

Application of Minimum Quantity Cooling Lubrication Technology in Cutting Processes

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Abstract

In spite of the manifold efforts to reach a total renouncement of the use of cooling lubricants in metal cutting for environmentally reasons, cooling lubrication is an essential condition to achieve an economical tool life and the required surface quality in many cases. Against this background, the minimum quantity cooling lubrication is an interesting possibility for an economical and environmentally compatible production which combines the functionality of the cooling lubrication with an extremely low consumption of cooling lubricants. With help of various results achieved in turning, milling and broaching experiments, this report describes the possibilities of application of minimum quantity cooling lubricating systems in machining with geometrically defined cutting edges.

Keywords: Production Process, Cooling Lubricants, Metal Cutting

Introduction

Nowadays, cooling lubricants are assessed with increasing caution because of the disadvantages incident to them like e. g. disposal problems, endangering of health and environment as well as the expenditure for cooling lubricants rectification and maintenance. Therefore many machining steps have been changed to dry machining yet.

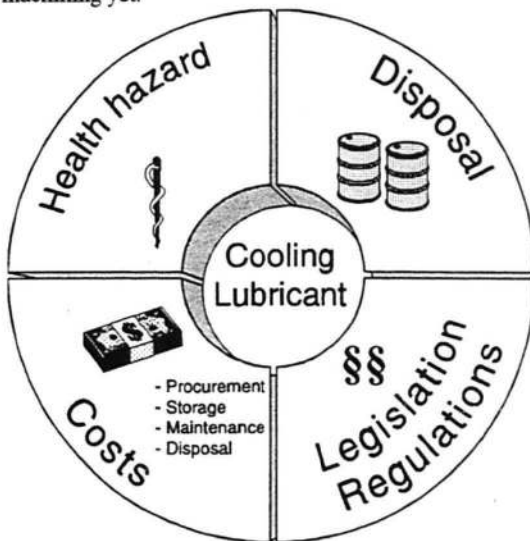


Fig. 1: Complex of problems caused by cooling lubricants

In spite of intense attempts to renounce cooling lubricants completely, a cooling lubrication is still essential in many cases to achieve an economical tool life and the required surface qualities. This applies in particular if narrow tolerances, a high dimensional and shape accuracy are required or if critical, hard to cut materials are to be machined. For that reason the minimum quantity cooling lubrication (MQCL) represents an interesting alternative which combines the functionality of the cooling lubrication with an extremely low consumption of cooling lubricants. So this is a connecting link between dry machining on the one hand and conventional cooling lubrication on the other hand. While in case of the standard use of cooling lubricants there is an intensive flooding of the machined surface, with minimum quantity cooling lubricating systems only the defined cutting area tool -

workpiece - chip is in contact with the cooling lubricant. In this cooling lubrication technology the lubricating function is ensured by the oil, the cooling function mainly by the compressed air. Compared with conventional cooling lubrication, numerous advantages result from the low consumption of cooling lubricant and the avoidance of a cooling lubricant circulation system:

- The quantity of cooling lubricant in relation to the machined workpiece volume is many times lower than in case of conventional flood cooling lubrication.
- No used up cooling lubricants arise for maintenance, dressing and disposal.
- Filtering materials and recyclings from the cooling lubricant maintenance can be avoided.
- The machined workpieces are almost dry. So a subsequent washing operation is unnecessary in many cases.
- The low content of oil remaining on the chips is uncritical for a reutilization.
- The application of biocides and preservatives can largely be renounced because only the quantity of cooling lubricant has to be provided in the reservoir of the minimum quantity cooling lubrication system which will be used in one day respectively one shift.

Since several years this technique is successfully used in various metal cutting processes, here above all in sawing, and in metal forming. Its advantages let expect a growing range of application.

