] According to Table 2. [e] A = aerosol. [f] V = vapor. [g] A + V = sum of aerosol and vapor. [h] (Upstream load − downstream load)/upstream load × 100 (%).

aerosol separation efficiency and also the maintenance rate. The performed comparison demonstrates that high loads of lubricant vapor are mainly related to the physical properties of the lubricant in use. Changing the MWF is a suitable and effective measure to reduce vapor emissions in addition to the installation of a vapor separation plant or avoiding air recirculation. This study confirms that appropriate service measures lower both aerosol and vapor concentrations due to the reduction of oil-wetted surfaces exposed to the air flow. In conformity with the results published in ref. 1, aerosol and vapor loads upstream of the demisting system were scattered over a wide range even for the same type of metal cutting process or phase of operation, respectively. However, an assessment at each individual workplace is still essential.

The described assessment approach is capable of analysing the complex situation at metal-working sites and of identifying major sources of airborne lubricant emissions. The background information provided about the machine tool, the lubrication and the suction plant system enables effective measures for reduction and avoidance of exposure to be proposed.

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