Cooling Lubrication Reduction when Machining Advanced Materials

Ekkard Brinksmeier, Paul Diersen, Anorte Zillmer, Rolf Janssen

IWT - Main Department Manufacturing Technologies and the ECO-Center for low pollution manufacturing technology
Foundation Institute for Materials Science (IWT)
Badgasteiner Straße 3
D 28359 Bremen, Germany

ABSTRACT. Coolant lubricants are an important technological constituent in metal cutting, especially in the machining of advanced and difficult-to-cut materials. For both economical and ecological reasons as well as due to the growing extent of legislation, efforts are made to reduce the great quantities of coolants and lubricants which are supplied to the process. Due to this, the introduction of dry machining and minimum quantity lubrication techniques (MQL) in machining processes increases. This paper shows an overview of the possibilities for influencing the machining process of advanced materials, e.g. titanium alloys and extreme low-sulphur steels. The research topics focus on cutting tool performance and wear mechanisms at high cutting speeds while using different lubricants and cooling supply strategies. The investigations have shown that the minimum quantity lubrication is a suitable alternative for an economical and environmentally compatible production. It combines the functionality of the cooling lubrication with an extremely low consumption of cooling lubricants and has therefore the potential to close the gap between overflow lubrication and dry machining. This paper gives a range of successful examples for the reduction of coolants in machining. In conclusion, it can be stated that it is essential to select appropriate machining parameters and suitable tools to use this potential, because it depends on the machining operation and the machining parameters whether this technology is suitable.

KEY WORDS: Dry machining, minimum quantity lubrication (MQL), hardened steels, titanium alloys, low-sulphur steels
1. Introduction

How to design an up-to-date the application of cooling lubrication? This question concerns the metalworking industry and poses problems for the users of cooling lubricants. Nowadays, a lot of information is needed for an effective and cost saving lubricant application especially for the machining of advanced materials.

In machining great quantities of coolants and lubricants are supplied to avoid thermal damages of the component, to reduce the friction between tool and workpiece, and to transport the cutting chips out of the contact zone and out of the machine tool. Nevertheless, cooling lubricants are often regarded as a supporting media that is just necessary, but not important. In many cases the cooling system is based on the assumption that the cutting process is supported better by using plenty lubrication.

The contact zone between workpiece and tool is often flooded without thinking about the requirements of the specific process. In the last decade, scientific investigations as well as industrial applications showed that the type of coolant and its supply has a great influence on the machining result. The quality of the workpiece and tool wear depend on the cooling/lubricating conditions. Thus it becomes evident that cooling lubricants are an important technological parameter in machining [BRI97a].

Advantages:
- Reduction of the used cooling lubricant
- Higher flexibility of the process due to abolition of one component (simplification)
- Better-to-reuse cutting chips

Disadvantages:
- Alternatives must be found for cooling, flushing, lubricating, transporting and conserving
- Loss of productivity is possible
- Thermal balance and residual stresses are problematic

Figure 1. Minimum quantity lubrication and dry machining (Wa 0057kesw)

On the other hand, it has to be pointed out that coolants represent a significant part of the manufacturing costs. Today almost 79,000 t of cooling lubricants are used in Germany every year, including 31,000 t of water soluble and 48,000 t of not water soluble lubricants. These lubricants have to be disposed after use. The disposal
costs range at about 250 € per ton. Furthermore, coolants may cause unhealthy effects for workers as well as for the environment. With regard to legislation regulations the renunciation of coolants would be desirable. Therefore, technological approaches to reduce the amount of cooling lubricants in cutting processes are of special interest. At present, many efforts are undertaken to develop advanced machining processes using less or no coolants. Interesting alternatives for conventional flooding coolant supply are the minimum quantity lubrication (MQL) and dry machining technologies, which make the advantages of a reduction or complete avoidance of coolants achievable (figure 1).

1.1. Minimum quantity lubrication

While a huge amount of lubricant is spilled out onto the work area when using conventional cooling lubrication methods, MQL only uses small quantities of lubricant of about 30 ml/h. The lubricant is applied by a fine spray to the work area. Different systems for the application of the lubricant and the mixture of oil and air are available on the market. All these systems are based upon the principle of a lost lubrication with dry chips and dry workpieces after the machining process (figure 2).

1. External application of lubricant supply: An external nozzle supplies the mixture of oil and air. Both components are mixed in the nozzle. This system is mostly used for subsequent integration.