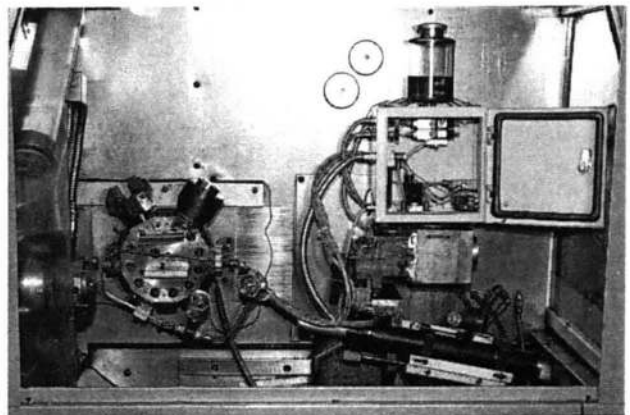


Fig. 2: Experimental arrangement in the Institute for Machine Tools (Stuttgart) for the investigation of minimum quantity cooling lubrication in turning

Up to now the influencing variables to be considered and the effects on the process result have been the subject of only a few studies [1, 2, 3, 4, 5, 6]. This paper deals with investigations about the application of minimum quantity cooling lubrication in surface milling (wbk Karlsruhe) and in turning (IfW Stuttgart) which have been carried out during the last year in both institutes in close co-operation with industrial partners.

Classification and design of minimum quantity cooling lubrication systems

Principally there are three different types of minimum quantity cooling lubrication systems. On the one hand these are the low pressure spray systems where the cooling lubricant is drawn in an air current and transmitted to the active surface as a mix. Those systems are distinguished by cooling lubricant volume flows of approximately 0.5 to 10 l/h. They are mainly used for the cooling lubrication with emulsions, produce a noticeable atomization and can only be dosed relatively roughly.

The second type of systems uses dosing pumps which pulsatory feed a defined quantity of cooling lubricant to the active surface without air. The flow rates are adjustable in a range between 0.1 and 1 ml per cycle with up to 260 cycles per minute. Those devices are mainly used in intermittent processes.

The third and mostly used type of minimum quantity cooling lubrication systems are the pressure systems where the cooling lubricant is transported to the nozzle by a pump through a separate supply pipe. There it is mixed with the separately supplied compressed air. So the quantities of air and cooling lubricant can be adjusted independently. This type of minimum quantity cooling lubrication systems is a particularly interesting alternative because it combines the functionality of the cooling lubrication with an extremely low consumption of typically 10 to 100 ml/h. At the same time, the co-axial mixture of cooling lubricant and air in the nozzle largely prevents from nebulosity. All the investigations described below refer to those systems.

Figure 3 shows a schematic diagram of a minimum quantity cooling lubrication system with the described pressure principle and its components.

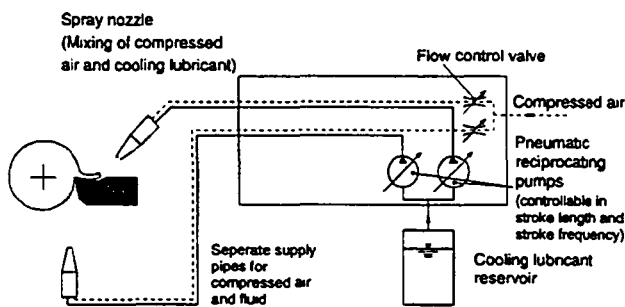


Fig. 3: Schematic diagram of a minimum quantity cooling lubrication system

The stability of the jet, that means the convergence of the air-fluid-mixture, is very important for the practical application in production machines because it determines the distance to the active surface and so the danger of collisions between minimum quantity cooling lubrication devices and tools, machine or work-piece. With different constructional solutions the various systems achieve the formation of an air-jacket around the actual spray-jet for its stabilization.

Methods for the technological investigation of different cooling lubrication technologies

For the judgment of the process-technical effects of certain cooling lubrication technologies either the process result parameters 'wear development' as well as 'surface quality and boundary influencing' or the in-process-variables 'cutting force' and 'temperature' can be used.

The judgment by means of the measurement of cutting forces has the advantage to show significant effects with comparatively little effort. So a multitude of different conditions can be considered in the investigations.

