Evaluating the performance of water-miscible cutting fluids in tribotests and actual machining processes

Dipl.-Ing. Stefan Joksch
Oemeta Chemische Werke GmbH, Uetersen, Germany
joksch@oemeta.com

1. Introduction

Modern high-performance metalworking fluids (MWF) are a very important tool for cost-effective, reliable production in the metalworking industry.
Water miscible cutting fluids have to fulfil a range of requirements, such as reducing friction, transporting heat, transporting shavings, corrosion protection, long life, etc.
The most important performance criteria for high-performance MWF are the ability to reduce wear and tear on tools and to ensure the surface quality of the material being machined.
Low wear and tear on tools and reliable compliance with quality requirements for the finished component are thus the main features of the optimum use of water miscible cutting fluids. In addition to MWF-specific factors, tool costs have a major influence on unit production costs. For instance, the use of a higher-quality, more expensive MWF can certainly have a very positive effect on the economic feasibility of a production process (Figure 1)

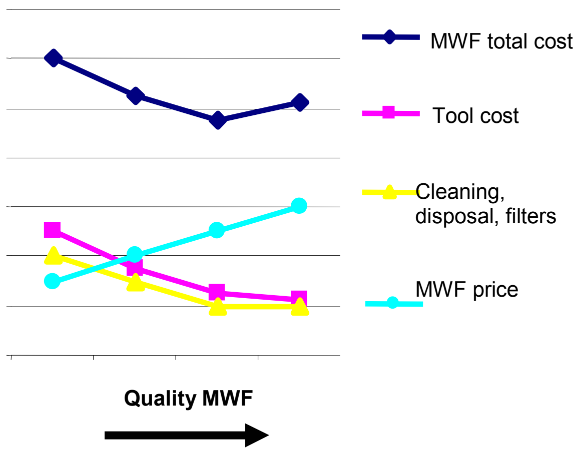


Figure 1: Economic factors MWF

In times of global competition every potential for practical cost reduction has to be exploited if the company is to remain competitive. Increasingly, companies are not only examining single processes but the entire process chain with its interactions and cross influences. For the developers and manufacturers of MWF the task is now to develop products that enable cost cutting potentials to be harnessed.
For this purpose, test methods are needed that generate basic data about the tribological performance of MWF formulations.
The main difficulty in determining suitable test methods or a test matrix is the large number of different metalworking processes. Considering the thousands of different tribological stresses, in which not even all the relevant underlying parameters are known (e.g. p, T at the cutting tip), any attempt to establish a universal test method would seem doomed right from the start. In actual fact, only relative performance comparisons of cutting fluids will be possible, even in future. It will not be possible to define a generally applicable, reproducible performance characteristic.
But surely, by skilfully combining various new and traditional test methods it would be possible to make life easier for cutting fluid developers and application technicians.

2. State of the art

The key to increase efficiency in the development of high-performance MWF is to have an understanding of the tribochemical and tribophysical processes between the material and the tool and their influence on the machining process.
Many studies into this topic have been conducted over the last 50 years. But up until the 1990s these were exclusively theoretical, as the measuring technology needed to provide evidence of the thin reaction layers of the lubrication additives on the surface of the metal were simply not available.

The resulting theories for absorption and reaction of additives are known and formed the basic knowledge for the development and optimisation of high-performance MWF for two generations of chemists (Figures 2 + 3).

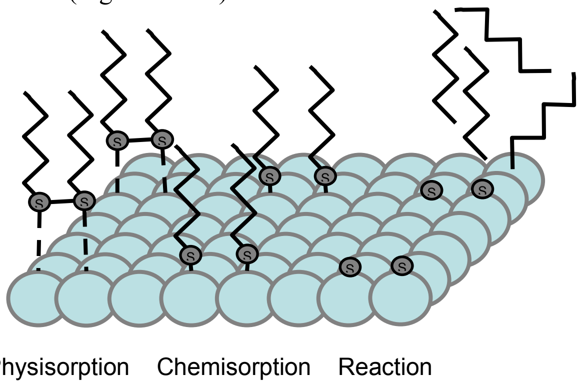


Figure 2: Theoretical model of interaction between sulphur-carrier and metallic surface S [1]

Polar substances with a high affinity to the metallic surface can be used as a lubrication carrier. Pressure absorption layers are formed by physiosorption, chemisorption and reaction. Which process takes place can be seen by the type of lubrication additive, its availability on the surface of the metal and the available activation energy.

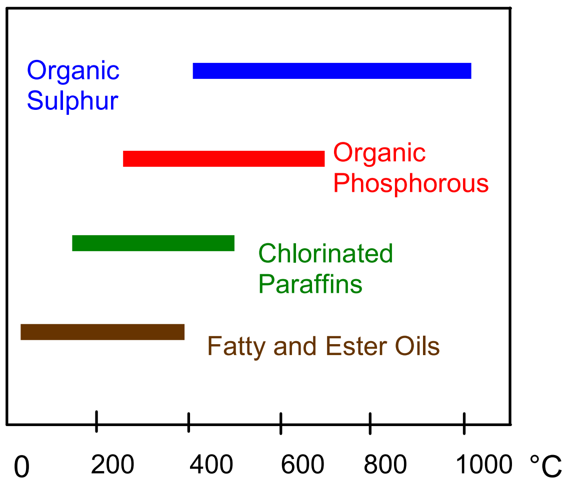


Figure 3: Activation temperature range of different lubrication additives

Through experimentation many of the theoretical models were confirmed and a deeper understanding of the processes taking place between the material and the tool was achieved.

In the past, assessment of the machining performance of MWF formulations was also the subject of various research projects. At the start of the 1990s Hübner and Heck attempted to assess the performance of non water miscible cutting fluids with simple, commonly used test methods. The results were compared with and validated on the basis of data from industrial applications and from machining tests on an automatic lathe. The authors came to the conclusion “that a reliable and comprehensive estimation of machining performance is possible only in practice.”
Only the Falex Tapping Torque Tester was able to provide usable data for the performance of the MWF formulations that were tested [2 + 3].

In 2005 a study by Rehbein und Emmer was published which focused on “Optimising the minimum quantity of cutting fluids” for the manufacture of threads in cast aluminium alloys [4]. In this study measured values from a short-time test of thread tapping, under conditions very close to reality, were compared with data from normal laboratory test methods. Again, with the traditional tribotest methods such as Reichert, Brugger, VKA and Almen-Wieland, it was determined that the results could not really be transferred to actual machining processes. However, the test rig with the model thread tapping/forming process did provide data with a high practical relevance. Only non water miscible lubricants were tested.
In other words, to the present day there is no simple laboratory test method available that could provide comprehensive, generally applicable data for the machining performance of cutting fluids.
The Tapping Torque Test still seems to have the greatest potential, but it is not 100 % satisfactory in terms of reproducibility and effort.
The author knows of no study in which the results of different tribological test methods with water miscible cutting fluids have been compared with each other and with data from practical applications.
The water miscible cutting fluids are more important than the non water miscible ones from an economic aspect. The volume of water miscible MWF in use is 10-20 times higher than the volume of non water miscible fluids.
Considering the water miscible MWF requirements, it is especially important to optimise and extend the available methods for evaluating performance.