2. Internal application of lubricant supply: The lubricant and the air are supplied through the spindle. Two different systems can be distinguished. The mix of air and oil can take place in the tank or the oil, and the air is separately supplied through the supply pipe. The mix and atomisation of oil and air then take place in the nozzle.

For the machining process a finely dispersed atomisation is necessary to achieve a good wetting of the contact zone between tool and workpiece. The selection of MQL parameters (flow rate, atomisation etc.) has to be done conscientious in order to achieve acceptable machining results. The influence of the atomisation on the cutting force when drilling CFK is shown in figure 3. In this investigation two adjustments on the micro lubrication system have been tested. It can be seen that the adjustment with the low flow rate reduces cutting forces compared to the conditions with higher flow rate. But the finely atomisation is connected with risks for the health of the workers because of the strain with aerosols. Due to this, the minimum quantity lubrication technology should only be used in a machine tool with an air exhaust installation.
Mixing, atomisation and application of oil and air

External application

- Mixing of oil and air in nozzle

Internal application

- Mixing of oil and air in spindle
- Mixing of oil and air at the toolholder

Figure 2. Variants of the mixture generation and application (source WZL)

Zi 0132be

Process: Reaming
Tool: Carbide, 3-cutters
Coating: TiAlN
Cooling lubr.: Micro lubrication system for internal lubricant supply through the spindle.

Cutting speed: \( v = 50 \text{ m/min} \)
Feed rate: \( f = 0.025 \text{ mm} \)
Workpiece material: CFK

Micro lubrication system for internal lubricant supply through the spindle.

Flow rate: 
Adjustment 1: 0.49 ml/min
Spray air adj.: 100%
Transport air adj.: 100%

Adjustment 2: 0.28 ml/min
Spray air adj.: 100%
Transport air adj.: 0%

Figure 3. Comparison of process forces under different MQL parameters
Even though stable processes exist for many applications, this economical and ecological friendly technology is not widely introduced in the metalworking industry. An evaluation of the Deutsche Bundesstiftung Umwelt, performed by the IWT [BRI00], showed that less than a quarter of the interrogated companies use minimum quantity lubrication. Figure 4 shows the degree of experience depending on the machining processes in the evaluated companies. It is obvious that there are differences between the manufacturing processes. It can be seen that sawing is the process where most of the experience can be found. Some companies already have experience in the application of MQL for milling and drilling and less than 2% of the companies have experience in grinding. It is also obvious that regardless of the machining process, only a few companies are planning to introduce MQL in their production.

![Figure 4. Application of minimum quantity lubrication in small and medium size enterprises](Zi 0156e)

1.2. Dry Machining

Dry machining is not an entire new technology. Many applications exist where machining without the use of cooling lubricant is possible. Dry cutting is especially used when turning or when cutting grey cast iron. Dry grinding is mainly used for hand grinders with no housing and very small feed rate. The reduction of the lubricant in the process leads to a higher process temperature. Therefore, the tools and the process parameters have to be adapted to the process.
Dry machining is less widespread than minimum quantity lubrication (figure 5). Milling and turning are the two machining processes where dry machining is most common. It is obvious that - compared with other processes - in turning processes 25 % of the companies want to introduce dry machining in the future.

![Application of dry machining in small and medium enterprises](image)

**Figure 5. Application of dry machining in small and medium enterprises (Zi 0157e)**

1.3. **Difficulties and Problems**

The advantages of MQL and dry machining are obvious. The need to dispose used lubricants is dropped. Cutting chips and grinding swarf are nearly oil-free and can be disposed as scrap. Another important advantage is that the maintenance of the lubricant is no longer necessary. As a rule the cleaning of the workpieces is also dropped and leads to cost savings in the field of manufacturing equipment, optimisation of the manufacturing process, and abolishment of a cost intensive disposal of cleaning agent. When using MQL or dry machining the main tasks of coolants in cutting processes must be successfully replaced [BRI96, BRU96, TÖN95, ZIE96]. Figure 6 lists the tasks of coolants in cutting processes and demonstrates which tasks have to be taken over by other solutions when reducing the coolant quantities. In dry machining the cooling of workpiece, tool and machine tool can not be ensured by a coolant and in MQL the small lubricant quantities can just conditionally serve this task. Hence, care must be taken for an optimal lubrication to reduce the heat generated by the friction between cutting tool and
workpiece. In the application of MQL for cutting processes the lubrication can be undertaken by suitable lubricating media. Another important task of cooling lubricants is the carriage of chips out of the contact zone to prevent a contact between hot abrasive chips and the generated surface. When establishing MQL or dry machining in industry, new solutions need to be developed to accomplish this decisive task [BRI95, KLO96].