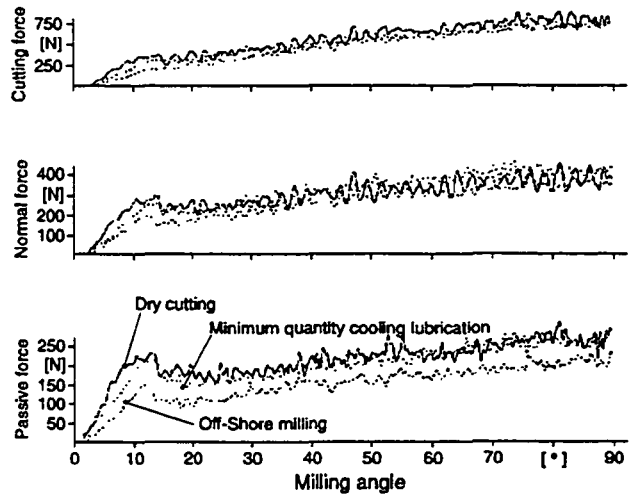


Fig. 4: Comparison of the machining forces for the cooling lubrication technologies 'dry cutting', 'off-shore milling (oil)' and 'minimum quantity cooling lubrication (oil)' (front milling of 16 Mn Cr 5 with carbide inserts P25; $v_c = 0,75$ m/s; $f_s = 0,25$ mm; $a_p = 1,5$ mm; $\varphi_{en} = 0^\circ$; $\varphi_{ms} = 90^\circ$; $\kappa = 45^\circ$; $\lambda = 18^\circ$; cooling lubricant: synthetic oil based on ester)

In the case of milling, the technology upcut milling is advantageous because the cutting edge starts to get into the workpiece material with a chip thickness of 0 mm, which means that there is a state of pure friction. This phase until penetration into the material often shows significant cooling lubrication effects.

Fig. 4 shows a comparison of cutting tests with the three different cooling lubrication technologies dry machining, conventional flood cooling lubrication (to achieve reproducible wetting conditions, the milling tool was totally dipped into cooling lubricant - the so-called off-shore milling) and minimum quantity cooling lubrication.

The transition between pure friction and chip generation is clearly perceptible at a milling angle (transition angle) of about 30° . In dry cutting this becomes exceptionally noticeable because of the perceptible drop of the forces. It is also to notice that the cutting force and the normal force level out at about the same level with growing milling angles. This behavior is not typical for the influence of the cooling lubrication [7]. Even though, there are significant differences in this machining operation between the starting phase and the time when larger effective thicknesses of cut are reached. It can be seen that the increase of forces with the tool totally dipped into the cooling lubricant is noticeably lower than with the two other cooling lubrication technologies. Moreover, it is perceptible that the force drop between the state of pure friction and chip generation can be influenced. Those force drops should be avoided because their emergence is caused by a remarkable friction load.

Systematic investigations with this method which is distinguished by low temporal and experimental efforts have shown interesting additional information. Another investigation method is the classical tool-life test, i. e. the measurement of the wear parameters in dependence on the tool path.

A comparison of the tool-life until reaching a width of wear land of 0.3 mm, taken from turning experiments under the condition of minimum quantity cooling lubrication, with the results of cutting tests using the conventional flood cooling lubrication shows, that very good machining results can be achieved even with a reduced quantity of cooling lubrication (fig. 5). In this specific case the wear curves are very close together and only start to diverge with increasing wear. All together, the tool cooled and lubricated with the oil and air mixture shows an about 10 % longer tool-life than the one used with standard cooling lubrication. In comparison to dry cutting this value increases even to 14 percent [8].

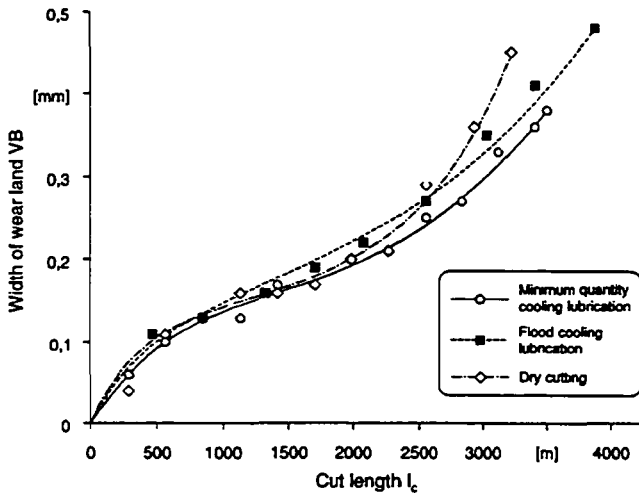


Fig. 5: Development of the tool flank wear in turning depending on the cooling lubricant used (turning of 100 Cr 6 with carbide inserts P25; cooling lubricant: ester; $v_c = 200$ m/min; $f = 0.25$ mm; $a = 1$ mm)