3. Objective and definition of the project

The objective of this study is to establish a suitable test matrix for determining the machining performance of water miscible cutting fluids. The technical data of the corresponding test methods is to be checked for its economic relevance in industrial field tests.
The general requirements for a suitable test matrix and the process used are:

- minimum time requirements
- low costs
- reproducible results
- results that can be transferred to practical applications

Of course this requirements profile is like squaring the circle, as grossly simplifying the actual processes, which is needed to limit the driving effort quite naturally reduces transferability [5]. Hence, the aim is to find a well-balanced compromise between the above-mentioned requirements. The entire study was broken down into three sub-projects with different project partners (Figure 4).

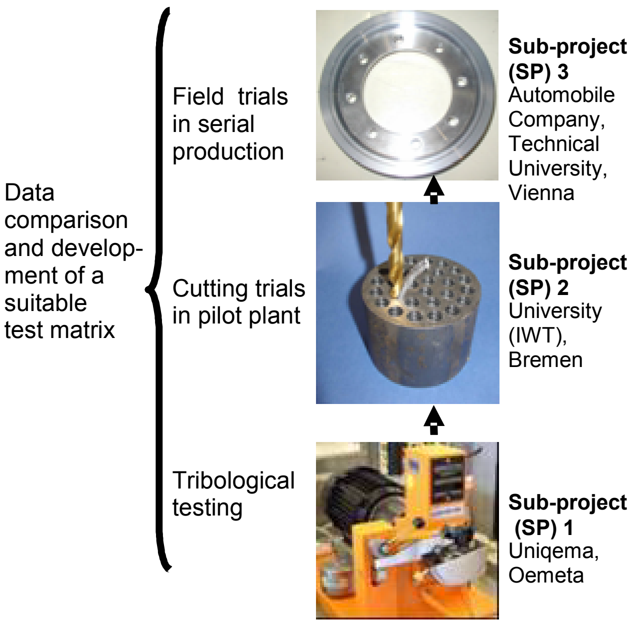


Figure 4: Project outline

3.1 Materials

Three different materials were chosen as being representative for the different machining properties of the alloys commonly used in mechanical machining. The properties of case hardened steel 16 Mn Cr5, globular cast iron GGG 60 and hypoeutectic Al alloy Al Si9 Cu3 cover a very wide range of the materials used in mechanical machining.

As test pieces of the 3 basic materials were not available for all processes, a total of 6 materials were used for the tests.

Material	Tensile Strength [N/mm^2]	Hardness HB 10
GGG 60	600	175-290 (HB 30)
16 Mn Cr5	800-1100	155-180
Al Si18	160-310*	90-140*
Al Si9 Cu3	290-310	80-110
Al Mg Si0.5	120-190	95
Bearing Steel **	N/A	700 (HV)

* Literature data, varies depending on heat treatment
** Reichert specimen

Table 1: Alloy data

Alloy code	Alloy type	
GGG 60	Globular Cast Iron	~ 3.5 % C
16 Mn Cr5	Case Hardened Steel	0.16 % C, 1.25 % Mn, 0.95% Mn
Al Si18 **	Cast Al-Alloy	18% Silicon
Al Si9 Cu3*	Cast Al-Alloy	9% Silicon, 3% Copper
Al Mg Si0.5	Wrought Al-Alloy	~ 0.5% Mg 0.5% Silicon

* = Hypoeutetic
** = Hypereutetic

Table 1a: Alloy definition

3.2 Test cutting fluids

Four different water miscible cutting fluids were defined as test candidates for the study to represent the entire performance bandwidth of the metalworking fluids. The cutting fluids were tested in various concentrations.
We used three conventional formulations (MWF A-C) and a development product (MWF D) for which no application experience has been made outside this project.
Table 2 shows the most important technical data for the cutting fluids and Table 2a contains a relative comparison of the practical properties on the basis of school marks.

MWF	Base oil	EP-add.	AW/ fric. mod.	V_{20}/ mm²/s	Water content in %
A	33 % Mineral oil	-	Fatty acids (as soaps)	124	22
A'	33 % Mineral oil	-	Fatty acids (as soaps)	60	27
B	29 % Mineral oil	S - KW 1 % S	Polyol-ester 8%	100	18
C*	75 % Polyol-ester	-	- Base oil	113	0
D*	40 % Complex-ester 25 % Mono-ester	S - KW 3 % S	- Base oil	150	0

Table 2: MWF data

MWF	Steel	GG	Al-Alloy
A	4	3	4
A'	-	-	-
B	3	2	3
C*	2	2	2
D*	(1)	(1)	(1)

* Data for D from sub-project 3

Table 2a: Field experience

3.3 Sub-project 1 – Tribological tests with laboratory equipment

In collaboration with project partner Uniqema the test methods to be considered in the first step were defined:

- Reichert friction-and-wear test
- Mini Traction Machine Reichert
- Micro Tapping Torque
- Falex Vee Block
- VKA wear/corrosion
- Optical measurement of the lubricating film thickness
- High Frequency Reciprocating Test Rig

A detailed definition and discussion of the listed test methods would far exceed the scope of this report. Table 1 gives a good, concise overview of the methods used and the relevant test parameters.
After initial screening of the methods, the suitable processes were to be examined further. To evaluate the quality of the results they were compared with the available results from the other two sub-projects and the application experiences of MWF formulations used in the market. Where necessary, in the last phase of sub-project 1 the test conditions were adapted to further improve the quality of the results.

3.4 Sub-project 2 – experiments on machining centre under "laboratory conditions"

At the Institute of Materials Technology (IWT), Production Technology Unit, the machining performance during drilling into case hardened steel 16 Mn Cr5, globular graphite cast iron GGG 60 and cast aluminium alloy Al Si18 was assessed. The cutting fluid tests were conducted on a Hermle milling/drilling centre U 630 T. (Figure 5).

