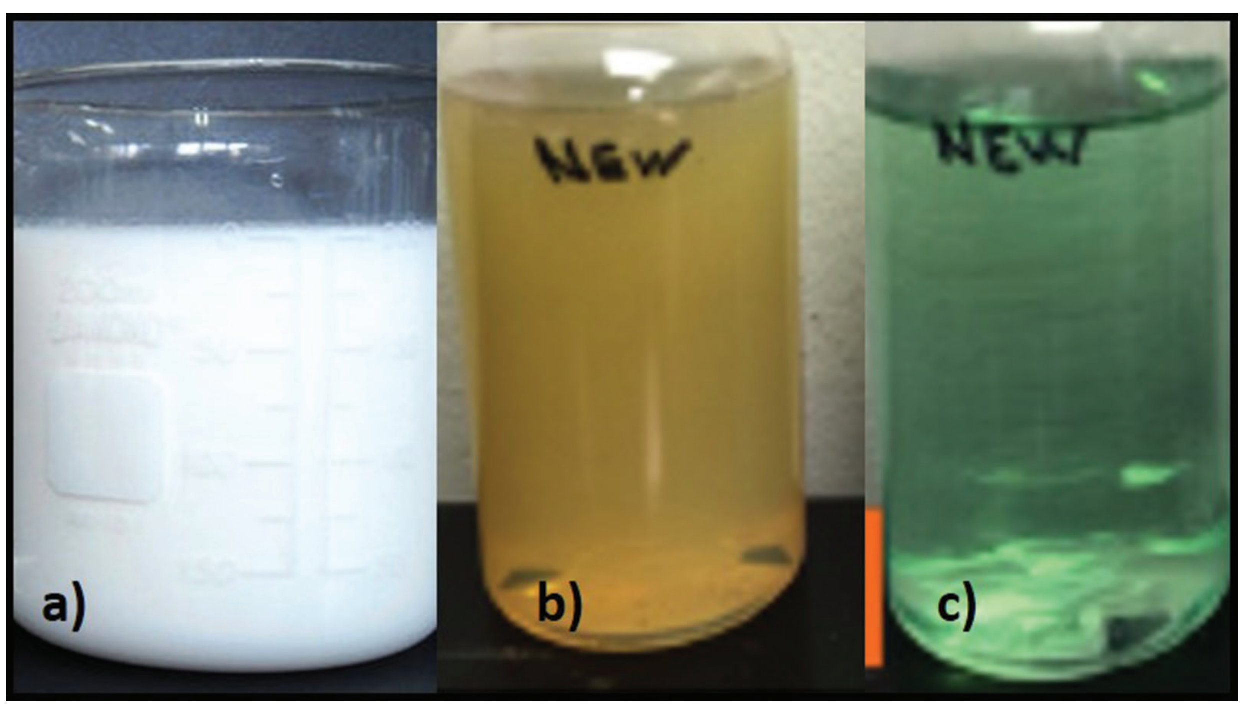
A GLOBAL OVERVIEW OF THE MACHINE LUBRICANTS AND METALWORKING FLUIDS MARKETPLACE

A recent survey conducted by Grand View Research, Inc. ascertained that the global metalworking fluids market, of both water-miscible and not water-miscible metal working fluids (MWFs), is expected to grow to 11.99 billion USD by 2022. This is due, in part, to increasing demand for MWFs in automotives and heavy machinery. Moreover, the MWF compounder market is highly fractionated. Although there are a few global companies such as Dubois, Fuchs, and QuakerHoughton [5], no single company controls more than 10 % of the market. More than 60 % of the market is shared among at least 1000 intermediate and small compounders. the existence of multiple small suppliers in this market ensures that MWF supply will continue to meet demand. Consequently, pricing will also remain competitive for the foreseeable future.

Furthermore, synthetic fluid use is predicted to growth, owing to their exceptional properties including increased tool longevity and superb surface finish. Although many of the performance limitations that have limited synthetic MWF use historically have been addressed, their use is unlikely for them to reach the level of semisynthetic fluids within the next seven years. Growth in the use of synthetics and semisynthetics will be slower in the Asia-Pacific region where end-users continue to focus on MWF unit cost, rather than annualized operational costs, and therefore continue to prefer low cost mineral oil-based, emulsifiable oils [15]. Globally, MWFs demand growth will continues to be greatest in the Asia-Pacific region. This is due to the massive consumer base in the region, most notably hailing from China and India [14]. In regard to OEMs in the Asia-Pacific region, price rather than value consciousness is a primary consideration informing demand for MWFs. This locale is not only the most salient market in this industry, but is also projected to experience an increase of 4.4% in the compound annual growth rate (CAGR) from 2015 to 2022 [11]. Anticipated to be a significant component catalyzing the market in this region is growing production volumes in a variety of sectors such as automobiles, marine, defense and aerospace.