Functions 'Cooling', 'Lubrication' and 'Chip Transport'

In figure 6 a simplified characterization of different cooling lubrication technologies (flood cooling lubrication, minimum quantity cooling lubrication and dry machining) regarding the functions cooling, lubrication and chip transport is shown.

| Media | Cooling | Lubrication | Chip transport |
|--------------------------------|------------------------------|-------------|----------------|
| Oil | Convection of flowing fluids | + | ++ |
| Emulsion | Convection of flowing fluids | ++ | + |
| Compressed air | Convection of flowing gas | ○ | - |
| Additional coolant | Convection of flowing gas | + | - |
| Air (flowrate = cutting speed) | Convection of flowing gas | - | - |

--- Range of Flood cooling lubrication
 - - - - - Dry cutting
 - - - - - Minimum quantity cooling lubrication

++ Large effect
 + Noticeable effect
 ○ Minor effect
 - No effect

Fig. 6: Characterization of different cooling lubrication technologies

Every applicer demands a certain part of all those functions for his specific manufacturing requirement (dimension, surface, automation, tool life). That is why the question about the practical capability of certain cooling lubrication technologies is only to be answered against the background of a specific machining task.

Concerning the chip transport, minimum quantity cooling lubrication has no effect. So this demand on the cooling lubrication has to be compensated by corresponding machine tool concepts or additional media for the flushing process.

Concerning the demand 'lubrication', the tendencies well known for the flood cooling lubrication are largely valid. Limitations will only occur if the volume flow is very low. Nevertheless it can be seen from the experimental results concerning tool wear and surface quality, that there is a good chance for a substitution of the conventional flood cooling lubrication regarding this function.

The cooling effect of the minimum quantity cooling lubrication is generated either by the convection of the air-and-oil-jet or by the evaporation enthalpie. A cooling by evaporation enthalpie should be avoided as far as possible because the eventually arising products of combustion are at least suspected to be detrimental to health.

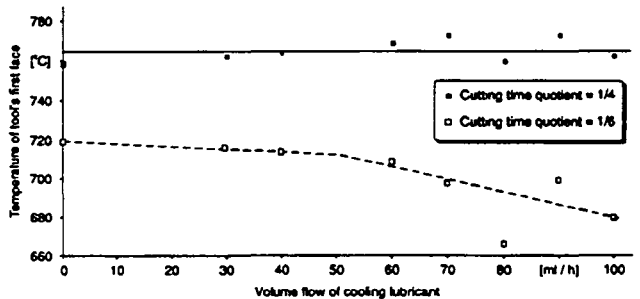


Fig. 7: Maximum temperature on the first face of a milling tool depending on the applied cooling lubricant volume flow (front milling of St 52 with carbide inserts P25; $v_c = 2$ m/s; $f_s = 0.16$ mm; $a_p = 1.5$ mm; $\varphi_{an} = 0^\circ$; $\varphi_{out} = 90^\circ$; $\kappa = 75^\circ$; $\lambda = 10^\circ$)

The cooling by convection with blownby gases can be neglected as long as there are no extreme temperature differences between workpiece / tool and cooling lubricant jet. Measurements of temperature on carbide cutting edges during the milling of steel (St 52) have shown, that in cases of very small cut lengths a low cooling effect can be noticed. Figure 7 shows a comparison of the cutting time quotients 0.25 and 0.167 where it is to observe that in the case of the smaller quotient and high volume flows a certain cooling effect occurs. The measurement was made with infrared films (see [9, 10, 11]).

Another advantage of the minimum quantity cooling lubrication is, that the strains caused by large temperature gradients which is typical for milling with conventional cooling lubrication do not appear. This is of importance especially in case of brittle cutting materials.

The fact that the cooling effect of minimum quantity cooling lubrication has to be examined process-oriented is clearly shown by results obtained from turning experiments. Temperature measurements with thermoelements underneath the cutting inserts of the tool show noticeable cooling effects (fig. 8). As it could be expected the measured temperatures are located between those of dry machining and those obtained from experiments with flood cooling lubrication.