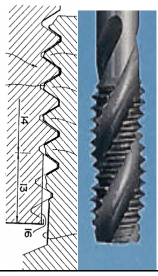
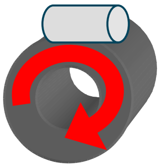
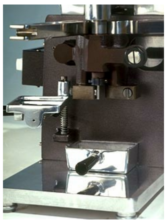
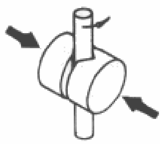
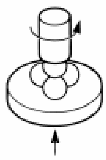
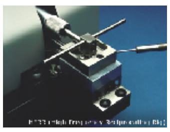
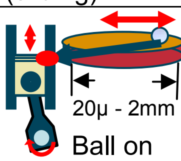
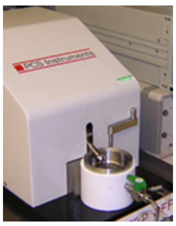
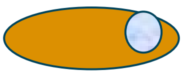
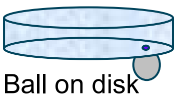
Table 3 Method		Contact	V Load	Spec .	Standard test for MWF Yes	No	Result	Re- marks
Micro-tapping torque			0.08-0.8 m/s 5 -220 Ncm Torque	–	X		Torque	Splash lubri-cation
Reichert		 Cylinder on ring	1.7 m/s	–	X		Size of wear ellipse	Splash lubri-cation
Falex Pin/ Vee block		 Pin on vee block	0.1 m/s 0 - 1350 kg	AST M D 2670 and D 3233		X	Wear, coefficient of friction (CoF)	Splash lubri-cation
Four-ball tester		 Ball on ball (sliding)	1 m/s 6 -800 kg	AST M D 2783	X nwm		Wear, failure load	Splash lubri-cation
High frequency reciprocating test rig		 Ball on disk (sliding)	10-200 Hz 0 – 1 kg	–		x	Wear, CoF	Mixed lubri-cation
Mini-traction machine		 Ball on disk (rolling)	0.02-4 m/s 1000 MPa max.	–		x	CoF (Stribeck)	Splash lubri-cation
EHD Ultra thin film test rig		 Ball on disk	0-5 m/s 700 MPa max.	-		x	Film thickness 1-1000 nm	Mixed lubri-cation

Figure 5: Hermle milling/drilling-centre U 630 T

Figure 6: Specimen 16 Mn Cr5/drill

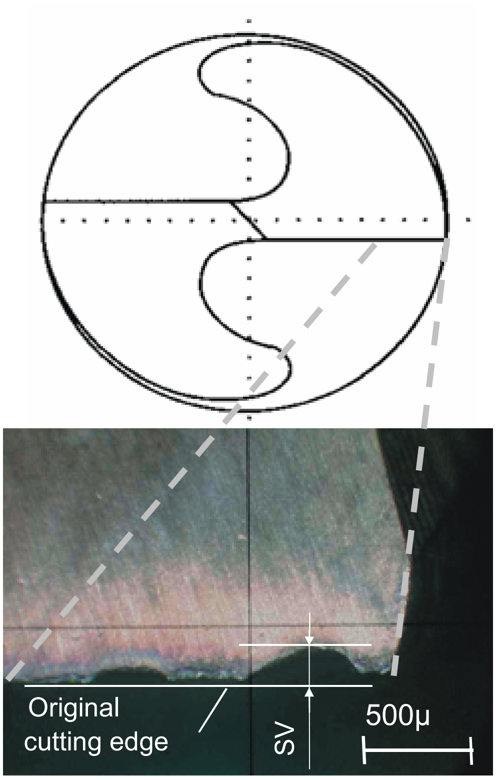


Figure 7: Cutting edge wear SV

Spiral drills DIN 338 HC/TiN with d = 8.5 and d = 6 mm, uncoated were used to machine the Al (Figure 6). In an initial test series the level of wear, the machining forces and the surface quality were measured (Figure 7). During the drilling process shavings were also removed to analyse the influence of the cutting fluids and the formation of the shavings.

In a second test series the test rig was extended by a facility to measure torque (Figure 8) and the MWF A, which was not examined in the first series.

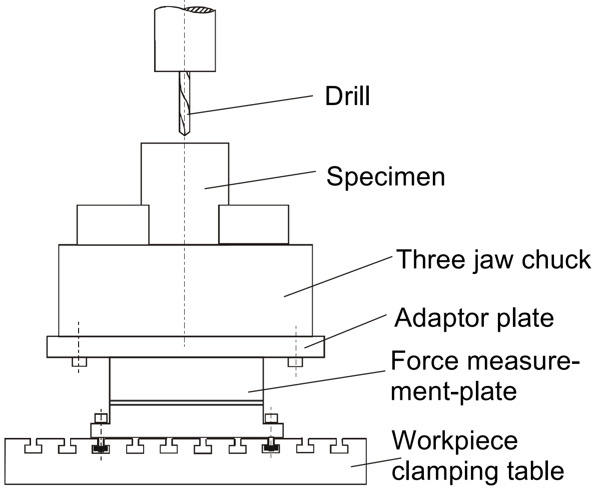


Figure 8: Experimental setup for drilling trial

3.4 Sub-project 3 – field tests in serial production at a car manufacturing company

Sub-project 3 was carried out together with the Institute of Production Technology at Vienna University of Technology and a car manufacturer within the scope of a thesis. The aim was to provide evidence of economic feasibility that would justify the high purchase price of a newly developed MWF (MWF D) with an increase in tool service life and continued material quality.
To obtain results that are as close to practice as possible, the tests were carried out during serial production. For this purpose three production units with different machining processes and different tool-material pairs were chosen. MWF C, which is used in serial production, was compared with the test product, MWF D. The data was gathered over a period of around 6 months.

Figure 9:
Field trials

So as not to interrupt ongoing production - with the involvement of the local quality assurance department and the line managers (production planners), the foremen, team spokespersons and the machine operators – the “Quality Readiness Process” was introduced to estimate all possible risks and to keep the costs of possible rejects as low as possible. This “Quality Readiness Process” was carried out using FMEA.

The following machining processes were investigated:

- Interior precision turning (component: Gear – Tapping)
- Turning (component: Bearing Box)
- Drilling (component: Fly Wheel)

A planned comparison test with MWF B could not be performed due to time constraints.

4. Results

This study was a long-term project, which was started in 2002. This is an interim report.

4.1 Sub-project 1

4.1.1 Micro-Tapping-Torque (Microtap)

The investigations were performed at two different locations. One laboratory used a forming tool while the other used a cutting tool. The Microtap test rig and the tests more or less correspond to ASTM D 5619-00 [3] and the Falex Tapping Torque Tester.

However, as opposed to the Falex machine the microtap rig records torque at the spindle and not on test material stress. This allows the use of pre-drilled test plates to reduce time and costs compared to the Falex Tester (Figure 10).

