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Procedia CIRP 88 (2020) 606–611

www.elsevier.com/locate/procedia

13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '19

Feasibility study of using microorganisms as lubricant component in cutting fluids

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Abstract

This work intends to lay the basis for a Biological Transformation in Manufacturing (BTM) industrial breakthrough aimed at developing new sustainable microbial-based cutting fluids for greener machining processes. The point of departure is that conventional cutting fluids for machining are either entirely based on mineral oils or, in the case of water-based cutting fluids, contain significant percentages of mineral oils. The world annual consumption of cutting fluid concentrate amounts to several billion litres, highlighting their importance for the manufacturing industry and their criticality in terms of environmental impact. Furthermore, the depletion of mineral oil reserves worldwide is already driving cutting fluid industries to search for new renewable raw materials. A contribution to the solutions of these problems can be provided by the development of microbial-based cutting fluids, incorporated in the machine tool, that contain microorganisms with significant lubricating properties in order to substitute mineral oil-based cutting fluids for use in metal alloy machining.

Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.

Keywords: Biologicalisation; Microbial cutting fluids; Carbon steel machining

1. Introduction

The present work is intended to lay the basis for a Biological Transformation in Manufacturing (BTM) industrial breakthrough aimed at developing new sustainable microbial-based cutting fluids for greener machining processes [1].

The point of departure is the fact that conventional cutting fluids for lubro-refrigeration in machining are either entirely based on mineral oils or, in the case of water-based cutting fluids, contain significant percentages of mineral oils (up to 10%) [2, 3].

The world annual consumption of cutting fluid concentrate amounts to several billion litres, highlighting their importance for the manufacturing industry and their criticality in terms of environmental impact [4].

Furthermore, the depletion of mineral oil reserves worldwide is already driving cutting fluid industries to search for new renewable raw materials [5, 6].

A contribution to the solution of these problems can be provided by the development of microbial-based cutting fluids, incorporated in the machine tool, that contain microorganisms with significant lubricating properties in order to substitute mineral oil-based cutting fluids for use in metal alloy machining [7-12].

Following Prof. C. Hermann's concept of BTM [13], this represents a bio-integration solution at process level, characterised by an absolute concept of sustainability focused on effectiveness rather than efficiency. As a matter of facts, it aims at the complete substitution of mineral oil lubricating components with microorganisms delivering the required lubrication function in the cutting fluids.

Under these conditions, the environmental impact of cutting fluids is expected to be totally eliminated (absolute sustainability concept) and not just reduced (relative sustainability concept), providing a 'good' sustainability innovation in machining processes rather than a 'less bad' sustainable development [13].

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Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.
10.1016/j.procir.2020.05.106

However, it is worth mentioning that the colonisation of water-based cutting fluids by microorganisms represents a serious issue that is critically felt in industrial practice [1].

Due to the metabolism of the cutting fluid components, safety and health problems can negatively result in the surroundings of the workplace and the working environment can be significantly deteriorated [2].

A well known example of this kind of situation is represented by the so called 'Monday morning odour' phenomenon, resulting from the normal microbial metabolism, that occasionally greets cutting fluid plant employees after a weekend shutdown [3].

Accordingly, in the industrial sectors where conventional cutting fluids are regularly employed, microorganisms are seen as polluting contaminants that must be eliminated to the maximum extent.

Thus, the main challenge of this work is represented by a total paradigm shift from the 'hostile' attitude regarding the presence of microorganisms in cutting fluids, towards a bio-integration approach aiming at exploiting the potential of substituting oil-containing cutting fluids with new microbial-based cutting fluids for metal alloy machining, where microorganisms provide a valuable and effective contribution to the fluid lubricating function.

The sustainability benefits expected from the microbial-based cutting fluid development and implementation in terms of circular bioeconomy can be summarized as follows [15-20].

- Carbon footprint and water footprint can be notably decreased: e.g. 1 Kg of biomass generation captures and fixes 1.83 Kg of CO_2.
- Cutting fluid environmental impact can be markedly reduced by disposing of microbial-based cutting fluids via highly sustainable processes such as anaerobic digestion.
- Biorefinery concepts can allow to exploit the spent fluids by employing them as energy vector in thermoconversion processes; spent fluids can be recovered to manufacture high value products (bio-plastics, bio-fibers) and utilised as raw material for biofuel production; end-of-life carbon recycling can be effectively used to produce new biomass.

