Coolants made of native ester – technical, ecological and cost assessment from a life cycle perspective

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Abstract
The use of conventional coolants at the machining of metals causes different environmental problems. Besides plant seed oil, animal fat and used cooking oil proved to be other possible raw material sources for alternative ester based coolants. In this paper their properties are compared with those of mineral oil and plant seed oil ester products regarding technical, economical and ecological aspects from a life cycle perspective. In this context grinding tests, Life Cycle Assessment and Life Cycle Costing were performed. The three disciplines are brought together in a material flow model and therefore results are well harmonized.

Keywords:
Coolant, Animal Fat, Used Cooking Oil, Life Cycle Assessment, Life Cycle Costing, Grinding

1 INTRODUCTION

Sufficiency, efficiency and substitution belong to the strategies of sustainable manufacturing [1]. For the machining of metals coolants − water miscible or non water miscible − are required. They are responsible for cooling and lubricating the contact zone between workpiece and tool and also for rinsing the resulting chips away. In general, conventional petrochemical products are used which lead to health risks for the people working with them as well as to environmental and disposal problems. One ecological disadvantage is the limited resource of mineral oil. In addition, used coolants and oily swarf (e.g. oily grinding chips) need special and expensive waste treatment. Dry machining (sufficiency) and minimal-quantity-lubrication (efficiency) are possible solutions to these problems but are often not applicable in practice. Therefore, it is of great interest to replace conventional coolants with alternative products based on renewable materials that are less toxic and produce less oily swarf [2].

2 ESTER COOLANTS

2.1 Alternatives

A substitution alternative has been found in products based on plant seed oil esters. Plant seed oil esters fulfil all technical demands. But in contrast to petrochemical products, it is not necessary to add critical additives to reach this goal. At the same time, the amount of coolant that adheres on the chips is comparatively small when using plant seed oil esters. Therefore, e.g. a given grinding process produces a reduced quantity of oily swarf. Additional advantages of the plant seed oil esters are their renewable source, their biological degradability, the lack of aromatic hydrocarbons and that they are not water-endangering. Despite these qualities, plant seed esters are still used in industry quite seldom due to their comparatively higher price. Because of their similar chemical structure animal fat and used cooking oil may be suitable coolant base stocks, too (Figure 1). Until recently, these cheap secondary raw materials have been in wide use as nutritional additive for cattle and other animals but now they have been banned because of their assumed role in the transmission of BSE (bovine spongiform encephalopathy). Therefore, they should be excluded from the food chain. Considering their high calorific value (e.g. 36,000 kJ/kg for animal fat), most of the so far proposed alternatives focus on an energetic use. But thinking in cascades, they should first be regarded as valuable raw material for technical products (e.g. for ester based coolants) and just subsequently as derived fuel.

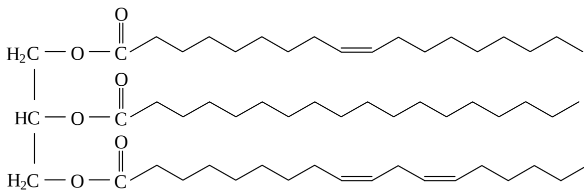


Figure 1: Common chemical structure of native fats and oils.

2.2 Animal Fat

Together with meat and bone meal, animal fat is a waste product of rendering. In Germany, 2.5 million tons of slaughtering offal and animal corpses have to be treated in rendering plants every year. As a result, Germany has an annual production of around 400,000 tonnes of meat and bone meal and additional 200,000 tonnes of animal fat [3]. After BSE crisis, rendering by-products are mostly used as derived fuels. Among different possibilities for animal fat, combustion directly at the rendering plant is getting more and more popular in Germany. For a use as lubricant base oil the fatty acid profile is of big interest. Approximately 45 % of animal fat's fatty acid compounds are saturated. Tribological tests showed that esters of these saturated fatty acids provide better technical skills than unsaturated ones [4]. In rapeseed oil (canola oil), for comparison, the suitable fatty acids make up only about 10 % whilst palm oil consists of 55% saturated esters [5].

2.3 Used Cooking Oil

In Germany ca. 120,000 tons of used cooking oil are collected every year, mainly from gastronomy and food industry. More than 90 % of this amount is exported to the Benelux countries (Belgium, The Netherlands, Luxembourg) and there used as derived fuel [6]. But 20 to 40 % of the fatty acid components are of the suitable kind (saturated). Hence, used cooking oil also has the potential to be a lubricant raw material.