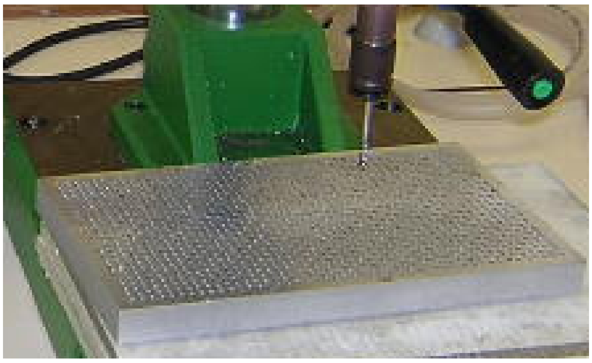


Figure 10: Microtap-testing plate

In an initial test series threads were formed in Al Mg Si0.5 and 1018 steel and threads cut in Al Mg Si0.5, Al Si18, 16 Mn Cr5 and GGG 60. After the results, especially with forming, showed a relatively good comparison with practical experiences, a second series of forming measurements was started.
This series of measurements was extended by the lower performance standard MWF A, which was included
later in the project. As several tribological tests were also performed with undiluted cutting fluids, the question as to how viscosity affects the results was raised. To answer this question a low viscosity version of MWF A, with the same proportion of lubrication parts was created and also investigated with the most interesting method, the microtap test.
Table 4 shows the results. The evaluation was made in a relative comparison of the measured values (positions 1-4) The MWF concentration was 8 %.

MWF	Cutting				Forming	
	Al 1	Al 2	Steel	GGG	Al 1	Steel
A	-	-	-	-	4	4
A’	-	-	-	-	4	4
B	2	2	1	2	3	3
C	3	2	2	2	1	2
D	1	2	2	2	2	1

A’ = MWF A - Low viscosity version
Al 1: Al Mg Si0.5 Al 2: Al Si18

Table 4. Ranking Microtap results

If we take the average values in relation to the different alloy types, we can create a ranking for the individual formulations. A comparison of the microtap ranking with practical experiences showed good to very good correlation (Table 5).

MWF		A	B	C	D
Al-Alloy	Microtap	4.0	2.3	2.0	1.7
	Practice	4.0	3.0	1.5	(1.0)
Steel	Microtap	4.0	2.0	2.0	1.5
	Practice	4.0	3	1.5	(1.0)
GGG 60	Microtap	-	2.0	2.0	2.0
	Practice	3	2.0	2.0	(1.0)
Total	Microtap	4.0	2.1	2.0	1.7
	Practice	3.7	2.7	1.6	(1.0)
Correlation		++	+	+	+

Table 5: Ranking practice/Microtap results

Depending on the material, microtap can also be used to determine the lubrication's dependency on the MWF concentration (Figure 11).

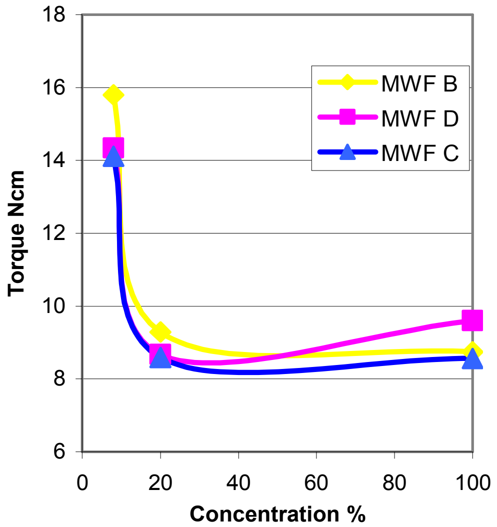


Figure 11: Thread cutting in Al Si18

In the above diagram it can be clearly seen that up to a concentration of 20 % in all MWF formulations it is possible to achieve a marked reduction in torque by increasing the concentration. This observation can also be made in practice when Al is machined. It would seem that no improvement is possible above this limit value.

Figure 12 shows the higher torque with forming and the clear differentiation between the different cutting fluids. It can be assumed that higher cutting pressures will occur with forming as opposed to cutting threads; nevertheless, EP-additive products do not automatically produce better values than those without additives.

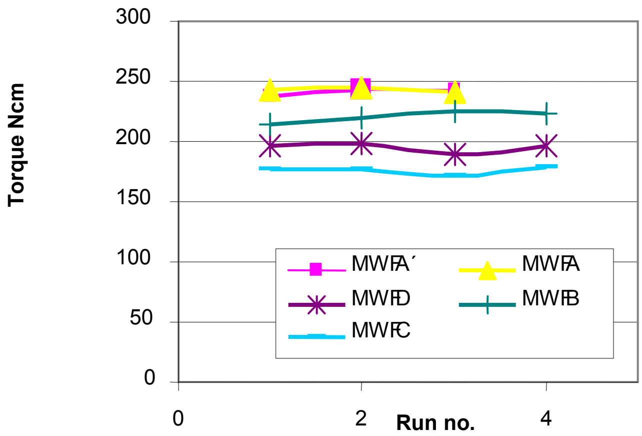


Figure 12: Thread Forming Al Mg Si0.5, MWF-conc. 8 %

When testing GGG 60 and 16Mn Cr5 the process was, interestingly enough, relatively independent from the concentration (Figures 12 + 13). A similar effect was seen with globular graphite cast iron in sub-project 3. In this case some tool service lives became even shorter with very high MWF concentrations.

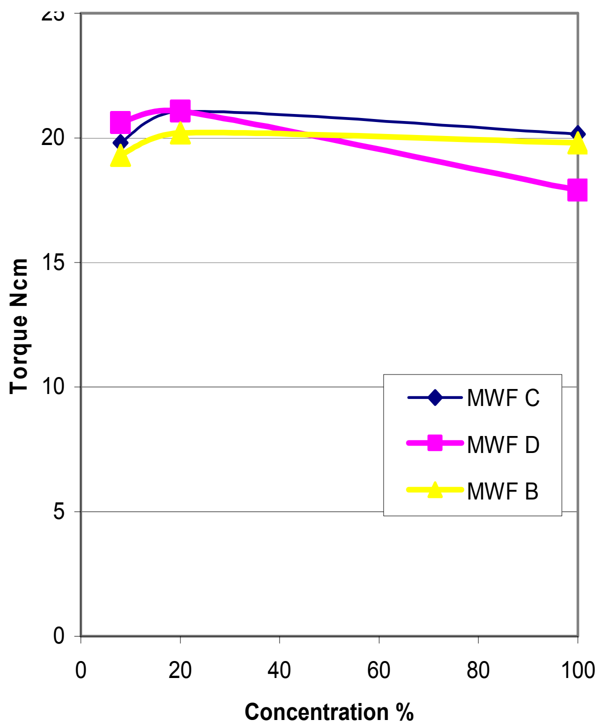


Figure 13: Thread cutting in 16 Mn Cr5

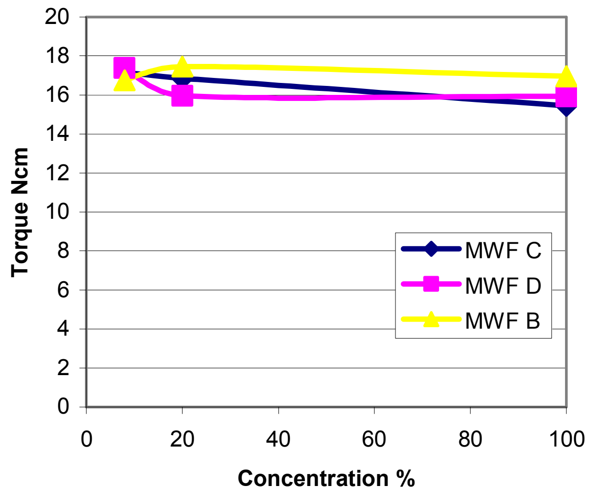


Figure 14: Thread cutting in GGG 60

On the whole the microtap test rig seems to have a certain potential for generating practice-relevant data for evaluating water miscible MWF. The thread forming process appears to provide somewhat better differentiated data than the thread cutting operation.