Metalworking fluids are formulated products that contain a base fluid and various performance additives. The number of ingredients in an MWF formulation can range from five to >20. The finished product is designed to achieve a diverse set of functions pertaining to the machining process. Currently, there are no universally-suitable MWFs. The three primary functions of all MWFs are cooling, lubrication, and chip removal [1]. Regardless of the operation, MWFs must improve tool life and facilitate the production of parts with the required surface-finish properties (more on this, below). For best performance, MWF formulations must be tailored to the specific operations in which they will be used. The demands on MWFs used for metal forming are different from those used for metal removal. Machining operations on soft, ductile alloys (for example, aluminum, brass, and specialty alloys) require different MWF properties than those on harder metals (for example, mild and stainless steel). Straight oils (also called neat oils) are adequate for operations with relatively low feed rates and extreme pressures at the tool-workpiece interface.



The three primary types of water miscible MWFs – a) emulsifiable oil; b) semisynthetic; and c) synthetic.

In these operations, lubrication is the MWF's primary function. As feed rates increase, cooling becomes increasingly important. Straight oils are formulated from base stocks (petroleum, synthetic, or vegetable oil) and functional additives – particularly extreme pressure (EP) additives and boundary lubricants.

Water-miscible MWFs typically provide better performance when

Collecting a grab sample of emulsifiable oil MWF from an individual machine sump.

cooling is a major MWF function. ASTM D2881 Classification for Metalworking Fluids and Related Materials identifies three categories of water-miscible MWF: emulsifiable oils, semi synthetics, and synthetics (fig 1). Emulsifiable oils (EO – often erroneously called soluble oils) contain >30% (vol) of a base oil. The balance of the MWF concentrate is composed of functional additives. When diluted with water for end-use, EOs form milky, macro-emulsions with average droplet sizes >1.0 m diameter. Semisynthetic (SS) MWFs contain from 20% to 50% of base oil. As for EOs, the balance of SS MWF concentrate is functional additives. When diluted with water for end-use, EOs form micro-emulsions with average droplet sizes <1.0 m dia. Synthetic (S) MWFs (formally synthetic solution MWFs) contain no base oil and do not form an emulsion when diluted for end-use. Depending on the metalworking operation, end-use diluted MWFs contain 3% to 10% of MWF concentrate.

Petroleum base stocks are typically either naphthenic or paraffinic oils. Naphthenic oils have better additive solvency and emulsion stability characteristics than paraffinic oils, but paraffinic oils have better oxidative stability and viscosity index properties. Common synthetic base stocks include polyalphaolifins (PAOs), synthetic oils (i.e., gas-to-liquid oils), and polyethylene glycols (PEGs). Acceptance of vegetable base oils was historically limited due to poor oxidative stability properties. However, this limitation has been largely overcome by improved oil production processes and antioxidant chemistries.

Functional additives include corrosion inhibitors, coupling agents, defoamers, dyes, emulsifiers, lubricity agents, microbicides (also known as biocides or antimicrobial pesticides), perfumes, and viscosity and viscosity index modifiers. The simplest EO formulations can contain as few as four ingredients: base oil, a corrosion inhibitor, a coupling agent, and an emulsifier. The most complex formulations can contain multiple chemistries within each functional category.

