Microbial Problems in Metalworking Fluids©

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All metalworking-fluid formulations share the common problem of susceptibility to microbial attack. This is not all bad news, since we need the used dilute fluid to be biodegradable for disposal purposes. However, the challenge for both formulators and metalworking facility operators, using water-based fluids, is to minimize the adverse economic impact of uncontrolled microbial contamination in metalworking operations. The following discussion will focus on water-extended fluids. A short glossary is provided in Table 1 to assist the reader who is unfamiliar with the microbiological terms used in this article.

Metalworking fluid spoilage can be defined as any change in the fluid which adversely affects its utility. Table 2 lists the most common indications of spoilage in metalworking fluids.

When any of these listed problems begins to occur with a coolant that has previously performed well, uncontrolled microbial contamination should be suspected, and corrective action taken.

In order to determine what action is appropriate, a manager must have a feel for the fundamental nature of the problem. We will discuss some of the more salient principles of metalworking-fluid microbiology.

Metalworking fluids become "rancid" because they contain rich blends of nutrients that encourage microbial growth. Mineral oil base stocks, glycols, fatty acid soaps, amines and other nearly universal constituents of metalworking fluid concentrates provide all of the essential nutrients required for growth. Not all fluids contain the same nutrients nor are they used under identical conditions. Consequently, the types of microbial contaminants which predominate may vary.

Two types of microorganisms contaminate metalworking fluids: bacteria and fungi. Bacteria are single-celled microorganisms which lack a true cell wall. Unlike higher organisms, their shape and nutritional requirements often reflect the environment from which they are recovered, rather than their genetic makeup. Consequently, a broad spectrum of genetic, physiological and morphological tests are generally needed for identifying a given bacterium. Gross classification can often be accomplished with as few as eight tests, but complete identification may require over 300 tests.

In contrast to bacteria, fungi have true cell walls, like the cells of all of the higher plants and animals. In coolant systems, fungi may appear as single-celled *yeasts* or as filamentous molds. Many fungi spend part of their life cycle as yeasts and part as molds. The factors which determine whether a fungus will propagate in one form or the other are beyond the scope of this discussion. Some of the bacteria and fungi most commonly found in metalworking fluid are listed in Table 3.

TABLE 2
PRIMARY SYMPTOMS OF MICROBIAL SPOILAGE IN METALWORKING FLUIDS

- Odor development
- Decrease in pH
- Changes in emulsion stability
- Increase in corrosion rates
- Increased incidence of dermatitis and skin irritations
- Surface-finish blemishes
- Clogged filters, screens and lines
- Increased work piece rejection rates
- Decreased tool life
- Unpredictable changes in coolant chemistry

TABLE 3
BACTERIA AND FUNGI FREQUENTLY RECOVERED FROM METALWORKING FLUIDS

BACTERIA	FUNGI
Pseudomonas aeruginosa	Fusarium sp.[1]
Proteus mirabilis	Candida sp.[1]
Enterobacter cloacae	Cephalosporium sp.[1]
Escherichia coli	
Klebsiella pneumoniae	
Desulfovibrio spp.[1]	

Note: 1) "sp." and "spp." are abbreviations for "specie" and "species," respectively.

In reality, the specific identity of a bacterial or fungal contaminant is of limited practical value in managing contamination problems. It is much more valuable to know:

- What are the contaminants doing to the system?
- What can be done to prevent that from happening?

By understanding a few basic concepts about microbial life, the plant manager can take effective measures to monitor microbial contamination and control it intelligently.