3 METHOD

Within the framework of two research projects coolants based on animal fat and used coking oil esters were developed in co-operation with the Chair for Energy and Environmental Technologies of the Food Industries, TU Munich, the Federal Institute for Materials Research and Testing, Berlin, the Institute of Ecological Chemistry and Waste Analysis, TU Braunschweig, and several industry partners including Volkswagen AG and Castrol Industrie GmbH. To investigate whether these ester coolants are really interesting alternatives for the user, technical aspects as well as cost aspects have to be considered. In addition, a life cycle spanning observation of their environmental impact is necessary to justify their marketing as eco-products. Hence, this paper does not only focus on the technical performance of the observed coolants but also includes economical and ecological criteria. As a reference, a conventional petro-chemical product and a plant seed oil ester product have been chosen. The technical tests of different coolants include screening of relevant physical properties and grinding tests on pilot station and on industry scale. To assess the potential environmental impact of the coolants throughout their life cycle, LCA methodology (life cycle assessment) is applied. In addition, a material flow oriented cost assessment is performed as one variant of LCC (life cycle costing). Technical, environmental and economical evaluation aspects are brought together in a material flow model and therefore are well harmonized allowing further interpretation of results.

4 TECHNICAL ASSESSMENT

4.1 Physical parameters

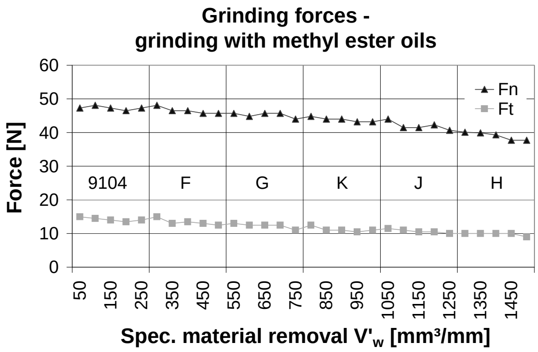
In a first step, the relevant physical parameters of more than 40 developed ester oils were observed. They all met the general requirements regarding flash point and viscosity. The only excluding criterion was the high pourpoint of the methyl, butyl and propyl esters of the stearic fraction. Finally, the methyl ester group and the 2-ethylhexyl ester group were chosen for further investigation because of their very good results and their probably lowest costs of production.

4.2 Grinding test

With these ester oils two different kinds of grinding tests were performed. On the one hand, they were directly compared to each other in uninterrupted tests for both groups (ca. 5 minutes delay between fluid changes). On the other hand, their influence on the tool wear was observed in separate long-time tests for every single ester. During these tests grinding forces, grinding force ratio and workpiece roughness were inspected. In addition, the wheel wear was monitored during the long-time tests. Grinding process parameters are summarized in Table 1. As a reference, a plant seed ester based product (9104) and a mineral oil based product (G500) from Castrol were used. A stable grinding process was possible with all tested ester oils. Figure 2 shows this in order of application for five methyl esters on behalf of grinding forces. The tendency to lower forces the longer the test lasts is caused by sharpening grinding wheel topography but not by the change from one ester oil to another. The grinding force ratios stay on the same level.

grinding process specification	
Grinding process	internal grinding
Grinding wheel specification	CBN, vitrified bonded, B126 M8 VD49
Wheel diameter	ds = 40 mm
Cutting speed	vc = 60 m/s
Workpiece material	100 Cr6, 62 HRC
Workpiece diameter	dw = 110 mm
Width of cut	ap = 10 mm
Spec. material removal rate	Q‘w = 2 mm³/(mm*s)

Table 1: Grinding process parameters.



9104 reference product (veg.) F animal fat methyl ester
G used cooking oil methyl ester K suet methyl ester
J lard methyl ester H oleic fraction methyl ester

Figure 2: Grinding forces using methyl esters as coolant [2].

The quality of workpiece surface was not influenced negatively by the developed native coolants. The measured values fluctuated in a normal range for a grinding process under the chosen conditions. Due to high grinding wheel prices and to the time effort necessary to change a grinding wheel, the influence on wheel wear is an important economic aspect when assessing a coolant. Probably caused by their relatively low viscosity the methyl esters seemed to forward wheel wear whereas the ethylhexyl ester oils based on used cooking oil showed an even higher performance than the reference products. An interesting question was if changing raw materials in the rendering plant (e.g. more pig cadavers have to be treated than normal due to an epidemic) will influence the animal fat’s suitability for coolant production. But as the results achieved by lard and suet methyl ester were nearly equal regardless of their differing fatty acid spectra, no adverse effects have to be feared.