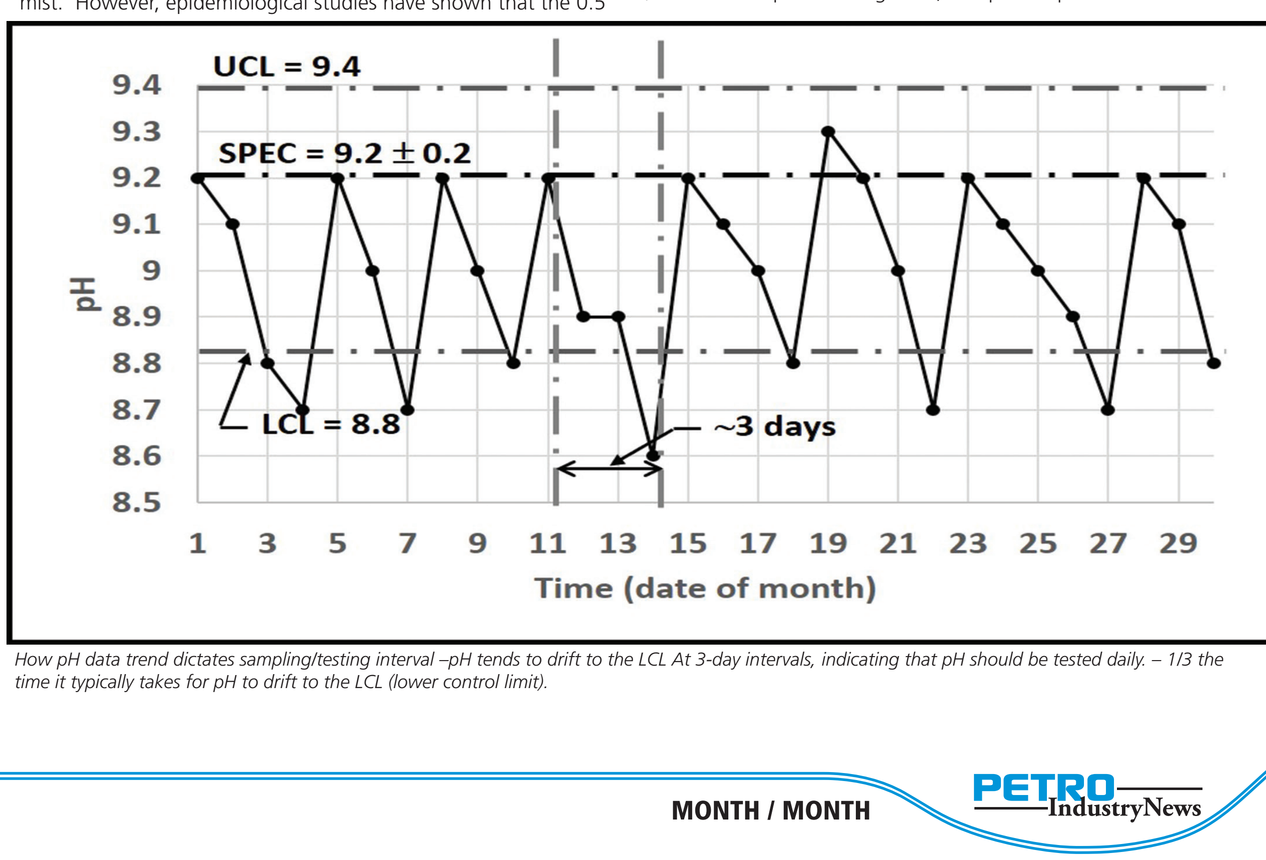
To be accepted for use, an MWF must meet performance criteria, have a benign toxicological profile, and be environmentally acceptable. As noted above, performance criteria vary among metalworking operations. For example, in aluminum rolling, the fluid must provide the finished roll with a smooth unblemished, unstained surface. MWF use for grinding operations must remove heat efficiently, carry very small chips (swarf) away from the work zone, and transport them to MWF conditioning equipment. Although the general properties of rolling and grinding MWFs are similar, their formulation specifics are substantially different. Although functional life is typically included among MWF performance specifications, this criterion really depends on system turnover rates. In some operations, the amount of residual MWF that remains adhered to the finished part is intentionally high to provide a protective, corrosion inhibiting film. The phenomenon is called drag-out. In these systems, MWF turnover rates can exceed 10% per day – 100% MWF turnover every 10-days. Wire drawing represents the opposite extreme in terms of MWF turnover. Drag-out is minimal in wire drawing systems, resulting in turnover rates <5% per month. Consequently, the importance of MWF stability increases as turnover rate increases. Factors impacting MWF stability will be considered below.