The industrial reference sectors for the introduction of this kind of BTM are wide-ranging: automotive industry; aerospace industry; machine tool industry; cutting fluids industry; energy production industry; any other industry where cutting fluids are relevant.

This feasibility study is well embedded in the overall BTM strategy [21] as it is aimed at realising a clear and explicit instance of direct use of resources from living nature for new innovation in manufacturing technology according to the bio-integration approach of BTM [22].

2. Principal scopes of the feasibility study

The feasibility study scopes can be summarised to fundamentally comprise:

- Set up of a research roadmap for a bio-integration approach in terms of direct use of resources from living nature for new sustainable innovation in manufacturing.
- Promotion of new design paradigms as novel design concepts for machine tools are required to allow for the employment of the innovative microbial-based cutting fluids in new sustainable machine tools for greener machining processes.
- Employment of smart process monitoring based on advanced sensors and sensor systems, feature extraction and pattern recognition procedures, artificial intelligence and machine learning paradigms with the scope to optimise the new bio-integrated machining process conditions provided by the novel microbial-based cutting fluids.
- Fostering the factories of the future where green manufacturing, ecological footprint minimisation, and resource efficiency maximisation are vital.

2.1. Sustainability content

While Industry 4.0 does not explicitly refer to ecological sustainability of production systems as a major objective, production research fully addressed ecological impact and sustainability in the past years.

Linking the concept of intelligence from the Industry 4.0 vision with established eco-sustainability theories, concepts of sustainable production are at hand and can be applied to arrive at truly intelligent, i.e. also environmentally sustainable, production systems of the future.

Basically, only production systems incorporating sustainability in their concept of intelligence will be competitive in the long-term.

Thus, the main scope of the work is related to setting up the development of sustainable microbial-based cutting fluids for application in the machining of metal alloys.

2.2. Main steps of the research roadmap

Firstly, a range of microorganism species is identified as appropriate lubricating components in the newly developed microbial-based cutting fluids.

Then, the selection of the most suitable strains for the purpose is carried out on the basis of their lubrication properties, easy availability, and low cost.

The characterisation procedures of the microbial-based component of the cutting fluids before and after machining are established.

The cultivation of the selected strains is performed to generate the fermentation broth for the preparation of the microbial-based cutting fluids for experimental testing.

The procedures for cutting fluid performance assessment, also in comparison with traditional cutting fluids, are selected including tribological benchmark testing.

The experimental machining operation, the work material, and the cutting tool material are decided on for the execution of machining tests with smart sensor monitoring implementation for process parameters optimisation and tool condition assessment.

Finally, the evaluation of the microbial-based cutting fluids performance is carried out in terms of tool wear, tool breakage, surface finish, and surface integrity.

3. Estimated impact

The estimated impacts of the research activities, within the specific context of BTM, are reported below in terms of expected results and benefits for industry.

3.1. Expected results

The implementation of microbial-based cutting fluids with high lubricant properties is expected to provide the ensuing green manufacturing effects while assuring process quality and productivity: (i) reduction of cutting fluids environmental impact; (ii) counteraction of mineral oil reserve depletion.

3.2. Benefits for industry

As regards the main benefits for the strengthening of industrial accomplishment in their reference market, the following are envisaged. The machine tool building industry can significantly increase the sustainability of machine tools functioning with microbial-based cutting fluids.

End users of machining processes can reach a notable reduction of the environmental impact and the related costs in the disposal of spent cutting fluids. The cutting fluid industry can achieve a considerable market advantage following the development of new eco-compatible microbial-based cutting fluids. Any industry where microbial-based lubricant fluids can substitute oil-based lubrication will be able to markedly improve the sustainability of its activities.

Finally, this bio-innovation impacts highly the flow of waste with the goal to reduce and ultimately minimise the environmental impact via green manufacturing solutions while maximising resource efficiency.