4.3 Praxis application

As a result of the grinding tests and practical aspects, 2-ethylhexyl esters of the animal fat stearic fraction and of used cooking oil were chosen for a praxis test at Volkswagen plant Salzgitter. They were produced in a quantity of 3 tons each and applied at the machining of crank shafts. Regarding their tribological performance, the praxis test confirmed the perfect performance of ester oils. But a high amount of free fatty acids in the test samples lead to problems with the filter system's auxiliary material. Therefore, low fatty acid content is a condition for market maturity.

5 LIFE CYCLE ASSESSMENT

Even though the usage of renewable sources is one of the main principles of sustainability, products based on renewable materials can also have adverse effects on the environment. To assess these effects, the entire life cycle of the product has to be considered and observed. As for this purpose, the mass and energy fluxes throughout the life cycles of five coolants are compared using the LCA (life cycle assessment) methodology according ISO 14040 family [7]. For the establishment of Cumulated Energy Demand (CED), procedure is based on VDI guidelines [8]. Among the five products one is based on mineral oil, others on rape seed oil ester, palm oil ester, animal fat ester and used cooking oil ester. System boundaries include life cycle phases from crude oil extraction, plant cultivation, slaughtering offal collection and used cooking oil collection respectively till coolant disposal. Environmental burdens are compared regarding a system output of 1,000 workpieces processed with the respective lubricant.

Figure 3 shows the results for global warming potential (GWP). Regarding this impact category, the application of used cooking oil and animal fat lubricants before plant seed oil esters and at last mineral oil based lubricants should be preferred. For all coolant types carbon dioxide has the lion's share on the GWP. In the case of rape seed oil ester, agricultural processes contribute with significant amounts of N_2O from fertiliser production to the GWP.

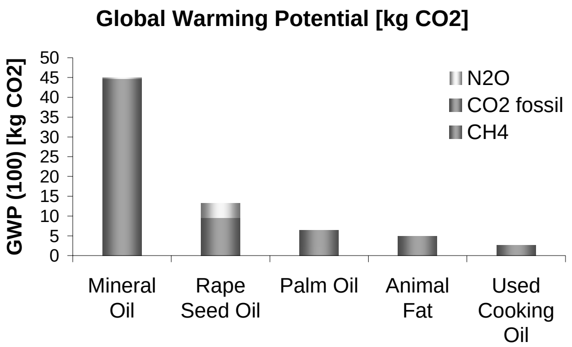


Figure 3: Global warming potential [2].

Altogether, eight impact categories were observed. In Figure 4 results are normalised to category high scores as reference. The indicators show that the used cooking oil product and consecutively the animal fat product cause the lowest potential impact on the environment whereas results for plant seed ester oils and conventional coolants are ambiguous. Advantage of native ester products is very clear in energy balance (CED) and abiotic resource depletion (RD) but in some impact categories scores of plant seed esters clearly exceed those of mineral oil. From the eight assessed categories the mineral oil based system scores the highest values in five categories (abiotic resource depletion RD, cumulated energy demand CED, global warming potential GWP, cancer risk potential CRP, photochemical ozone creation potential POCP) followed by the rape seed oil ester system (acidification potential AP, nutrification potential NP). The palm oil ester system is the reference for particulate matter with a diameter less than 10 µm (PM10). The used cooking oil based variant always has the lowest contributions.

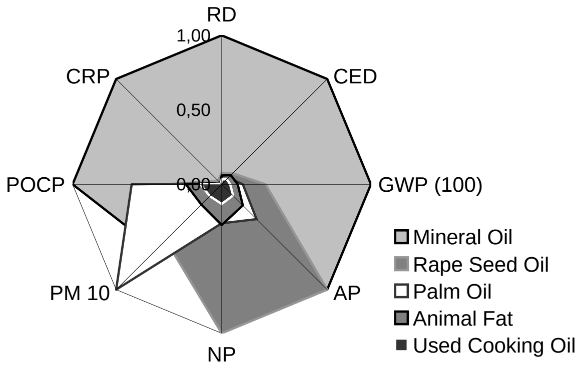


Figure 4: Results for chosen impact categories [2].

