CIRP Annals - Manufacturing Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Microbial-based metalworking fluids in milling operations

Daniel Meyer [a,b], Marvin Redetzky [a,b], Ekkard Brinksmeier (1)[a,b,*]

[a] Foundation Institute of Materials Science, Division Manufacturing Technologies, Badgasteiner Straße 3, 28359 Bremen, Germany
[b] University of Bremen and MAPEX Center for Materials and Processes, Bibliothekstraße 1, 28359 Bremen, Germany

ARTICLE INFO

Keywords:
Milling
Lubrication
Microorganisms

ABSTRACT

Most commercial metalworking fluids (MWFs), as applied in cutting operations contain mineral-oil. Colonization of water-based MWFs by microorganisms is considered a problem due to metabolism of the MWF components. This paper presents a paradigm shift by exploiting the potential of substituting oil-containing water-based MWFs in machining processes by microbial-based fluids. For the first time, specifically selected microorganisms have been applied in milling experiments and were examined regarding their lubrication performance. Compared to conventional water-based MWFs a prolonged tool life and superior surface finish were obtained in milling. From the results, the working mechanisms of microbial-based MWFs are deduced and discussed.

1. Introduction

In many manufacturing processes such as forming, grinding, and cutting, metalworking fluids (MWFs) play a decisive role in terms of minimizing energy consumption [1], as well as enabling higher productivity and superior part quality [2]. The worldwide annual consumption of several billion liters MWF-concentrate [3] underlines their importance for manufacturing processes. Generally, the main function of MWFs is to affect the tribological mechanisms in the contact zone between tool and workpiece by reducing the friction (lubrication) and by improving heat dissipation (cooling). In 1883 (published 1906), Taylor discovered that higher cutting speeds can be applied without thermally damaging the tool or workpiece solely by the use of water as a coolant [4]. Today, traditionally mineral-oil-containing MWFs are applied in an oil-based or water-based state [5]. Compared to dry machining, a better surface finish and as e.g. Denkena et al. showed, a reduced tool wear can be achieved by application of MWFs [6].

The investigations of the past 100 years have shown that the growth of microorganisms (bacteria and/or yeasts) metabolizing the components of the water-based MWFs is an unavoidable problem and leads to uncontrolled variation of the MWF's chemistry. Thus, large amounts of biocides are used to slow down microbial effects. However, Vijay et al. showed that most biocides carry the risk of being harmful to the machine operator [7].

Due to the decreasing oil reserves, the MWF-industry is already looking ahead for new raw materials. Renewable vegetable raw materials [8] and oils obtained from algae [9] are already used or in the stage of development.

To overcome some of the limitations of mineral-oil-containing water-based MWFs, Redetzky and colleagues suggested a paradigm shift by applying microbial suspensions instead. In tribological tests they were able to verify their high lubrication ability [10]. A dependency of the lubricity from the microbial cell concentration was observed [11]. However, microorganisms have not yet been used in machining operations, which show different contact conditions compared to tribological tests.

Consequently, this paper focusses on the application of microbial-based MWFs in cutting processes. In a two-stage approach, the defined conditions of a tribotester were used first to identify a benchmark regarding the general lubricating ability of the microbial-based MWFs, which were then subsequently applied in milling processes. For grinding processes and large volumes of conventional MWFs the qualitative transferability of results gained in tribological tests has already been proven by Meyer and Wagner [12]. However, no scientific findings have been published, indicating how microbial-based MWFs will perform in cutting processes. Therefore, a systematic study on the performance of these innovative MWFs in a milling process is presented in this paper for the first time, leading to unique insights regarding the working mechanisms of microbial-based MWFs.

2. Experimental setup

Commercial water-based MWFs were tested against the microbial-based MWFs. The performance of both fluids was evaluated by analysing the worn area (standardized tribotest) as well as cutting forces, tool wear and surface finish (milling experiments).