TABLE I

GLOSSARY OF USEFUL MICROBIOLOGICAL TERMS FOR THE METALWORKING INDUSTRY

Aerobe	A microorganism that can only grow when adequate oxygen is present. Oxygen serves as the terminal electron acceptor.
Anaerobe	A microorganism that can only grow in the absence of oxygen. Nitrate, sulfate or organic compounds serve as terminal electron acceptors in different species.
Bacterium	A single-cell organism. Bacteria are the smallest living units capable of carrying out, independently, all of the basic functions that characterize living beings (respiration, growth, assimilation, metabolism, excretion and reproduction). Bacteria may be as small as 0.1μm (4 x 10^{-6} in.) in diameter and may appear as spheres, rods, commas, or spirals under a microscope. As a kingdom, the bacteria represent a vast diversity of nutritional and survival capabilities.
Biocide	A chemical that kills living organisms.
Biofilm	Complex layer comprised of microorganisms and their secretions as well as detritus trapped within the biofilm matrix. Biofilm thickness may range from a few microns to several centimeters. Physical and chemical conditions within biofilms are controlled by the microorganisms growing there, and may be very different from conditions in the bulk fluid. Many species of microorganisms form the biofilm community.
Biomass	The total amount of living organisms in a given volume of material. Difficult to measure directly, biomass is generally extrapolated from the measurement of a chemical component of the living cells within the mass. Optimally, the average concentration (per cell) of the chemical being measured is either known, or a standard conversion factor has been established.
Biostat	A chemical substance that prevents the growth or proliferation of living organisms, but does not necessarily prevent metabolism.
Colony	The mass formed on the surface or within the matrix of microbial growth media as a result of the reproduction of ostensibly one cell. A bacterium with a generation time of 1 hour (population doubles each hour), will form a colony containing over 2 billion cells in about 30 hours. The colony, visible to the naked eye, is easier to count than individual microbes. Problems arise because not all microorganisms grow on the same nutrients or under the same conditions. Bacteria and fungi growing in a coolant often fail to form colonies on solid growth media.
Corrosion-enhancing microbial activities	Some bacteria, like the sulfate-reducing bacteria, contain the enzyme "hydrogenase," which scavenges hydrogen ions and creates a galvanic cell. Corrosion is accelerated at the cathode of that cell. Many microbes manufacture organic acids which attack metal surfaces directly. The very presence of nonuniform biofilms causes electropotential gradients to develop. All of these activities tend to accelerate corrosion rates.
Detritus	Unwanted particles floating on the surface, suspended in the bulk mass or precipitated out to the bottom of metalworking fluid. Swarf, flocs of biomass, detached rust deposit fragments all make up typical detritus in coolant systems.
Dip stick/dip slide	One of a number of paddle-like devices either coated or saturated with a growth medium. They are dipped into the coolant to be tested, incubated for 1-2 days and observed for the development of colonies. They provide a simple means of getting very approximate plate count data.
Disinfect	To destroy or inactivate harmful bacteria. *Not* equivalent to sterilization.
Electron-acceptor molecule	A molecule like oxygen that captures electrons and becomes reduced to water. All cells derive their energy from a sequence of reactions involving the transfer of electrons along a "cascade" of molecules. The last molecule in this sequence is the *terminal electron acceptor*. For aerobic organisms, oxygen is the terminal electron acceptor. Sulfate serves this function for sulfate-reducing bacteria.
Enzyme	A molecule or cluster of molecules composed of long chains of amino acids. The enzymes are the cell's metabolic factories. They act as catalysts for the metabolic reactions of all biochemical pathways. Active enzymes can cause fluids to become rancid even though the cells may be judged "dead" by some other criterion, such as plate counts.
Essential elements	Carbon, hydrogen, oxygen, phosphorous and sulfur are the elements without which life, as we know it cannot exist. All of these elements are present in abundance in metalworking fluids.
Facultative anaerobe	A bacterium that lives like an aerobe when oxygen is present, and like an anaerobe when oxygen is absent. Facultative anaerobes play a key role in creating and maintaining environments in which anaerobes can grow.
Fungicide	A chemical that preferentially or selectively kills fungi.
Fungus	The simplest microorganisms having a true cell wall. They appear as single-cell yeasts (approximately 10,000 times the volume of most bacteria) or as filamentous "molds." These filaments are long strands (hyphae) of cells which form the fibrous network of growth one sees when looking at moldy food. The colored bodies found in a filamentous mat contain spores. One of these bodies may contain several hundred spores, each of which can give rise to a fungal colony.
Growth	Growth is the measurable increase of an individual's or population's biomass. See definition of "biomass."
Growth rate	The amount by which the biomass increases per unit period of time (usually hours). Often growth rate is reported as the amount of time it takes for the population to double, assuming that biomass per organism is constant.
Inhibition	The prevention of any particular activity. Corrosion inhibition, microbial growth inhibition and foam inhibition are examples of inhibiting functions required of metalworking fluids. Inhibition is rarely absolute, so cost-benefit ratios should be computed to determine the merits of various inhibitor products.
Metabolism	The enzymatic reactions by which cells break down food sources (anabolism) and create new cell material (catabolism), giving off heat and waste "metabolites" in the process.
Microbially-mediated process	Processes such as corrosion and pH drop which are the direct or indirect result of microbial activity. For example, bacteria secrete organic acids which react with pH buffers, leading to a loss of pH control. The consequent drop in pH is microbially-mediated.
Microbicide	(Often written "microbiocide") is an agent which is designed to kill microorganisms, ie., both bacteria and fungi.
Mold	See "Fungus."
Nutrient	Any substance that an organism needs in order to grow and proliferate. In order for a chemical to function as a nutrient, the organism must be able to assimilate it (bring it into contact with the appropriate enzymatic machinery). Nutrients are "essential" if an organism cannot survive without them. "Non-essential" nutrients are important for healthy growth, but not for survival.
Pasteurize	To heat-treat a fluid (usually with steam) in order to kill-off potentially pathogenic microorganisms. Pasteurization requires exposure to 61–63°C (142–145°F) for 30 min. Note: many non-pathogenic microorganisms generally survive pasteurization.
Plate counts	A standard method for enumerating bacteria and fungi. A small sample portion is spread onto the surface of a suitable nutrient-containing gel. After incubation, colonies develop. (see "Dip-sticks") This traditional technique is called the "plate count" because the nutrient gel is generally contained in a standard 100 mm "petri dish" or "plate." Like dipstick methods, microbes must grow on the nutrients provided to form visible colonies. Consequently, these methods are often referred to as "viable counts."
Proliferation	The increase in the number of individuals in a population. It may or may not be proportional to growth: for example, if cells are dividing, but there is no net biomass increase, the population is proliferating but not growing. Often, in metalworking systems, biomass increases are not accompanied by increased cell numbers. If viable counts are the only measurements of microbial contamination being used, the data may be dangerously misleading.
Sterilize	The complete destruction of biological activity.
Yeast	See "Fungus."