Additional scenarios made clear that the positive effect for the environment is several times higher when using animal fat as coolant base stock compared to the actually favoured combustion at rendering plants. A cascadic use of animal fat and used cooking oil – which means the combination of technical use (coolant) and energetic use (fuel) – would be most preferable (Figure 5).

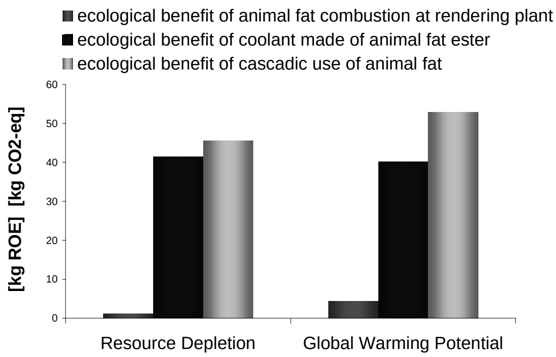


Figure 5: Ecological benefit of animal fat use [2]

6 LIFE CYCLE COSTING

The main disadvantage of native products based on plant seed oil is their relatively high market price. These higher prices cause extra costs for a new filling of a filter unit in case of ester application but they can be compensated by savings due to extended tool life and reduced coolant loss. To achieve transparency in this context, a material flow oriented cost assessment was performed as one variant of LCC (life cycle costing). Therefore, the existing material flow model from LCA procedure was used to assess market prices for used cooking oil and animal fat esters on the one hand and the overall coolant costs for the user on the other hand.

6.1 Market prices

As a conventional mineral oil based coolant costs around 1.35 € per kg, a plant ester product has got a market price of approximately 3.30 € per kg. The examination of cost flows resulted in a production price of 0.93 € per kg for the used cooking oil ester and of 1.01 € per kg for animal fat ester because of significantly lower raw material costs. Including 1.25 € per kg for filling, packaging, sales and profit, market prices of 2.18 € per kg and 2.26 € per kg are achieved (Table 2). So, the developed ester coolants take a mid-position between mineral oil product and plant seed oil ester.

nwmb coolant based on	market price [€/kg]
mineral oil	1,35
plant seed ester	3,30
animal fat ester	2,26
used cooking oil ester	2,18

Table 2: Market prices for different types of coolant [2].

6.2 Life Cycle Costs

Even though users are often attracted by low market prices real costs come clear only when looking at the overall costs of product application. Figure 6 shows life cycle costs for ester oil usage (used cooking oil ester) in comparison to those of mineral oil application from user perspective. Costs for necessary re-filling volumes as well as for disposal and recycling are shown over time. Calculations were made for the modelled contour grinding process. Given a filling volume of 3 tons of coolant per machine tool and a production of 30,000 workpieces per machine tool and week, the extra costs for a new filling (2,500 €) will be compensated by savings due to reduced coolant loss after less than two months.

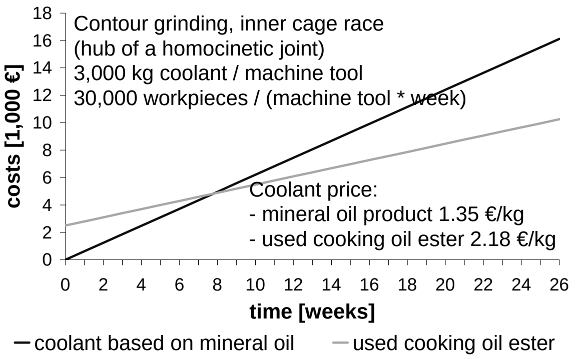


Figure 6: Re-invest of used cooking oil ester coolant

For different machining processes payback periods will vary in dependence of coolant loss rate, workpiece surface and intensity of machine use. Especially in case of ladling workpiece elements re-invest times can sometimes be critical.

7 CONCLUSIONS

Looking at the market prices in relation to the potential environmental impact, it is most striking that the mineral oil product can be offered cheapest while potentially causing biggest harm to the environment (Figure 7). Ongoing rise in crude oil prices will lessen this disproportion. Plant seed ester oils take a mid-position regarding environmental impact, but are most expensive in purchase phase. Animal fat and used coking oil esters show the best ratio − low environmental impact combined with medium market prices. In Figure 7 market prices were chosen instead of life cycle costs because of their still crucial influence on consumers' choice. Size of ellipses stands for technical maturity of the different coolants. While mineral oil and plant seed ester products are fully developed, last steps are necessary for animal fat esters and used cooking oil esters until market maturity (free fatty acid reduction).