4.1.2 Reichert friction-and-wear test

This process has been used for many years to evaluate water miscible and non water miscible cutting fluids. Despite this, no one who works with the Reichert machine can really be satisfied with the expressive power of the results. The Reichert test is known to react well to active EP additives; but it is less sensitive to the important adsorptive agents found in Al machining. The advantages of this process are its simplicity and the availability of test specimens in different materials.
Generally steel rolls are used for the Reichert test. GGG 60 test specimens cannot be purchased. We chose not to manufacture GGG 60 rolls because of the costs involved. However, test specimens made from Al Mg Si0.5 are available. When Al specimens are used, the loading weight has to be reduced from 1.5 to approx. 0.5 kg, as otherwise the wear ellipse could be too extreme (Figure 15).

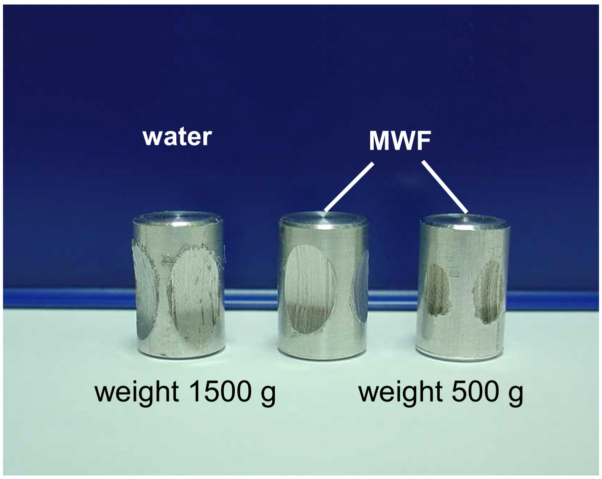


Figure 15: Wear scar on Al Mg Si0.5

The investigations were carried out independently of each other in two different laboratories. The tests in both laboratories were identical apart from one point. In the Uniqema laboratory mineral oil with no additive was used to clean and “run in” the ring wheel, the Oemeta laboratory used distilled water. Table 5 shows the summarised results of the measurement series. The data was again compiled into a type of ranking.

MWF	Al Mg Si0,5			Steel		
	Unq.	Oem.	Avg	Unq.	Oem.	Avg
A	4	3	**3.5**	4	4	**4.0**
B	3	4	**3.5**	2	3	**2.5**
C	1	3	**2.5**	2	2	**2.0**
D	1	1	**1.0**	1	1	**1.7**

Unq.: Uniqema Lab
Oem.: Oemeta Lab

Table 5: Ranking of Reichert values

The comparability can be regarded as moderate. It is possible that the differences are caused by the different "running in" media. The values in the table relate to an application concentration of 8 %.
If we take an average of the rankings from the two laboratories and compare this to the data known from practice, the transferability of the Reichert values does not look so bad (Table 6).

MWF		A	B	C	D
Al-Alloy	SP 1	3.5	3.5	2.5	1.0
	Practice	4.0	3.0	1.5	(1.0)
Steel	SP 1	4.0	2.5	2.0	1.7
	Practice	4.0	3	1.5	(1.0)
Total	SP 1	3.5	3.0	2.3	1.4
	Practice	3.7	2.7	1.6	(1.0)
Correlation		(+)	(+)	+	+

(+) Good total correlation, variations of some materials

Table 6: Ranking Reichert-results/practice

Investigations into the Reichert data's dependence on concentration produced some more interesting results. While with all steel specimens we noticed a reduction in wear when we increased the concentration of all cutting fluids (Figure 16), the corresponding data for Al alloy specimens was quite surprising (Figure 17).

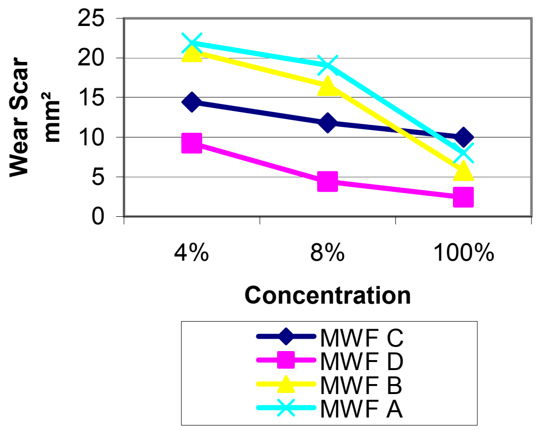


Figure 16: Reichert steel roll wear depending on MWF concentration

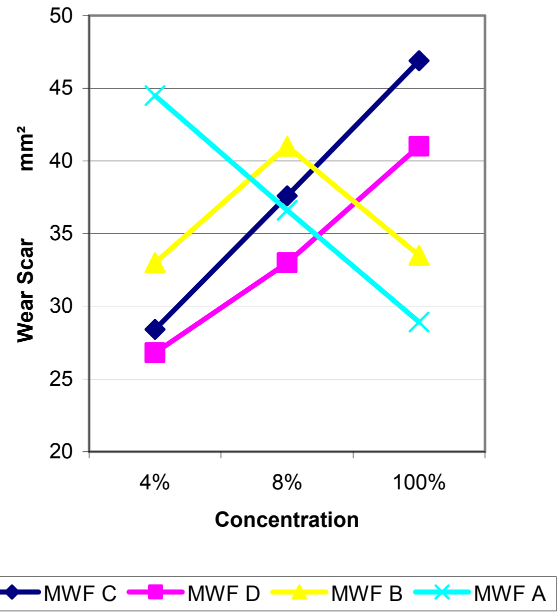


Figure 17: Reichert Al roll wear depending on MWF-concentration

In all products with large amounts of AW additives wear increased as the concentration was increased, while the products without additives acted in the same way as the steel rolls. MWF B, with an average amount of AW additives, is at a lower level when it is undiluted. This effect occurred in both the Oemeta and Uniqema series of measurements.
This phenomenon can be explained by the cooling effect of water miscible cutting fluids.