The fact that the temperatures in turning are about 200 - 300° higher than to those occurring in milling operations, leads to a higher temperature gradient and to a higher heat transmission.

On the other hand, the stationary cutting edge of a lathe tool is continuously placed in the cooling air-and-oil jet while a cutting edge of the rotating milling tool has only very short time to get into contact with the cooling jet.

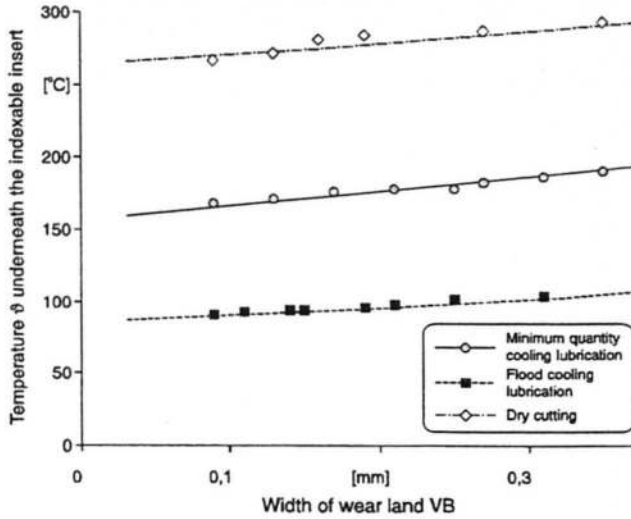


Fig. 8: Dependence of the temperature under the indexable cutting insert on wear and type of cooling lubrication (turning of 100 Cr 6 with cutting insert P25; cooling lubricant: ester; $v_c = 200$ m/min; $f = 0,25$ mm; $a = 1$ mm)

Based on the theory that the temperatures on the active surface are a certain constant amount higher than those measured underneath the indexable insert, it is possible to draw the conclusion that the tools used with minimum quantity cooling lubrication have a relatively long tool life. One of the reasons for this phenomena is that in case of flood cooling lubrication it is not possible to reach the temperatures which are necessary to soften the material in the active surface. Therefore the material is much harder to machine and causes higher wear. On the other hand the extremely high temperatures occurring during dry machining have a negative effect on the lifetime of the cutting edge. Thermal expansion during the process and the following cooling phase cause a change in the dimensions of the workpiece especially in the case of workpieces with small diameters.

The results achieved with minimum quantity cooling lubrication are due to the heat remaining in the cutting area. Investigating these facts has to be the main subject of future research activities. In comparison to other cooling lubrication technologies the actual tests show that processing with minimum quantity cooling lubrication produces better surface qualities and more accurate workpiece dimensions as well as it extends the tool's service life.

Lubricants for minimum quantity cooling lubrication systems

In minimum quantity cooling lubrication systems, non-water soluble cooling lubricants are mainly used, but hardly mineral oils. It has to be taken into consideration that because of the very low quantities of lubricants used, the costs should not prevent the use of more expensive high-tech compositions in the field of basic oils and additives.

Within the scope of the investigations, different sorts of cooling lubricants have been checked with regard to their use in minimum quantity cooling lubrication systems. The development of wear, the achievable surface quality and the cooling lubricant's

behavior during the machining process are used as criteria for judgment.

Using cooling lubricants which are designed for the use in conventional flood cooling lubrication systems is not advisable because in this case a strong atomization and evaporation, which are considered to injure health, can be observed. The more the cutting speed and connected with it the process temperatures increase, the greater the problems in this matter become. Therefore, the use of basic oils with a higher viscosity and adaptations in the field of additives is recommended. In connection with these questions, the manufacturer of the cooling lubricant should be contacted.

As expected, a comparison of the tool life (criterion is the wear of the cutting edge) between the use of emulsion and oil in milling of 16 Mn 45 with carbide inserts P25 shows the obvious advantages of the oil. Looking at various mineral oils or synthetic esterbased oils there are hardly any differences to notice between the oils in this machining process. In milling of Ck 45 with TiN-coated super-speed steel blades the latter goes for flank wear and wear of the cutting edge too.