2.1. Tribotester, machine tool and measurement devices

The initial tribological benchmark tests were carried out on a modified Brugger-tribotester (Triboproof T100 according to DIN

* Corresponding author at: Foundation Institute of Materials Science, Division Manufacturing Technologies, Badgasteiner Straße 3, 28359 Bremen, Germany.
E-mail address: brinksmeier@iwt-bremen.de (E. Brinksmeier).

http://dx.doi.org/10.1016/j.cirp.2017.04.019
0007-8506/© 2017 Published by Elsevier Ltd on behalf of CIRP.

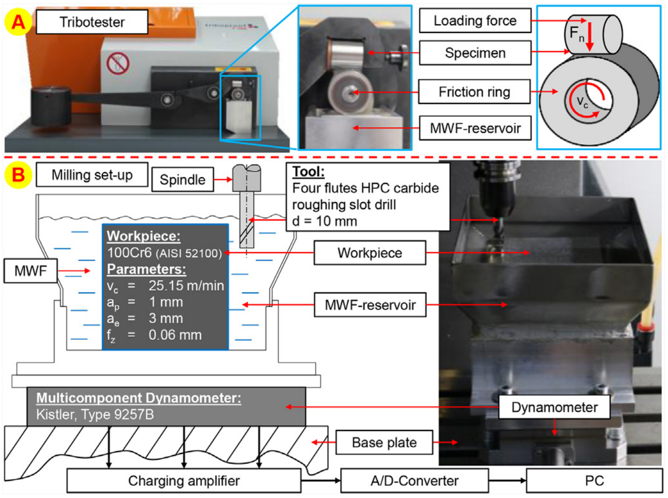

Fig. 1. Experimental setup for the utilization of the (A) tribotester and (B) the milling operations in a flooded environment.

51347, Fig. 1A) with a continuous MWF-supply and a test cylinder being worn out by a friction ring (cf. [11,13]). The results are documented as the worn surface area at the test cylinder in mm^2 against the applied variation of the MWF. A small value stands for a low wear and therefore a high lubricity of the tested medium. Subsequently, the transferability to milling processes has been analyzed in comparative studies. The discontinuous cut allows for a constant transport of the MWF into the contact zone between tool and workpiece. As the production of large volumes of microbial suspensions with highly defined properties is comparably challenging at a laboratory level, a test environment with a total MWF-volume of 2 l maximum, was designed and implemented. For the comparability with the tribological test the workpieces which were made of 100Cr6 (AISI 52100, untempered, 25 HRC) are located below the fluids' surface (cf. Fig. 1B).

The milling operations were carried out on a milling machine (type OPTImill F4TC). The face end-milling was performed as an up-milling process which has been recommended by Li et al. [14] to generate a higher tool wear rate compared to down-milling. The machining parameters (cf. Fig. 1B) were chosen based on the results of a preliminary performed parameter study on the influence of conventional MWFs in milling processes. It was shown that parameters which are usually applied in the machining of hard-to-cut materials are promising for a comparison of different MWFs. Focussing on the lubricating effect in this study, a comparably low cutting speed was chosen to reduce the thermal effect. Four flutes HPC carbide roughing slot drills with a diameter of d = 10 mm were used in the milling tests.

The tests were carried out fourfold, each until a wear criterion of VB_{max} = 0.2 mm was reached. The tool wear and the surface roughness were determined in fixed intervals by using an optical microscopy (Zeiss-Axio-Vision 4.5) and a perthometer (MahrSurf XCR20) respectively. The cutting forces were continuously recorded using a piezoelectric multicomponent dynamometer (Kistler 9257B). In order to avoid sedimentation of the microbial cells, the microbial-based MWFs were stirred during the test intervals. The influence of the process on the integrity of the microbial cells was analyzed by optical light microscopy.