TABLE 4

MONITORING MICROBIAL PROCESSES IN METALWORKING FLUIDS

PROCESS	MEASUREMENT
• Biofilm development	• Surface scraping dry weight
• Organic acid production	• PH, alkalinity
• Oxygen consumption	• Oxygen-volumetric test
• Organic compound metabolism	• Gas chromatography liquid chromatography mass spectrometry radiotracers
• Emulsifier/demulsifier production	• Emulsion stability test
• Growth & proliferation	• Viable counts chemical assays

TABLE 5

NUTRIENTS IN METALWORKING FLUIDS

ORGANIC	INORGANIC
Mineral Oil	Cations:
Mineral waxes	Chloride
Fatty oils	Calcium
Fatty acid soaps	Sodium
Synthetic esters	Magnesium
Phosphate esters	Manganese
Amines	Iron
	Anions:
	Sulfate
	Chloride
	Phosphate

Microbiologists concerned with spoilage prevention try to define microbial activities. Populations can be defined by their impact on the coolant or system. Table 4 lists some microbial activities that can be monitored in metalworking fluids and methods used to measure these activities. Gross observations of the phenomena listed in Table 2 are also important for monitoring microbial activity. Control is achieved by taking measures which will minimize the rates at which these microbially-mediated adverse processes occur.