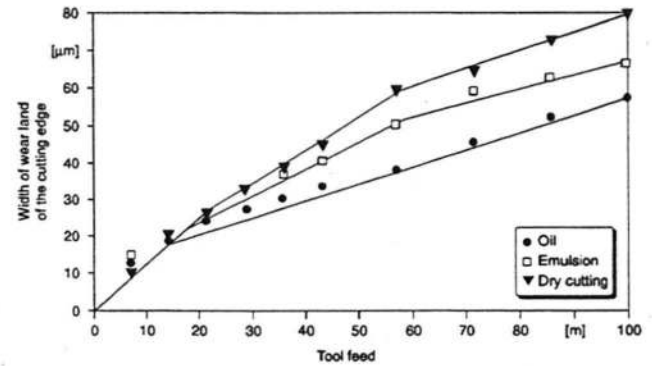


Fig. 9: Wear development on the cutting edge in dependence on the applied cooling lubricant (front milling of St 52 with carbide inserts P25; $v_c = 2$ m/s; $f_z = 0,16$ mm; $a_p = 1,5$ mm; $\varphi_{in} = 0^\circ$; $\varphi_{out} = 90^\circ$; $\kappa = 75^\circ$; $\lambda = 10^\circ$)

Possibilities to influence the cooling process during milling

Considering the problems of cooling the cutting edges caused by the use of minimum quantity cooling lubrication systems, there are still possibilities to achieve a better cooling effect. These possibilities are interesting because they offer a chance for an individual and defined adjustment of the functions 'lubrication' and 'cooling' (e. g. by adjusting the volume flow and the jet temperature). The following effects can theoretically be realized by an increased cooling effect:

- For cutting materials which get to their limit of heat resistance in certain processes, e. g. high cutting speeds, the process temperature could be lowered under the critical limit. A negative aspect in this case is the increase of temperature gradients which lead to thermal stress. This might cause cracking and shattering processes. Caused by the type of heat transmission, the temperature gradients will here be lower than with a conventional cooling lubrication system.
- The cooling has a positive effect on the surface of the workpiece if the boundary layer should only be affected as slightly as possible.

The appearance of certain wear mechanisms such as adhesion, abrasion, triboxydation and the amount of wear caused by those factors, depends on the conditions of pressure and temperature in the zone of friction on the cutting edge's surface. The appearance of adhesion for example could be reduced by cooling.

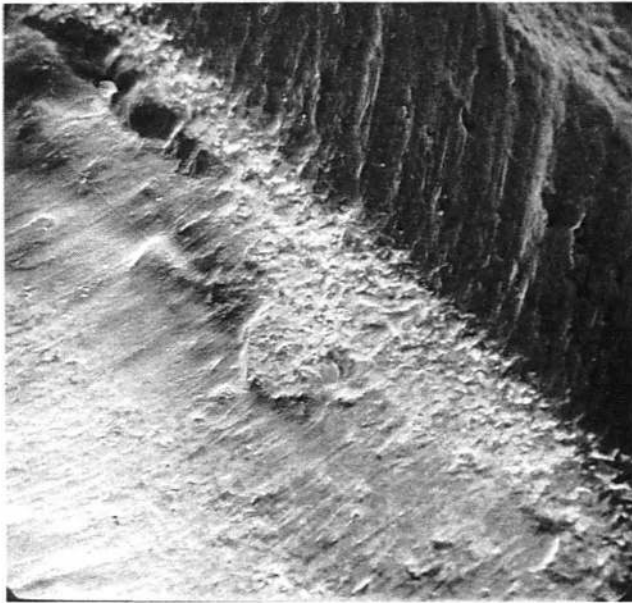


Fig. 10: Dry cutting: major cutting edge of a cutting insert P25 after machining normalized 16MnCr 5, $v_c = 3 \text{ m/s}$; $f_z = 0,25 \text{ mm}$; $a_p = 1,5 \text{ mm}$ (magnification $\times 1000$)