4. Research roadmap

Proposal of a range of microorganism species to use as lubricating component in the newly developed microbial-based cutting fluids

An extended list of strain species was identified on the basis of literature review (Table 1). Finally, one short list of strain species was selected as promising for application (Table

Table 1. Extended list of strains from literature survey

Bacteria	Yeasts	Microalgae	Cyanobacteria
Bacillus subtilis	Saccaromyces cerevisiae	Chlorella sorokiniana	Synechocystis species
Pseudomonas fluorescens	Candida lypolitica	Nannochloropsis	
Brevibacillus brevis	Mortierella isabellina		
Rodhococcus erythropolis	Rhodosporidium toruloides		
Acinetobacter radioresistens	Meyerozyma guillermondi		
Paenibacillus glucanolyticus			
Rodhococcus opacus			
Bacillus megaterium			
Leucothrix			

Table 2. Short list of strains for possible application

Bacteria	Yeasts	Microalgae	Cyanobacteria
Pseudomonas oleavorans	Saccharomyces cerevisiae	Chlorella sorokiniana	Synecocystis species
Bacillus subtilis			Spirulina arthrospira maxima
Paenibacillus lucanolyticus			
Rhodococcus erythropolis			

Characterisation procedures of microbial-based component before and after machining tests

Before machining tests, the characteristics of the strain cells utilised as lubricant component in the microbial-cutting fluid were identified: cell form (spherical, rod-like); cell size (equivalent diameter in microns); cell wall characteristics; cell concentration (number of g/l, number of cells/ml).

After machining tests, the conditions of the strain cells in the spent microbial-based cutting fluid were analysed in terms of cell integrity and cell disruption.

Selection of the strain to use as lubricant component in the bio-based cutting fluid

The specific strains to be used as lubricant component in the bio-based cutting fluid were chosen on the basis of the following main criteria:

- strain safety for use in a manufacturing work environment;
- good lubricant properties of the strain;
- easy availability of the strain;
- low cost in the production of the fermentation broth;
- previous experience with the specific strain.

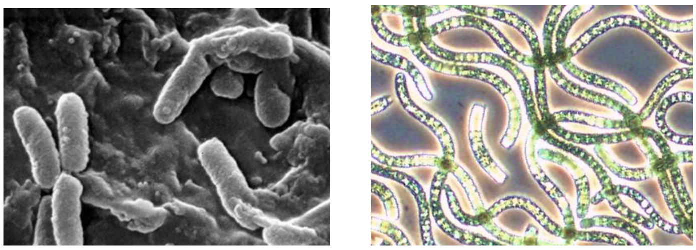
Based on these criteria, two strains were selected (Fig. 1):

- one bacteria species: *pseudomonas oleovorans*;
- one micro-algal species: *spirulina arthrospira maxima*.

In this work, particular focus is dedicated to the micro-algal species *spirulina arthrospira maxima*, which belongs to the class of cyanobacteria (blue-green algae) (Fig. 1b).

It is a microalga that can be consumed by humans and animals [23] (Fig. 2). It is cultivated worldwide to produce what is considered an excellent natural nutritional supplement used as dietary complement or whole food [24].

On this basis, its employment is fully sustainable with regards to the environment as well as totally risk free for human health [25].



(a) (b)

Fig. 1. (a) Pseudomonas oleovorans; (b) Spirulina arthrospira maxima.

Fig. 2. Spirulina arthrospira maxima superfood: 100% raw powder.

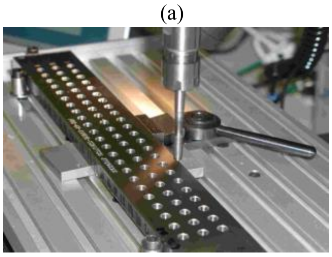
Cutting fluid performance evaluation, including identification of tribological bench tests

Tribological benchmark testing procedures for cutting fluid performance assessment, also compared to current cutting fluids, are identified as reported in Table 3.

Table 3. Tribological benchmark testing procedures

Testing procedure	Measurement type	Test material
Reichert test	Wear	Steel on steel
Brugger test	Wear	Steel on steel
Microtap test	Friction	Coated tap on steel or Al
Anton Paar tribometer	Friction and wear	Flexibility in testing diverse materials

(a)



(b)

(c)

Fig. 3. (a) Reichert testing instrumentation: wear measurement; (b) Microtap testing instrumentation: friction measurement; (c) Anton Paar tribometer: wear and friction measurements.