On the one hand, this is defined by the water concentration in the fluid and on the other, by the availability of the water on the surface of the metal to ensure rapid heat transport. Products C and D contained such a high quantity of AW additives that we can actually assume delayed heat transport from a certain product concentration. As opposed to products C and D concentrates, there was no more water in products A and B. In particular relatively “soft” wrought alloys, such as Al Mg Si0.5, are very sensitive to a lack of cooling during the machining process.
The fact that in the microtap tests the “overheating” effect only occurred at higher concentrations (Figure 11) can probably be attributed to the different balance in the ratio of heat generation caused by friction to heat removal through the tool, material (large drilling plate with microtap) and MWF.
Figure 18 shows that the surface of Al alloys is coated with relatively low concentrations of MWF C, which has a high quantity of AW additives. It is practically impossible to improve the level of wear protection above an activation concentration of around 2 %. This correlates with practical experience when this product is used. High performance in machining Al alloys at relatively low concentrations.

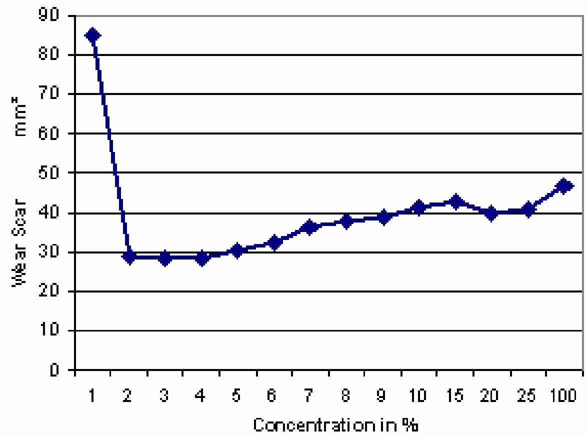


Figure 18: Reichert Al rolls activation concentration MWF C

As already investigated in the microtap test series, the influence of the MWF concentrate viscosity on measures data was now examined with the Reichert machine.
The result was repeated. The results were not dependent on the viscosity of the concentrate.

4.1.3 Falex Pin & Vee Block

The Falex Pin & Vee Block test was carried out with the friction pairs, steel (pin SAE 3135)/steel (block AI SI 1137) and steel (pin, see above)/Al alloy (block Al Mg Si0.5). GGG 60 specimens are not available on the market and would have been too expensive to manufacture for the purpose of method screening.
With the steel specimens no relevant wear was determined with any of the cutting fluids that were tested (MWF B, C, D).
In the tests of Vee Blocks with Al alloy with 2% emulsion, we were able to differentiate between wear and coefficient of friction. The ranking in the case of wear was: 1. MWF D, 2. MWF C, 3. MWF B.
With the coefficient of friction the situation was as follows:
1. MWF C, 2. MWF D, 3. MWF B
The results correspond to the expectations if we look at the product ingredients and practical experience with the respective cutting fluids.
The EP test (continuously increasing the load) could not be performed, as the specimens broke apart before the scuffing load capacity was reached.
Although the results showed the performance of the tested products quite well, it was clear that the Falex Pin & Vee Block test is not as suitable for testing water miscible cutting fluids as other methods that are performed with the same or less effort.

4.1.4 Four ball tester, EP properties

With the four-ball tester the EP properties can be determined only with undiluted concentrations. Thus, the test has a limited expressive power for water miscible MWF.
Nevertheless, it was integrated into the study because it is a generally recognised standard method.
The results clearly show the known selectivity of the test for EP additives. The ranking is similar for scuffing load capacity and wear.
1. MWF D, 2. MWF B, 3. MWF C.
The results are too one-dimensional and have relatively little practical relevance for evaluating MWF formulations. The four-ball test does not provide any information that could not also be provided by more suitable methods.

4.1.5 High Frequency Reciprocating Test Rig (HFRR)

The HFRR is good for showing the film forming properties of the cutting fluids. Figure 19 clearly shows the ranking in terms of friction coefficient:

1. MWF C, 2. MWF D, 3. MWF B, 5. MWF A and A'.

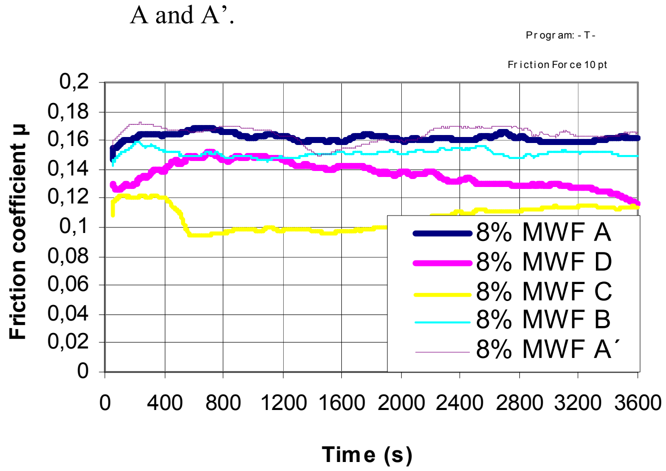


Figure 19: HFRR run with MWF emulsions, conc. 8 %

If, instead of emulsions we measure concentrates, with the changes in friction values along the time axis we can again clearly distinguish between the ester products with high levels of AW additives, the EP-free products (Figure 20) and the mineral oil products containing EP. With the ester products lubrication is immediate, while with the mineral oil products with EP the EP additive first has to "start up", then the friction coefficient is quickly reduced. With the EP-free mineral oil product we saw a continuous reduction in the friction coefficient. This could have something to do with the increasing activation of free fatty acids. In the end phase of the run the curve sketching is very difficult (> 3300 s), this requires clarification.

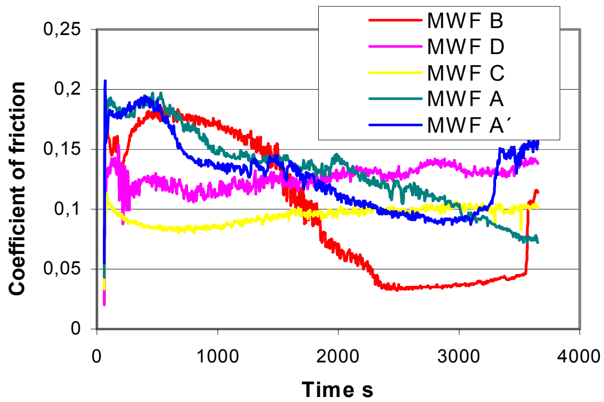


Figure 20: HFRR run with MWF concentrates

4.1.6 Mini Traction Machine (MTM)

Initially in the Mini Traction Machine test the Stribeck curve of the concentrates is recorded (Figure 21). This is as expected; in other words with lower friction speeds the ester products have much lower friction coefficients. At higher speeds in the hydrodynamic range no real differences are found between the individual products.