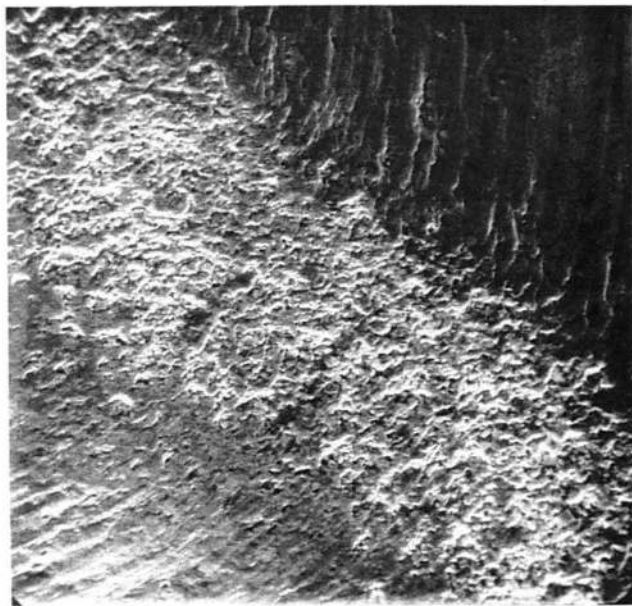


Fig. 11: Liquefied nitrogen and cooling lubricant: major cutting edge of a cutting insert P25 after machining normalized 16MnCr 5, $v_c = 3 \text{ m/s}$; $f_z = 0,25 \text{ mm}$; $a_p = 1,5 \text{ mm}$ (magnification $\times 1000$)

It can not be answered definitely which one of these effects influences the tool life. It is certain that there will be as well cases of machining where cooling has a positive effect as some cases with even a deterioration of the results. In many cases other effects might be predominant so that it is not possible to assign a significant influence to the cooling. Nevertheless, a separate cooling system still offers the possibility to influence the process specifically.

An interesting approach is the cooling of the spray jet by mixing the compressed air with liquid nitrogen. This solution is to be preferred because it tries to tackle the problem with the conception of the minimum quantity cooling lubrication system. This trend of research is the subject of actual projects in the Institute for Machine Tools and Production Science (wbk) in Karlsruhe.

The preliminary investigations carried out have shown promising results. Figures 10 and 11 show that compared with dry machining the mixing of cooling lubricant with liquid nitrogen causes an almost complete disappearance of weld-ons.

Aspects of health hazard

To be hazardous, the cooling lubricant has to get into contact with the human being. Thus, the release of the cooling lubricant is closely connected with the intake by the person. The possible ways of intake are:

- intake through stomach - intestine system (oral intake),
- intake through respiratory organs,
- intake through skin and mucous membranes.

Looking at minimum quantity cooling lubrication systems, the aspect of intake through respiratory organs is very important. The risk of health hazards caused by the intake of cooling lubricant through the skin and mucous membranes respectively by the oral intake is similar to the one caused by other cooling lubrication technologies.

In order to enable a thorough examination of this subject, it is necessary to have a detailed knowledge about the particles relevant for breathing in, which are occurring during the use of a minimum quantity cooling lubrication system. In particular information about both the size and the type of particles is necessary where the latter could be oil vapor, oil mist and oil smoke.

The emergence of these particles can be put down to several reasons. The formation of oil mist is mainly caused by the function of the minimum quantity cooling lubrication systems. They use the generated air-and-liquid-mixture for the cooling lubrication. Oil vapor is almost only developed due to thermal reasons because all the oils used in this case are low on vaporization. Then the particles of the oil mist hitting the cutting area are partially evaporated on the strongly heated up chips and cutting edge. The occurring temperatures are even so high (temperatures on carbide-blades up to 800°C) that a part of the oil is burned. This is indicated by fuming chips and smoke development on the tool.

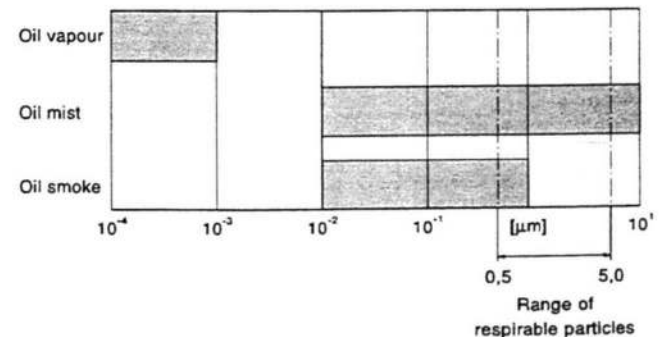


Fig. 12: Dimension of the parts originated in the minimum quantity cooling lubrication / 12 /

Injuries to the human organism can only be caused by the particles which are able to get into and remain in the lungs (the so-called "Respirable Particles"). The diameter of the particles considered for this process varies between 0.5 and 5 μm (see fig.