The developed esters are less costly alternatives to other environmentally friendly ester products. They stand for a reasonable technical use of high-grade secondary raw materials that should neither be just incinerated without using their technical properties nor re-enter the food chain (Figure 8). Their example is a proof for the high potential of use cascades and should encourage further research.

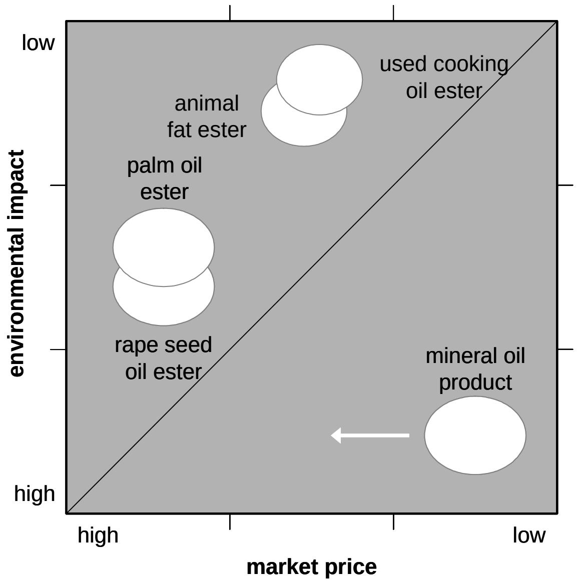


Figure 7: Market price / environmental impact portfolio

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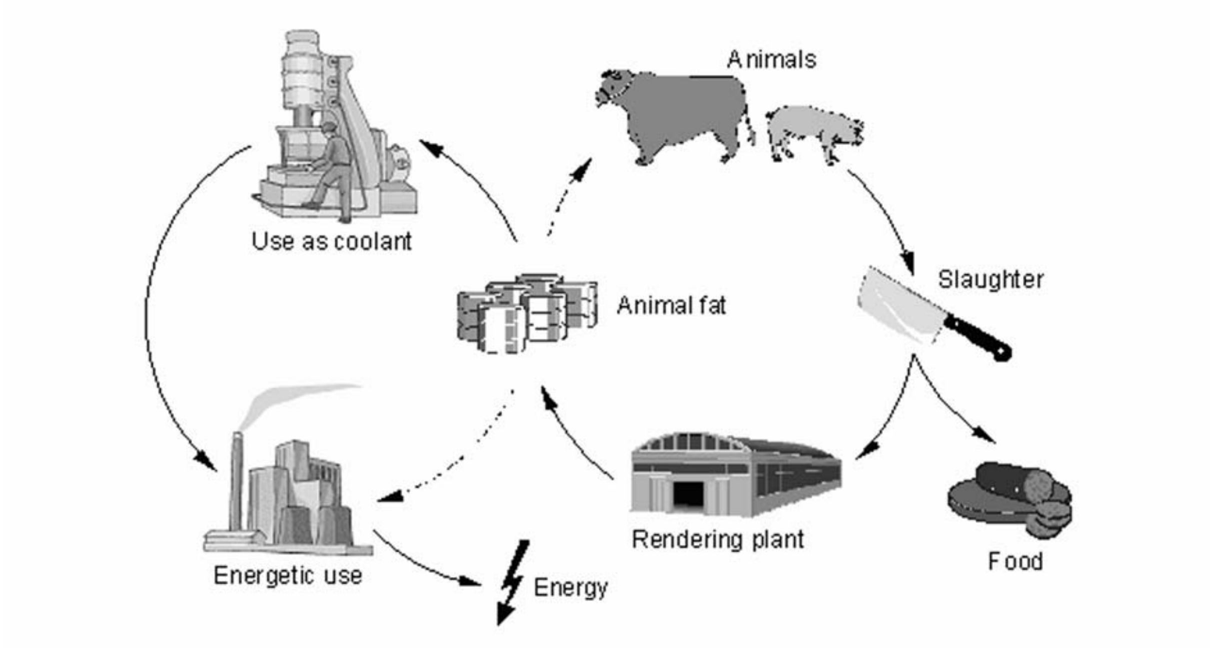

Figure 8: Alternative use of animal fat as coolant instead of re-entry in the food chain or incineration