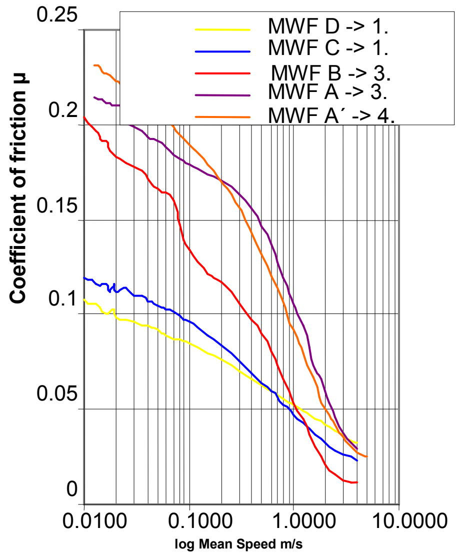


Figure 21: MTM Stribeck curves of MWF-concentrates

But the situation is quite different with emulsions. While no clear differentiation is possible at a MWF concentration of 8 % (Figure 22), the ranking of concentrate investigation seems to be reversed with 4 % emulsions (Figure 23).

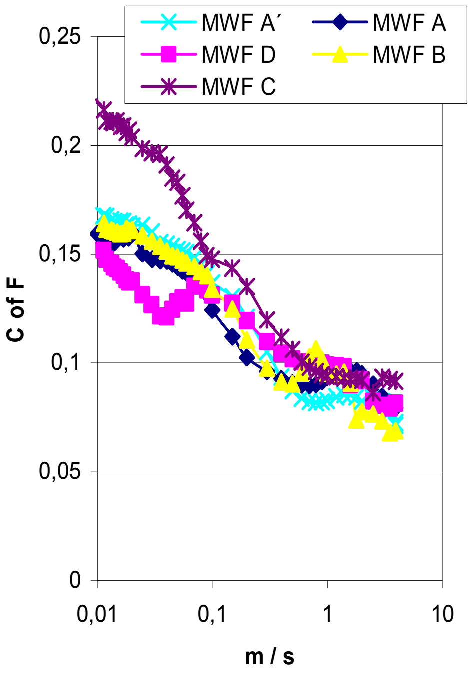


Figure 22: MTM Stribeck curves of MWF 8 % concentration

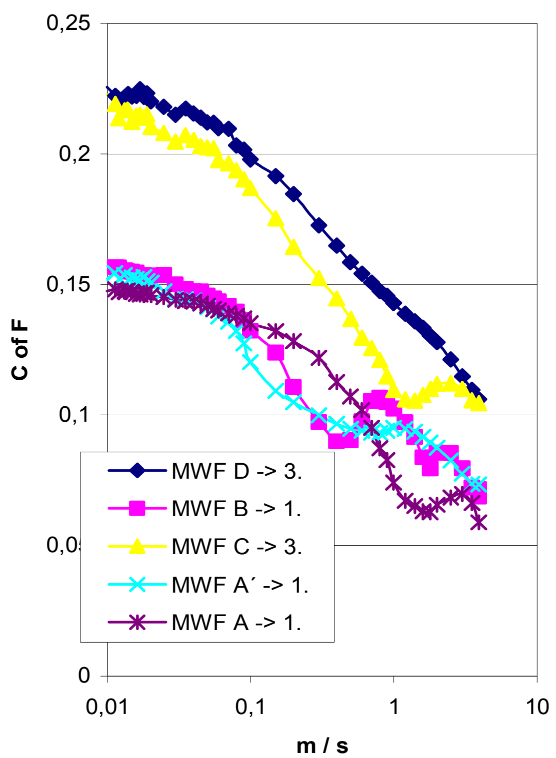


Figure 23: MTM Stribeck curves of 4 % concentration

The results for the 4 % emulsions clearly contradict the practical experiences and the results of the HFRR test.
Before the MTM can be regarded as a useful tool for evaluating the performance of MWF, the causes for these contradictory results first have to be clarified. At present there is no theoretical clarification approach. Possibly, further investigations will be made in this area.

4.1.7 EHD Ultra Thin Film Test (Optical Rig)

Unfortunately it is not possible to measure the emulsions directly, as the measured film thickness is near the detection limit and correct, reproducible measurements are not possible for such thin films with inhomogeneities in the film (oil drops, calcium soaps, etc.) (Figure 24).

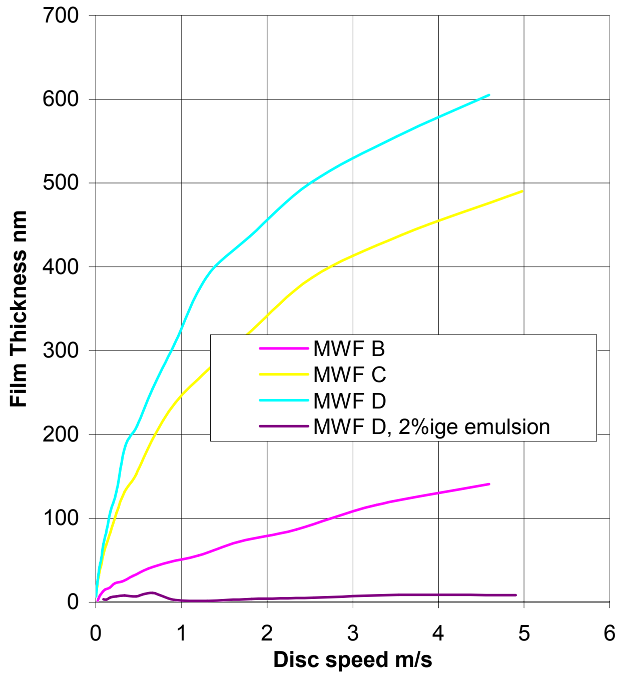


Figure 24: Optical Rig - Comparison film thickness concentrate/emulsion

The investigation of concentrates with the thin film test rig confirmed the previous results with a direct statement about the formation of film for the different products.

Again, in this investigation the ester products are better than the mineral oil products (Figure 25).

Of course we have to question just how much the measured results that were determined with concentrates can be transferred to practical applications with water miscible products. However, the comparison with experiences from practice would suggest that they can be transferred to a certain extent. In the case of applications where a good film formation or "AW properties" is important due to the process and material properties, e.g. Al alloys – products with high concentrations of esters are the most suitable MWF formulations.