Tribological benchmark tests on microbial-based cutting fluid and traditional cutting fluid for comparison

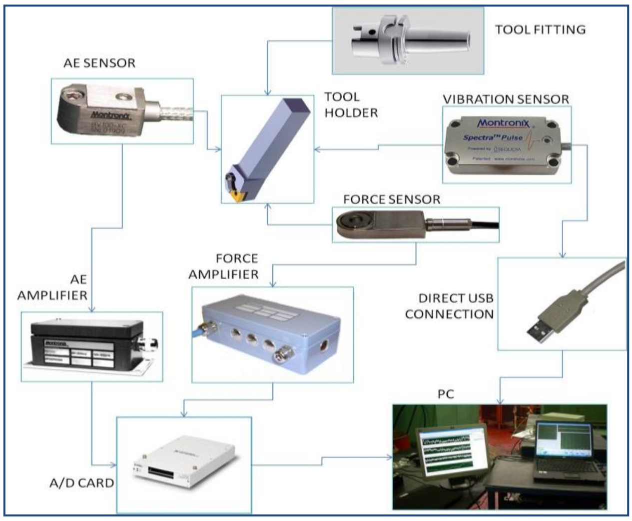
Two microbial-based cutting fluids, containing as lubricating component *pseudomonas oleovorans* and *spirulina arthrospira maxima*, respectively, were sampled and evaluated using the Reichert, Microtap and Anton Paar tribometer bench testing (Table 4).

In Fig. 3, the instrumentations for tribological benchmark testing of microbial-based cutting fluids and traditional cutting fluids are shown.

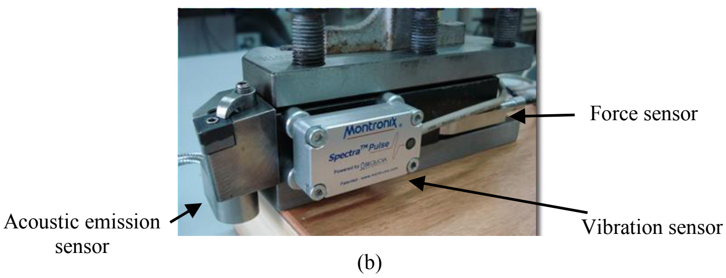
Table 4. Results of the tribological benchmark testing (an 8% oil in water was used as traditional cutting fluid reference)

Product	Bio-fluid sample	Mix of oil in water
Concentration	0.2 %	8 %
Reichert wear / mm^2 - steel	12	21
Microtap Fw mean / Ncm – steel	> 650	296
Microtap Fw Revmean / Ncm – steel	n.d.	42
Tribometer avg. friction – steel	0.38	0.08
Tribometer wear / mm^2 - steel	6.80	0.10

Very low Reichert wear values were verified for the sustainable samples which is a very good result for extreme pressure performance. Using Microtap testing, the measurement could not be completed as the maximum torque was exceeded before the drill reached the hole end. The Anton Paar tribometer test results yielded a higher friction coefficient and wear vs. the traditional cutting fluid.