Health, safety, and environmental (HS&E) concerns play an increasingly important role in MWF selection. Machinists are invariably exposed to MWFs. They are exposed dermally [3] as they handle machined parts. They also inhale MWF mist (aerosol) [3] unless machining operations are fully enclosed and vented through properly functioning and maintained mist collection systems. Although there has been much debate on the topic, there is no universal consensus on the protective concentration of mist in metalworking facilities (the protective concentration is the amount of mist – in mg m^{-3} – to which workers can be exposed with no risk of respiratory disease). The US Occupational Safety and Health Administration (OSHA) has set a 5.0 mg m^{-3} TWA_8 (8h time-weighted average) permissible exposure level (PEL) for straight oil MWF mist exposure. The US Centers for Disease Control's (CDC's) National Institute for Occupational Safety and Health (NIOSH) has established a 0.5 mg m^{-3} TWA_8 recommended exposure level (REL) for straight oil and water miscible MWF mist. However, epidemiological studies have shown that the 0.5 mg m^{-3} TWA_8 reduces but does not eliminate respiratory disease risk. Notwithstanding the ongoing debate about a protective PEL, all industry stakeholders agree that measures taken to reduce mist exposure must be taken to minimize disease risk. The primary health risk associated with dermal (skin) exposure is contact dermatitis [3]. The primary health risk associated with mist inhalation is respiratory disease [3]. MWF contact dermatitis is typically an allergic reaction. Its severity can range from mild reddening to debilitating skin damage. MWF mist exposure can result in allergenic disease. Allergenic disease severity due to mist inhalation can range from mild irritation (runny nose) to potentially fatal hypersensitivity pneumonitis (HP). The latter condition is quite rare (as of this writing there have been fewer than 300 cases reported among machinists since the sentinel outbreak in 1992; in contrast to the 25% incidence rate among pigeon breeders). Although changes to MWF formulation chemistries can reduce MWF allergenicity and mist forming tendency, they cannot eliminate either. However, there is a global trend towards using MWF with innocuous toxicological profiles. The Global Harmonized System of Classification and Labeling of Chemicals (GHS) provides formulae for calculating the human and ecotoxicity risks (hazards – H-codes) of finished MWF formulations (i.e. MWF concentrates). Formulators must beware that despite GHS' name, there are many differences among countries and regions. To be sold legally, MWF concentrates must meet the regulatory requirements in each target region. It is not uncommon for chemistries forbidden in one region or country to be preferred in another. Disparities among regulatory agencies create considerable challenges for MWF compounders wishing to sell their products globally.

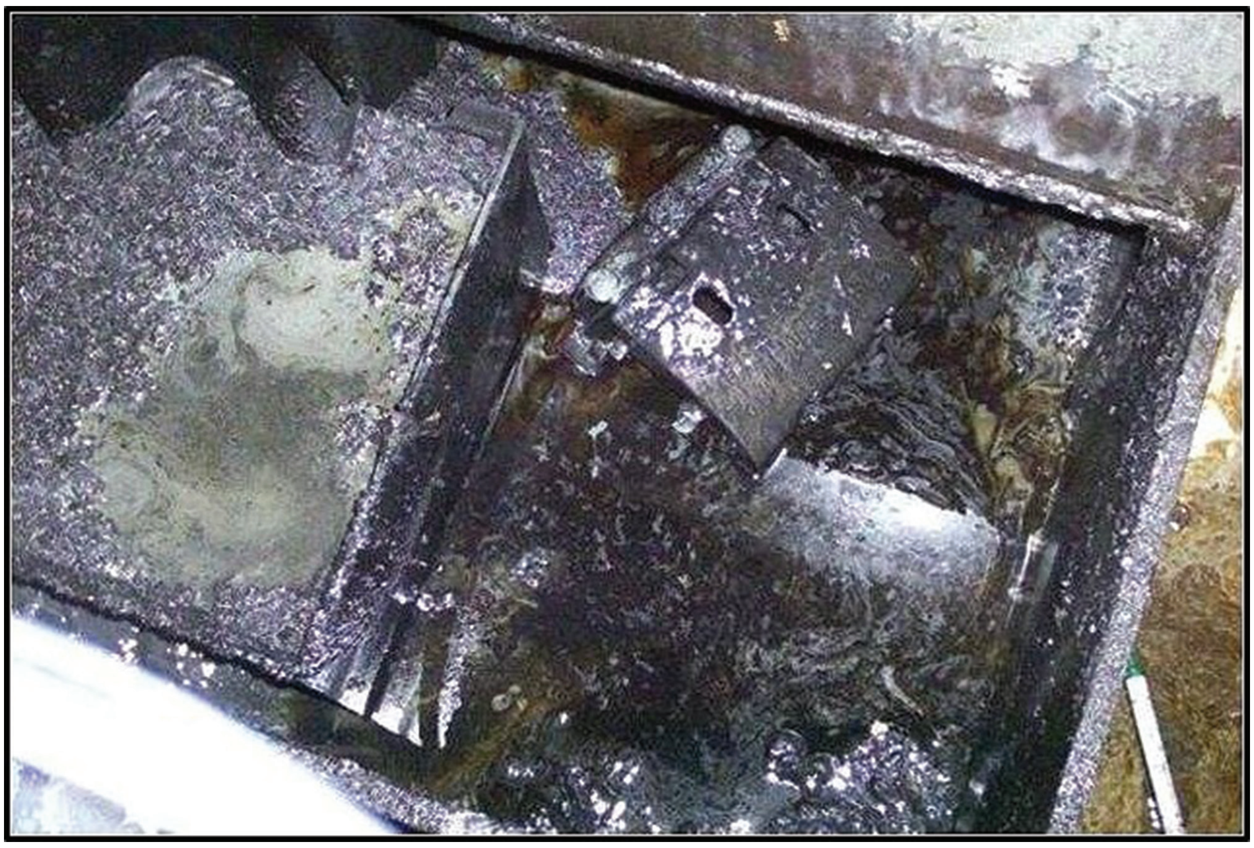
Beyond addressing the human health issue, modern MWFs must meet the criteria established for environmentally-acceptable lubricants (EALs). Although EAL criteria were developed to reduce the release of toxic substance from marine vessels into natural bodies of water, the desire to use so-called green products has spread throughout the lubrication industry – including MWFs. Three criteria define EALs:

- Biodegradability
- Aquatic Toxicity
- Bioaccumulation

For a detailed explanation of EAL, refer to US EPA 800-R-11-002. Biodegradability refers to the ease with which a compound (or formulated product) is broken down by microorganisms. There are a variety of ASTM, OECD and US EPA test methods used to determine primary, ultimate, and inherent biodegradability – how readily a compound biodegrades. Primary biodegradability is "the loss of one or more active groups in a chemical compound that renders the compound inactive with regard to a particular function" (EPA 800-R-11-002). Inherent biodegradability refers to the breakdown of a compound during the course of a biodegradability test. Compounds that breakdown during the early stages of a test are considered to be readily biodegradable. The exposure periods that define compounds as being inherently or readily biodegradable are specified in the respective test methods. Ultimate biodegradability is the degree to which a compound is mineralized to carbon dioxide (CO_2), water, and mineral salts under test conditions. Finding the appropriate degree of biodegradability has been a balancing act since water-miscible MWFs were first introduced to industry. On one hand, end-users want products to remain eternally stable in-application. On the other hand, end-users want MWFs to biodegrade rapidly once they are sent to a waste treatment facility. The search for MWFs that provide long-term, exceptional performance in-



How pH data trend dictates sampling/testing interval –pH tends to drift to the LCL At 3-day intervals, indicating that pH should be tested daily. – 1/3 the time it typically takes for pH to drift to the LCL (lower control limit).



Individual machine sump - example of bad practice. If the system is not kept clean, the best MWF will fail.

application and satisfy the conflicting demands of biostability and biodegradability continues. In contrast to mineral oils – considered to be persistent – PAGs, synthetic esters, and vegetable oils, are generally rated as readily biodegradable [15], driving market trends towards their increased use in MWF formulations. In addition to the EAL factor, waste treatability is a driving factor for MWF acceptance from an operational cost perspective. End-users invariably prefer MWFs that can be handled effectively by preexisting, on-site, waste treatment systems. Installing a new water treatment system to accommodate a MWF that cannot be treated by the existing equipment requires a considerable capital expenditure. Metalworking facility health, safety, and environmental (HS&E) managers will reject MWFs that might cause the facilities wastewater discharge to fail local, regional, or national water quality criteria.

Aquatic toxicity is assessed by performing one or more standard tests, such as OECD tests series 201-4 and 209-212 that include exposures of various organisms (algae, daphnia, and various fish species) to test compounds. MWFs with benign aquatic toxicity profiles are preferred over those that are more toxic. Perhaps not surprisingly, the relative toxicities of mineral oils, PAGs, synthetic esters and vegetable oils parallels their respective biodegradability [15]. The latter three all have relatively low aquatic toxicity.