Four factors predominate in controlling microbial life: an energy source, nutrients, and acceptable thermal and pH conditions. Energy comes either from light, as for photosynthetic microbes and plants, or from the breakdown of oxidized organic molecules. The pathways involved in energy metabolism require molecules such as oxygen, sulfate or specialized oxidized organic molecules which can act as Lewis acids (i.e., molecules which tend to accept electrons in a chemical reaction) to drive the process along. These molecules accept the electron liberated at the end of a cascading series of oxidation-reduction reactions and are consequently called "terminal electron acceptors."

Cells of all higher life forms (including the fungi) use oxygen as their terminal electron acceptor. *Aerobic* bacteria require oxygen for energy metabolism. However, *anaerobic* bacteria cannot grow in the presence of oxygen. Some species use sulfate, others use nitrate, but most anaerobes use "high energy" organic molecules as their terminal electron acceptors. The four-carbon organic acid, fumarate, is one such molecule. *Facultative anaerobes* grow whether or not oxygen is present. When oxygen is present, they use it just as other aerobes do. When oxygen becomes depleted, they shift to an anaerobic mode of metabolism. Thus, they play a critical role in creating hospitable environments for odor and corrosion-enhancing microbial activities, which occur principally under oxygen-free conditions.

Organic compounds and mineral salts present in metalworking-fluid formulations and makeup water are listed in Table 5, and have been discussed above. Besides serving as nutrients, inorganic salts appear to make microbial populations more resistant to biocide treatment.

Typically, growth rate and metabolic activity increase as temperature increases, up to a point. (Living microbes have been recovered from Arctic ice and from deep-sea vents where temperatures exceed 120°C (248°F)). Further temperature increases inactivate enzymes and cause rapid die-off. The temperature at which die-off occurs is species-specific. Thus, pasteurization (brief exposure to 61–63°C (142–145°F)) inactivates most common pathogens, but prolonged superheated steam treatment (15 min at 121°C (250°F)) is required to kill many of the species commonly recovered from metalworking fluids. Despite brief exposure to extreme temperatures at the tool-work-piece interface, metalworking fluids do not normally achieve bulk temperatures sufficient to control microbial growth. In fact, in most systems the bulk-fluid temperatures are optimal for growth.

A number of bacterial species commonly found in metalworking fluids grow at pH 9.2–9.5. Like the facultative anaerobes which create micro-environments for the anaerobes, these pH-tolerant bacteria create moderate pH environments for pH-sensitive microbes.

Microorganisms create "micro-environments" in which conditions may be very different than they are in the bulk fluid. These micro-environments are protected from changes in coolant temperature, chemistry and pH by the slime, or glycocalyx matrix that the microbial population produces. In terms of pH, this means that even though a coolant may be maintained at pH 8.5–9.0, the pH within the micro-environment may be below 7.0. PH control often affects symptoms rather than the underlying problem of microbial growth.

In summary, uncontrolled microbial growth can create problems ranging from gross odors and slimes to more subtle effects on coolant performance. All microorganisms require an energy source, nutrients, and a suitable thermal and pH environment. The essence of coolant system management is optimizing operating conditions while keeping the environment of the metalworking fluid inhospitable for microorganisms. Worker health and safety considerations are of paramount importance in this equation.

Although it is beyond the scope of the present discussion to delve into health and safety questions associated with metalworking, a couple of points should be stressed: Metalworking fluids are complex mixtures of chemicals which are constantly changing due to the chemical, physical and microbiological factors which typify metalworking systems. Moreover, elevated concentrations of potentially pathogenic microorganisms are occasionally recovered from aerosols in metalworking plants. The risks posed by these conditions are understood only poorly. The existing data suggest that good personal hygiene and health care minimize the risks due to coolant exposure in metalworking shops. People who have good personal-care habits do not seem to be at any greater health risk than any other portion of the general population.