12). Particles with larger diameters are already filtered out in the nose; most of the particles with a diameter smaller than 0.5 μm are largely expelled again with the staled inhaled air. Only parts of the range of oil mist and oil smoke belong to the group of the respirable particles. Möller and Boor [12] consider them as relatively harmless too, because there are no injuries of the respiratory track recorded even with higher concentrations of some g/m^3 . This is inconsistent to the recommendations of the Professional Association's Institute for Industrial Safety (Berufsgenossenschaftliches Institut für Arbeitssicherheit: BIA) which suggest a maximum total concentration of oil mist and oil vapor of 20 mg/m^3 . According to the BIA's recommendation, the single concentration of oil mist should not exceed 5 mg/m^3 . However, the function of a minimum quantity cooling lubrication system is based on the generation of exactly this oil mist. Up to now, there are only insufficient facts available concerning the damaging effect of minimum quantity cooling lubrication, as well regarding the cooling lubricants as systems. Considering the potential of health hazard for the operating personnel, it seems to be absolutely necessary to realize thorough investigations in this subject area.

Even so there are already various possibilities to reduce the environmental impact by the application of minimum quantity cooling lubrication systems. There is either the possibility to use lubricants with a lower vaporization and atomization or to add so-called anti-mist additives to the basic oil. The aim of those methods is to generate cooling lubricant drops during the atomization with diameters as large as possible. The use of special nozzles is another possibility to reduce the contamination of the air with oil mist. By surrounding the spray-jet with an air-stream, the mixing of the spray-jet and the ambient air can largely be avoided. As soon as the spray-jet meets the tool and the workpiece, the jacket jet loses its effect. Another possibility to decrease the workplace's contamination is the use of special suction systems. They can be used directly at the processing area or for the filtering of the complete ambient air.

Summary and prospects

The evaluation of these test results and the experience of the metal-working industry allow the conclusion that furthermore a complete renouncement of the use of cooling lubricants in metal-cutting processes will not be possible. In many cases they will be necessary for technological reasons and will make good economic sense, even in the future. Parallel to the known technologies, alternative forms of cooling lubrication with a lower consumption of cooling lubricant have to be paid more attention to. Minimum quantity cooling lubrication systems are a considerable possibility to realize the function 'lubrication', necessary for instance to realize a certain surface quality or to achieve economic tool-life, with a minimum amount of cooling lubricant. It depends on the machining operation and the technology, whether this cooling lubrication technology is practicable. In this case the importance of the cooling lubricant for the chip transport has to be considered. The results of the latest experiments illustrate that minimum quantity cooling lubrication can be applied in praxi for various machining operation. An additional potential for the increase of the economic efficiency is given by the loss of the waste disposal problems for the worn out cooling lubricant

and oiled-up chips or the possible renouncement of workpiece washing operations.

All the described investigations deal with the processes turning and milling with TiN-coated carbide inserts. Various parameters have been tested. In case of milling, the results show that the important parameters are the volume flow of the cooling lubricant, the number of nozzles and the milling angle where the cooling lubricant is effecting the cutting operation. Parameters like the distance between the nozzle and the cutting area, the spraying angle or the adjustment relative to first face and tool flank seem to be of less importance. This makes it easier to apply minimum quantity cooling lubrication to production machines.

The function 'cooling' has to be viewed process-specifically. When using moving cutting edges, like in the case of milling, the cooling effect with the current systems can only be realized in a limited way. In the turning process the possibility of wetting the cutting edge is very limited because of the continuous cutting action where the blade is covered by the chip most of the time. A prerequisite for future investigations is to gather further knowledge about the way, the cooling lubricant gets between tool and workpiece respectively tool and flowing chip.

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