It can be seen that there are still a lot of problems when integrating these technologies. Figure 7 shows the results of the survey concerning the current problems. It is apparent that technological problems like reduced tool life, chip transportation, and the quality of the workpiece are the mostly mentioned problems. Involving the mentioned problems with the stage of application of the companies, interesting interpretations can be found (figure 8). It is noticeable that companies with no experience in MQL see different problems than those who have introduced MQL. Companies with no experience see most problems in reduced tool life and quality of the workpiece. Companies which have introduced this technology, however, see more problems in chip transportation. Still, chip transportation and tool life are the main problems when integrating MQL. It is surprising that tool life is a main problem even for the companies with introduced MQL, although scientific research shows that the tool life increases. It is deducible from the results of the quotation that still a lot of prejudices exist.
Figure 7. Problems when integrating MQL and dry machining (Zi 0158e)

Figure 8. Problems when integrating MQL and dry machining depending on stage of application (Zi 0159e)
2. Machining of low-sulphur steels

The relationship between workpiece material properties and tool wear has to be known to improve the economical aspects for the machining of steels. The machinability of steels is highly influenced by workpiece material properties as there are [TÖN93]:

- Material structure,
- non-metallic inclusions,
- chemical composition and
- mechanical properties.

There is an interdependence between these parameters, e.g. the material structure is influenced by the chemical composition of steels, so possible interactions have to be considered. The influences of different chemical components of workpiece materials on the tool wear can be used for a metallurgical improvement of the machinability. An increase of the sulphur content in steels leads to inclusions of sulphides in the material structure. The sulphides initiate chip formation and thereby, improve chip breaking. Steels with an extremely low content of sulphur have a higher strength and fatigue strength than high sulphur steels. Due to the higher durability and reliability for motive engineering parts the industrial users are interested in reducing the content of sulphur in workpiece material. Nevertheless, latest scientific research shows problems when machining low-sulphur steels. A higher sulphur content causes greasing at the lip of the tool during the cutting-process. The improved lubrication by sulphides leads to a decrease in abrasive tool wear [DAH93, BER97] (figure 9). Considering that this positive effect does not exist for extremely low-sulphur steels, other material treatments or manufacturing activities are necessary to improve the machinability.

![Figure 9. Influence of sulphides on chip building](image)

Figure 9. Influence of sulphides on chip building
Up to now reproducible statements on machinability of low-sulphur or sulphur-free steels cannot be made. The aim of the investigations was to develop a method to improve the cutting results and reliability. Investigations on the machinability of the sulphur-low materials will be carried out for the machining processes cutting-off, profile-turning, drilling and gear shaping. Manufacturing activities are an optimised tool geometry with chip forming edges, the choice of qualified cutting material with coatings, adaptation of the cutting speed and feed and special cooling lubricants. The material science activities are heat treatment, especially soft-annealing [DIE99]. The quality of the machined material was assessed by measuring the surface finish, subsurface damage, chip-geometry and cutting forces. Investigations on tool wear are made by light-optical microscope and surface electron microscope.

Investigations on heat treatable steel with sulphur content of 0.001% and 0.007% were carried out on a multi-axis CNC-machining center and a shaping machine. For this experiments coated HSS-drills and carbides were used. The effect of cooling lubrication on the cutting-forces during the shaping process is shown in figure 10. It illustrates the reduction of forces due to the application of MQL by an excess pressure spraying system with 10 ml/h. The largest measured force occurs at the cutting force. The proportions of the other forces and their decrease, if MQL is applied, are significantly smaller. This decrease of the forces entailed an improvement of the surface quality and tool life of 20%. It is assumed that the possible reason for this result is that the lubrication effect provided by the manganese sulphides can be substituted by the MQL.

