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Metalworking fluids—Mechanisms and performance

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ABSTRACT

In various manufacturing processes, metalworking fluids (MWFs) are applied to ensure workpiece quality, to reduce tool wear, and to improve process productivity. The specific chemical composition of an applied MWF should be strongly dependent on the scope of application. Even small changes of the MWF-composition can influence the performance of MWFs in manufacturing processes considerably. Besides defined variations of the composition, the MWF-chemistry furthermore changes over the service life of the fluid. This paper presents the current state of the art regarding the assumed working mechanisms of MWFs including the effects of desired and undesired changes of the MWF properties.

1. Introduction

Metalworking fluids (MWFs) have been addressed in several CIRP Keynote Papers in the past as they play a significant role in manufacturing processes such as forming [12], cutting [268], and grinding [27]. They influence heat generation in metalworking processes by reducing friction between tool and workpiece. Cooling is furthermore achieved by dissipating and conducting the generated heat. By their lubricating and cooling properties, MWFs contribute to the avoidance of thermal damage of the workpiece material and reduce wear of the tool [28]. They are of high relevance for the generation [29,100] and understanding [129] of the surface integrity in metalworking. In machining processes chip transportation out of the working zone is a further important subtask of MWFs. The research focus up to now has mainly been on phenomenological studies looking at the improvement of the performance of certain manufacturing processes by MWFs. Less effort was made to clarify their mechanism of action. However, the aforementioned research builds the ideal basis for a cross-process discussion of the shared working mechanisms and the potential regarding knowledge-based improvements of the performance of MWF.

Bay et al. addressed environmental aspects of lubricants in forming processes including approaches to substitute the MWF by applying special coatings or structured workpiece and tool surfaces [12]. The authors give an excellent overview regarding the potential of oil-based MWFs and emulsions to increase productivity of different forming processes. Although models for the lubrication effect of emulsions are briefly presented, the chemical working mechanisms and the specific impact of varied MWF compositions on the process performance remained untouched.

For cutting processes, a comprehensive summary of the potential to reduce MWF-consumption (for economic and environmental reasons) is given in the 2004 CIRP Keynote Paper by Weinert and colleagues, who present a definition of minimum quantity cooling and/or lubrication (MQL) approaches as well as scopes regarding the fields of application of both dry machining and MQL [268]. Comparisons between the achievable tool life were made and the requirements regarding tool materials and coatings were derived.

Brinksmeier et al. [27] focused on the avoidance of thermal workpiece damage in grinding processes. Different common concepts of grinding fluids (chemical composition), the state of the art of MWF-supply (nozzles, nozzle positioning, and fluid dynamics) as well as comparative results from grinding experiments revealed the potential of MWFs to decrease the workpiece temperature during machining.

Less focus has been given to the chemical interactions of the surface of the workpiece material and the MWF. Consequently, this paper aims to reveal fundamentals of MWF-chemistry and the presentation of theories on their working mechanisms. Furthermore, a systematic overview on today's possible scenarios for future MWF-concepts are given.

For this purpose, this paper defines metalworking fluids as liquids, which are supplied to a manufacturing process in a way that allows for increased productivity based on lubricating and cooling effects. As general aspects of the fluids are discussed, which are mainly independent from the manufacturing process, commonly used terms such as coolant, lubricant, grinding oil, cutting fluid are summarized as MWFs.

Liquids which are included in the term MWFs have been classified based on different criteria like formulation (oil-based, water-based), manufacturing process (cutting fluid, grinding oil, forming oil, etc.), or quantity (flooding, MQL, etc.). Not all of these classifications are suitable to discuss MWFs and their properties from a mechanism-oriented point of view. According to DIN 51385, MWFs are classified following their composition as oil-based or water-based MWFs [59]. Specific properties are achieved by

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adding specific chemical substances (additives). Fig. 1 shows the classification of MWFs according to DIN 51385 and includes some typical classes of additives, which will be addressed in more detail in Section 1.1 of this paper.

The lipophilic part of oil-based MWF may consist of natural, synthetic, and/or mineral oil: vegetable synthetic, naphthenic, paraffinic, or petroleum oil [11,138] (cf. Section 4.2). MWF-emulsions are stabilized to an oil-in-water (O/W) emulsion by an emulsifier system (often also referred to as surfactants or tensides). Emulsifier-molecules feature a hydrophilic and a lipophilic part. The ambivalent molecules enclose the oil drops and the hydrophilic end of the emulsifier interacts with the water-phase.

Water-based MWFs are purchased as oil-based concentrates, which are dispersed with water at the place of use. Common dilution levels are concentrations of 3–10% of the MWF-concentrate in water [36]. The droplets formed by emulsifiers (cf. Fig. 2) are called micelles. The oily phase inside the micelles includes all lipophilic additives.

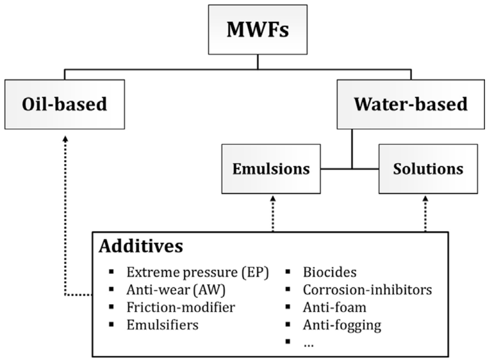

Fig. 1. Classification of the MWF types according to DIN 51385 (simplified) [59,259].