2.2. Conventional and microbial-based MWFs

Two yeasts and three bacterial species were chosen for the benchmarking tribological tests. The selected species are known for their viability at higher pH-values and are therefore suitable for an environment of a machine tool where lower pH-values would lead to undesired corrosion. Particularly, the viability in a machine tool is of special interest in terms of a possible future application. Rod-shaped and spherical microorganisms with different cell wall

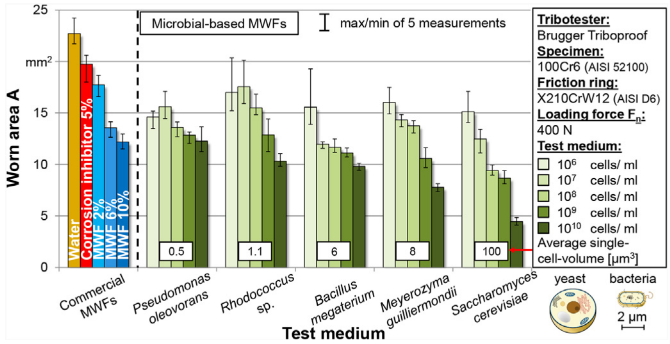

Fig. 2. Benchmark results using the tribotester: influence of the microbial cell concentration on the lubricity of microbial based MWFs. Comparison with commercial MWFs.

structures (gram-positive/gram-negative, pro-/eukaryotic) were selected in varying single-cell-volumes ranging from 0.5 μm^3 to 100 μm^3 (cf. Fig. 2). The variation of cell properties allows for insights regarding the specific mechanism leading to the lubrication ability. To minimize undesired side-effects influencing the lubricity, e.g. a formation of extracellular polymeric substances by the microorganisms as well as for ensuring defined experimental conditions, the microbial cells were inactivated after cultivation in CASO Broth. For the tribological tests, the concentration of cells in water was varied by means of cell counts (cells/ml). Throughout the experiments a 5% corrosion inhibitor (Isononanoic acid, MEA, TEA and fatty acids) was added to the tested fluids.

Based on the results from the tribological tests presented in Fig. 2, only the two yeast species *Meyerozyma guilliermondii* and *Saccharomyces cerevisiae* as well as the bacterium *Pseudomonas oleovorans* were selected for assessment of their performance in the subsequent milling experiments. The oval to spherical eukaryotic yeasts, with cell volumes of 8 μm^3 and 100 μm^3 respectively, show the largest cells of the microorganisms tested. The bacterium *Ps. oleovorans*, one of the most frequently isolated bacteria from MWFs, shows an average cell volume of approximately 0.5 μm^3 (rod-shaped and gram-negative cells). Thus, the selected microorganisms are suitable for the analysis of the direct influence of the cell form, the cell size, and the cell-wall-characteristics (gram-staining). For the milling experiments, the microbial cells were diluted in water and 5% corrosion inhibitor to obtain cell counts of 10^9 cells/ml, which represents approximately the maximum of an open microbial system [15]. In addition, a conventional MWF-emulsion with concentrations of 2%, 6% and 10% as well as a baseline MWF (water with 5% corrosion inhibitor) were used as a reference.

3. Results and discussion

3.1. Tribological experiments

Similar to commercial MWFs, where the concentration reflects the percentage of concentrate diluted in water, the concentration of microbial-based MWFs by means of cells/ml is a crucial factor regarding the lubricity. As indicated in Fig. 2, it was shown that already low microbial concentrations lead to smaller worn areas compared to the 12–13 mm^2 of the 10% commercial MWF. Furthermore, the average single-cell-volume (given in the overlaid white captions) seems to have an effect on the wear, too.

Especially the two yeast species *M. guilliermondii* and *S. cerevisiae* reveal a superior lubricity compared to conventional MWFs. To tap the full potential of the microbial-based MWFs, and to show the influence of the cell size, the two yeasts as well as *Ps. oleovorans* were selected for an application in the milling tests.

3.2. Milling experiments

For the performance evaluation of the microbial-based and commercial MWFs, the cutting forces, roughness parameters as