![Figure 10. Reduction of cutting forces by MQL](image-url)
In addition, the effect of cooling supply strategies for drilling with High Speed Steel drills (HSS) was also investigated. Drilling of low-sulphur steels is a particularly difficult process, because the generated chips have to be transported out of the generated hole. The effect of cooling lubrication on the tool wear of the drills is shown in figure 11. It illustrates the possible number of holes drilled until the maximum width of wear land reaches $V_{B_{\text{max}}}=0.3 \text{ mm}$. The investigations show that the use of overflow lubrication with a 5% emulsion reduces the tool wear significantly. It can be established that drilling under dry conditions is possible, but the tool life amounts to only 50% compared to wet drilling. In the case of the conversion of dry to overflow drilling the difference between the two sulphur versions increases. Concerning the surface quality and the roundness there were no considerable differences, so that the component quality is secured.

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**Figure 11. Tool life when drilling low-sulphur steel**

3. Milling of titanium alloys

Titanium alloys exhibit high specific strength and heat resistance (strength-to-density ratio), but in any cases they are difficult to machine. The low thermal conductivity and high chemical reactivity of titanium alloys cause increased tool wear, high cutting temperatures and strong adhesion between tool and part surface [ECK91, SCH96]. Due to this, welded chips on the tool surface lead to premature process disturbances (figure 12).
Accordingly, practical milling investigations on the titanium alloy TiAl6V4 were carried out on a multi-axis CNC-machining center. For this a representative series of uncoated and coated end mills of carbide metal and high speed steel were selected for the experiments. Experimental research focuses on cutting tool performance (e.g. breakage of cutting edges under high speed milling conditions and wear mechanisms while using different lubricants and cooling supply strategies). To characterise the performances of different tools and parameters, the cutting forces, the tool wear, the surface quality and the chip forming were analysed. The experiments were carried out with high speed steel (HSS) and carbide tools. Compared with HSS tools the carbide tools have shown clearly better performance under high speed cutting conditions. Increasing cutting speeds also lead to reduced tool life travel, but in opposition to HSS tools higher cutting speed can be achieved.

The effect of cooling lubrication on the tool wear of carbide tools is shown in figure 13. It illustrates the progress of the width of wear land $V_{B_{\text{max}}}$ in relation to the tool life travel. Generally, the correct use of coolants during machining operations greatly extend the tool life. Especially in the case of milling the use of minimum quantity lubrication is suitable to reduce the tool wear [BRI96, BRI97b]. In this case a special device atomises the coolant and supplies it with very low flow rates. It can be established that the use of minimum quantity lubrication decreases the tool wear.
clearly. The investigations have also shown that the use of overflow lubrication with a 6% emulsion reduces the tool wear visibly. It is evident that the reduction of the heat generated by the process reduces also the tendency of welded chips on the tool surface.

![Figure 13. Effect of cooling lubrication on the tool wear](Ja 0309b)

In addition, the effect of different cooling supply strategies for the use of High Speed Steel tools were investigated. Under this conditions the improvement with minimum quantity lubrication is clearly better. The effect is nearly the same as for the use of overflow lubrication. For the use of HSS tools, it can be established that the tendency of the titanium to pressure weld to the tool flank can almost completely avoided by the use of oil mist lubrication. These results are applicable for all investigated MQL-lubricants. The slight differences between unadditivated and high-additivated lubricants are presented in figure 14.
Products with a high amount of anti-wear additives lead to a further increase of the tool life. In this case it turned out that high-additivated products lead to better results compared with emulsions in overflow conditions. The lower tool wear leads also to an improvement of the accessible surface roughness.

4. Conclusions

Cooling lubrication assists to achieve specific results in metalworking processes. They are recognised as undesirable factors in terms of tool life, surface quality and accuracy. In recent years, the disadvantages of cooling lubricants such as disposal problems, health problems and economical reasons have lead to implement strategies to reduce the amount of cooling lubricants in metalworking. The evaluation of the described experimental results and the experiences in industry lead to the conclusion that a complete avoidance of cooling lubrication in metalworking will not be possible without deductions in tool life or surface quality. In addition the cooling lubrication is necessary for technological reasons such as chip transport or machine tool cooling. The investigations have shown that the minimum quantity lubrication is a suitable alternative for an economical and environmentally compatible production. It combines the functionality of the cooling lubrication with an extremely low consumption of cooling lubricants and has therefore the potential to close the gap between overflow lubrication and dry machining. This article gives
a range of examples of successful reduction of the amount of coolants in machining. In conclusion, it can be stated that it is essential to select appropriate machining parameters and suitable tools to utilise this potential, because it depends on the machining operation and the machining parameters whether this technology is suitable. Therefore, a detailed analysis of the whole cutting process consisting of workpiece, tool, coolant and machine tool is necessary.

5. References