Due to the lack of lipophilic parts, water-based solutions are free of emulsifiers. In solutions, the water is additivated with active polar hydrophilic substances. In Table 1, a comparison of a typical, general formulation of a solution, an emulsion and an oil-based MWF is given.

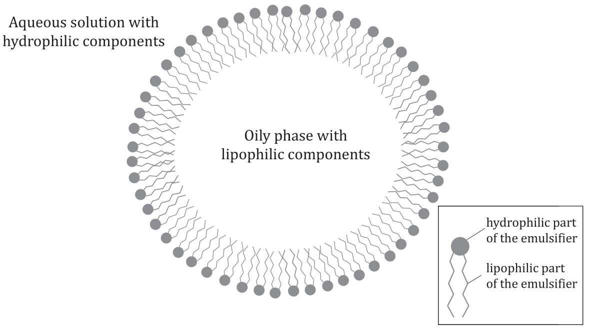

Fig. 2. A micelle of an oil-in-water-emulsion, according to [17,82].

Table 1
Examples of formulations of MWFs of different types [36,207].

Component	Amount (wt %)		
	Solution	Emulsion (5%)	Oil-based MWF
Mineral oil	–	3.5–4.0	75–100
Emulsifiers	–	0.5–1.0	–
Coupling agents	–	0.05–0.25	–
pH buffer	5	–	–
Corrosion inhibitors	10	0.25–0.50	0–5
Extreme-pressure additives	4	0–0.5	5–20
Biocides	2	Unknown	–
Antioxidants	–	–	0–2
Boundary lubricity additives	9	–	0–10
Water	70	95	–

The performance of a certain MWF is influenced by factors such as the type of manufacturing process, the working material, and the tool. Oil-based MWFs e.g. are especially used in processes which require efficient lubrication whereas water-based MWFs are applied when the dissipation of heat is more important than lubrication. However, besides some general approaches for specific manufacturing tasks (cf. Section 3.1), the choice of the most efficient MWF today still is experience-driven in most cases.

The parameters influencing the performance of MWFs are summarized in Fig. 3 including the sections of this paper, which cover the relevant fields of this complex topic.

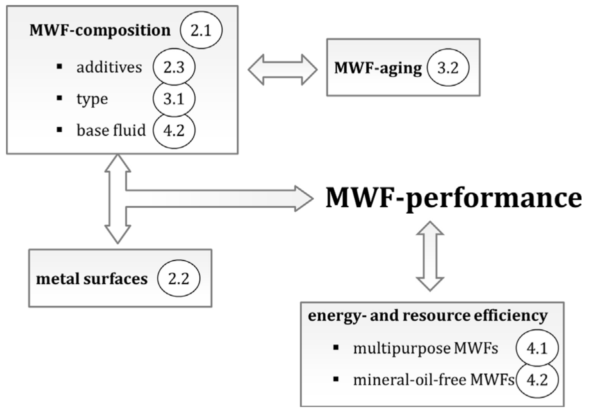

Fig. 3. Parameters influencing the performance of MWFs. Encircled: sections of this paper, addressing the corresponding parameters.

1.1. *History and demand for MWFs in manufacturing technology*

Early approaches for the support of metalworking processes by fluids utilize two basic properties of liquids: their ability to dissipate heat and to reduce friction by lubrication. Leonardo da Vinci created several test set-ups allowing for the analysis of friction under varied conditions (Fig. 4). Beside of the use of pure fats and oils, early MWFs were mixtures of water (which has the highest heat transfer coefficient) and additional substances for the improvement of the MWFs' properties, especially the lubrication ability.

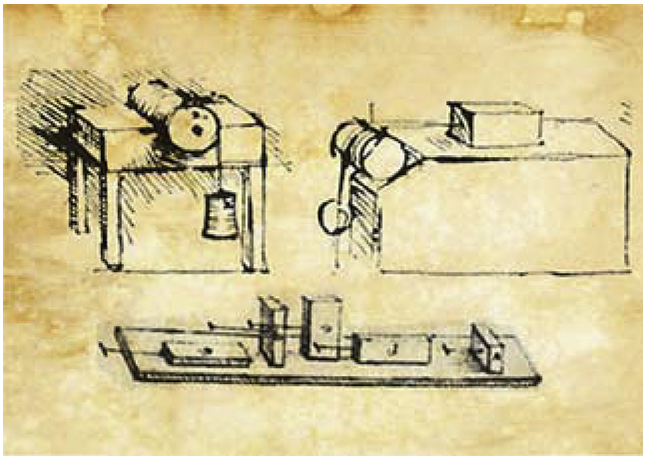

Fig. 4. Leonardo da Vinci's sketches of tribological test set-ups for the analysis of friction [154].

Natural products such as animal oils and fats (primarily whale oil, tallow, and lard) as well as vegetable oils from various sources such as olive, palm, castor, oil plant and other seed oils were used to compose the first MWFs. They were applied in manufacturing processes e.g. for the production of metal artwork and weapons in the middle age [36,62]. In further work of da Vinci, a mixture of oil and corundum was applied for lubrication purposes in an internal cylindrical grinding machine. Special grooves were inserted to the grinding wheel to allow for efficient supply of the MWF to the tool [284].

In the early 19th century, the design of machine tools made considerable progress and simultaneously, the techniques for the