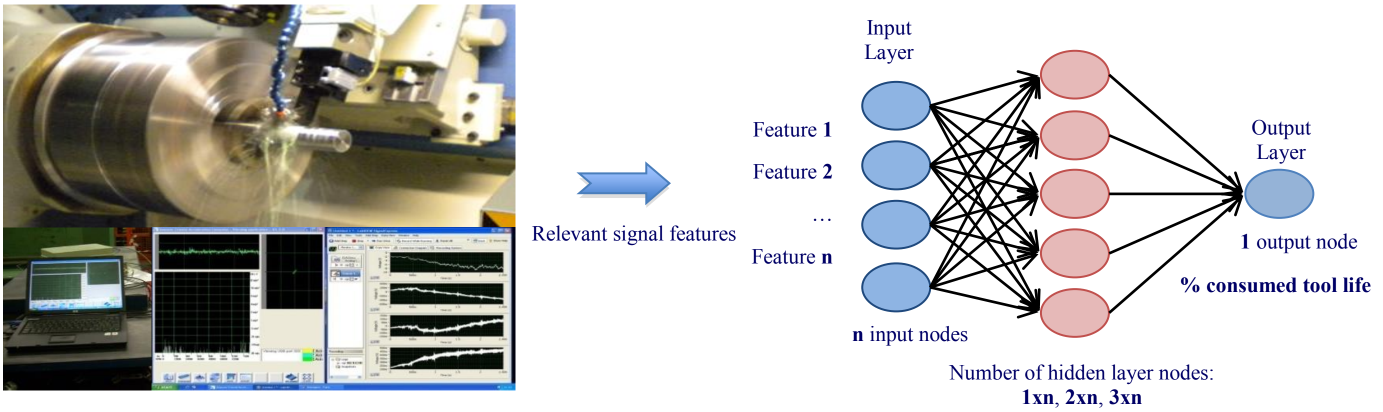


(a)



(b)

Fig. 4. (a) Multi-sensor monitoring system. (b) Turning tool equipped with force, acoustic emission and vibration sensors.



(a) (b)

Fig. 5. (a) Multi-sensor monitoring with cutting force, acoustic emission, vibration sensors. (b) Neural network based evaluation of tool life and surface integrity.

Experimental campaign of machining tests with microbial-based cutting fluids and performance evaluation procedures

The selected machining operation is cylindrical turning carried out on AISI 1045 carbon steel bars.

The metrological measurements performed during turning tests include tool wear measuring for tool life evaluation and surface roughness evaluation for surface finish assessment.

A DoE method was employed to select the experimental test conditions in order to determine the relationship between the factors affecting the process and the output of the process: cutting speed v = 150-200-250 m/min; feed rate f = 0.06-0.12-0.18 mm/rev; depth of cut d=1.0-1.5 mm. Cutting tools are sintered carbide inserts with rake angle 6° and chamfer angle 5°. Lubrication conditions include: dry cutting; conventional cutting fluid; microbial-based cutting fluid. Tool wear measurements are carried out through a shopfloor microscope.

A smart process control system for process optimisation and tool life diagnosis was set up for multi-sensor monitoring using force, acoustic emission and vibration sensors mounted as near as possible to the cutting edge (Fig. 4).

The detected sensor signals are subjected to signal analysis procedures comprising signal pre-processing (filtering, amplification, A/D conversion, segmentation); extraction and selection of relevant signal features correlated with process/tool conditions; sensor fusion technology to integrate information from sensors of different nature; machine learning based on neural network pattern recognition for smart tool life prediction and surface integrity assessment (Fig. 5).

5. Conclusion and future developments

The next steps of the research roadmap on the development and implementation of microbial-based cutting fluids for machining will focus on the following aspects. Experimental machining tests with microbial-based cutting fluids and traditional cutting fluids will be carried out for comparison purposes. Smart process monitoring techniques for optimal process parameters selection and tool conditions prediction will be applied during machining. The characterization of microbial-based lubricating component will be carried out on an off-line basis. The microbial-based cutting fluid performance will be evaluated in terms of tool life (wear development, tool breakage) and workpiece quality (surface finish, surface integrity). Model mechanisms for the lubrication action of microbial-based cutting fluids will be proposed and validated. A machining process demonstrator using microbial-based cutting fluid and smart sensor monitoring will be set up. Intelligent sensor monitoring will be applied for process optimisation, tool cost reduction and tool life enhancement, machine tool and workpiece damage risk minimisation.

The main scope of the overall research work is to factually demonstrate: the feasibility and effectiveness of introducing the newly developed microbial-based cutting fluids in machining systems; the efficacy of smart monitoring procedures for process optimisation and tool life assessment under the new machining conditions established by the novel microbial-based cutting fluid.

Acknowledgments

The research results presented in this paper are based on the activities carried out in the framework of the Fraunhofer BioMANU II project (2018 – 2019).

The Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh J_LEAPT UniNaples) at the University of Naples Federico II, is gratefully acknowledged for backing the research work.

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