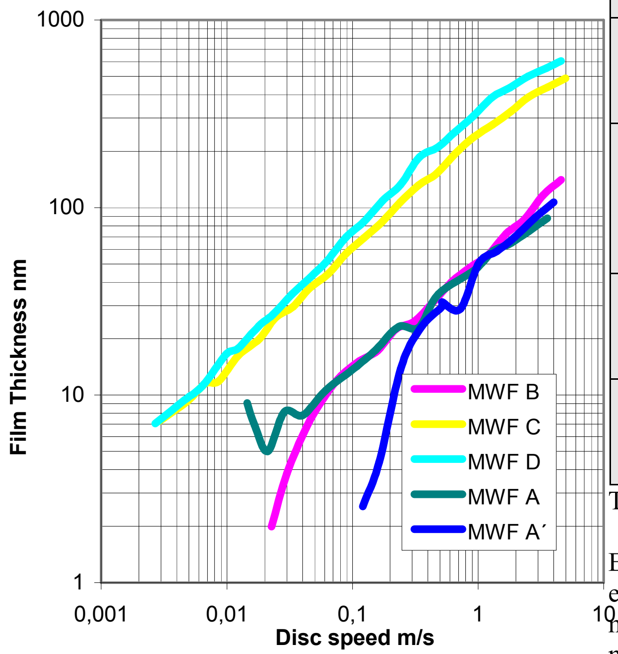


Figure 25: Optical Rig - Comparison of film thickness of different concentrates

4.2 Sub-project 2

The results of the machining tests on a Hermle machining centre are shown as a ranking table as follows:

MWF/ Conc.	16MnCr5 Tool life	GGG 60 Tool life	AlSi18 Tool life	Average
MWF B, 4%	**6**	**5**	**4**	**5.0**
MWF B, 8%	**5**	**6**	**/**	**5.5**
MWF C, 4%	**4**	**2**	**4**	**3.3**
MWF C, 8%	**3**	**1**	**2**	**2.0**
MWF C, 20%	**2**	**3**	**/**	**2.5**
MWF D, 4%	**1**	**4**	**3**	**2.7**
MWF D, 8%	**4**	**4**	**/**	**4.0**

Table 7: Ranking of MWF in pilot plant trial

Essentially, the tool life was used for the evaluation. The feed force, surface properties and microscopic investigation of the shavings provided no good data that would be suitable for differentiation of the products.

In some cases the results of the machining tests vary quite considerably from what would have been expected for the conventional products according to data from the tribo tests and practical experiences. To clarify this, a supplementary series of measurements was defined in which MWF A was also included. A facility to measure torque on the material being machined and at the seat was also installed.
The results of this investigation were not available when this report was written.

4.3 Sub-project 3

The main difficulty with sub-project 3 was to set up the processes so that the performance of the MWF could exercise a relevant influence on the tool replacement intervals. In many cases tools are replaced because a defined time has been exceeded or because tool defects keep occurring.
Of course, under such conditions it is not possible to determine the tool life prolongation potential of cutting fluids.
In sub-project 3 the involvement of a graduate student and the active cooperation of the involved departments, such as tool management, process engineering, production planning and materials technology, enabled the appropriate underlying conditions to be created.
The results were as follows.

	Al Si9Cu3	16Mn Cr5	GGG 60	Average
MWF C 4%	3	2	/	2.5
MWF C 8%	3	3	/	3.0
MWF C 10%	/	/	3	3.0
MWF C 20%	/	/	2	2.0
MWF D 4%	1	1	/	1.0
MWF D 10%	/	/	1	1.0

Table 8: Tool life ranking with different MWF at real machining processes

It was possible to increase tool life by up to 100 % compared to serial production. The savings potential in relation to tool and MWF costs is max. 30 %.
The results determined in sub-project 3 provide a good basis for evaluating data from the other two sub-projects. It would have been desirable to evaluate all 4 MWF types in practical applications.
It is planned to continue sub-project 3 with industrial partners in order to improve the data situation.
For users this will provide an opportunity to determine the most economic products for their processes.

5. Interpretation of the results - outlook

The results that have been gathered to date show that a skilful combination of different tribological laboratory investigations can certainly allow a relatively good description of the performance of water miscible cutting fluids. However, at this point it is not possible to make a final assessment. But Table 9 shows an interim result.

Method	Correlation practice	Remarks
Microtap	good	Forming better than cutting
Reichert	mean-good	Al Alloy critical, very S-selective
Falex Vee Block	bad	No differentiation possible
VKA	bad-mean	Very S-selective
HFRR	mean	Has to be discussed
MTM	mean-bad	Illogical values for emulsions
Optical Rig	-	Additional information film thickness

Table 9: Comparison of the tribo-test-results

A multi-stage laboratory test according to the following scheme would provide a good picture of the lubrication properties of a cutting fluid.

1. Reichert (perhaps plus tests on film formation or friction coefficient HFRR and/or Optical Rig)
2. Microtap (thread forming)

If possible, the material used in the actual process should be used as a specimen or at least a distinction should be made between steel and Al alloys.
Testing different application concentrations can provide important additional information. At present there are certain problems with the definition and implementation of a simple machine experiment. Further investigations are necessary to answer the unresolved questions and to optimise test conditions. The data situation in terms of actual potential for prolonging tool life must also be improved.

It can only be hoped that a MWF user is prepared to work along with this project so that the corresponding technical and economic data can be determined.

Even in future assessing the performance of water miscible cutting fluids will be a task that cannot be managed with a simple, standardised test method. However, it should be possible to close a large part of the big gap between the information provided by the simple, quick laboratory test and the results of the time-consuming field test.

Acknowledgements

I would like to thank the institutions and people who cooperated in this project:
Dr. Ing. Walter and Mr. Garbrecht from IWT in Bremen,
Mr. John Eastwood and Mr. Lee Thompson from Uniqema, UK and
Prof. Dr. Weseslindtner, Mr. Sauprigl and Mr. Vlaschitz from Vienna TU

Literature, references

[1] Walter, André: Bildung von Sorptions- und Reaktionsschichten durch KSS-Additive bei der Zerspanung. Mineralöltechnik, 6 (2003), Beratungsgesellschaft für Mineralöl-Anwendungstechnik, Hamburg

[2] Hübner, Heck: Kann die Zerspanungsleistung von nichtwassermischbaren Kühlschmier-stoffen mit Hilfe von Kurztest abgeschätzt werden? International Tribology Colloquium, TAE, Ostfildern

[3] N.N.: Comparing Metal Removal Fluids using the Tapping Torque Test Machine, ASTM D 5619-00, ASTM International, West-Conshohocken, PA, USA

[4] Rohbein, Emmer: Optimierung von Minimalmengenkühlschmierstoffen für die Gewindefertigung in Aluminiumguss-legierungen, Tribologie und Schmierungs-technik, Technical Report No. 21-05, ISSN 0342-4288 1525

[5] Grebe; Feinle: Anwendungsgebiete, Vorteile und Grenzen der tribologischen Model-lprüfung. 14. International Tribology Colloquium, TAE, Ostfildern 13.-15.01.04