Bioaccumulation is the accumulation of a chemical compound within an organism's tissues over time. Non-polar molecules like oils tend to partition into fatty tissues and bioaccumulate in them. Polar (water-soluble) molecules are less likely to bioaccumulate. Consequently, a product's oil-water partition coefficient (K_{ow}) is commonly used to assess a compound's bioaccumulation potential. $Log_{10} K_{ow}$ is computed from the relative concentrations of a compound in the n-octanol and water phases of a container to which the compound has been added. The container is shaken vigorously and allowed to stand for a designated period before the compound's concentration in each phase is determined. Compounds with $Log_{10} K_{ow}{}^3$ are unlikely to bioaccumulate. 50 L/min Those with $Log_{10} K_{ow}{}^3$ are likely to bioaccumulate. Recognizing that EO and SS MWF formulations contain both polar and non-polar components, the bioaccumulation potential of finished formulations can be difficult to assess accurately. Because all components of S MWFs are polar, the $Log_{10} K_{ow}$ of these formulations are typically <3. This is one of the factors providing impetus to the growing market share of S MWFs. In contrast to mineral oils, neither PAGs, synthetic esters, nor vegetable oils tend to bioaccumulate [15].

Ultimately, MWF performance depends on first matching the formulation with the application, and second maintaining the fluid properly. There are numerous ASTM, EI, ISO and other consensus test methods that can be used to test MWF performance characteristics. Major original equipment manufacturers (OEMs) specify qualification tests that must be performed on MWFs before the fluids will be considered for field evaluation. Although test rigs do a fair job of simulating field conditions, they cannot mimic them completely. Therefore, candidate MWFs that have passed laboratory tests, must be further evaluated through field trials. Only after a MWF has demonstrated acceptable performance under field conditions should it be adopted for general use. As noted above, a MWF formulation that is a top performer for one metalworking operation might prove unsuitable for others. This becomes a particular challenge at larger machining facilities in which various metal alloys are machined by a number of different metal removal operations (i.e., broaching, milling, grinding, tapping, reaming, etc.) Metalworking facility managers strive to find a balance between using an overwhelming number of different MWFs – each used as the optimal product of a limited number of machines – and ensuring that production runs smoothly (i.e., the production rates meet targets with minimal need for rework).

Once an MWF has passed qualification testing, cost-effective condition monitoring (fig 2) and maintenance is essential to optimize fluid performance and functional life. It is critical to link MWF condition to operational data such as tool life, production rates, and rejected fished part data. As explained above, MWFs are formulated with a variety of functional additives. Metalworking operations place different demands on each functional additive. Consequently, even when a MWF's gross properties meet control criteria, loss of critical functional additives will be reflected in decreased tool life (i.e. parts produced or surface area – or total mass – of metal removed), degraded machined (or formed part) rejection rates, increased incidence of post-production corrosion, or a combination of these phenomena. As important as MWF condition monitoring is, fluid condition data, not interpreted in context with operations data, are not as useful as they should be. Consider the cost of a typical MWF concentrate (<$10 kg-1) versus the cost of a typical tool (can easily exceed $1000). Efforts spent to extend MWF life when tool life is plummeting is a false economy.

The basic elements of a cost-effective condition monitoring program include sampling, testing, and data trend analysis. Sampling programs are defined by collection frequency and location. Under most conditions, the frequency sweet spot is a period equal to one-third of the time it typically takes for the tested parameter to drift from optimal to outside its control limits. For example, as illustrated in figure 3, if an MWF 's optimal pH is 9.2 with a 9.4 upper control limit (UCL) and 8.8 lower control limit (LCL), and pH typically falls to 8.8 after three days, pH should be tested daily. Representative samples are typically collected from lines leading to machines or MWF return sluices. The former provides a sample that is representative of clean MWF and the latter provides one that is representative of MWF heading to the system's reconditioning sub-system. Diagnostic samples are taken from nozzles delivering MWF to the tool-workpiece zone or zones most likely to be problematic (for example, filtration media surfaces, and fluid back-flow (eddy) or stagnant zones). For a complete discussion of MWF condition monitoring see Foltz, 2018 {Foltz, G., 2018, Chapter 13 Metalworking Fluid Management and Troubleshooting, In J. Byers. Ed. Metalworking Fluids, 3rd Ed. CRC Press, Boca Raton, pp: 310-333. ISBN: 9781498722223}.

Each MWF, MWF system, and operation is unique. Assuming that a single condition monitoring plan will suffice for all systems can lead to increased failure frequencies. In addition, design and executed fluid management programs can reduce annual operational costs at a metalworking facility by >10 %.

All fluids, regardless of the fluid type or application, demand maintenance of some kind. Although they are virtually maintenance-free, even straight oils, require some level of maintenance. Metal fines suspended in recirculating straight oil can scar or leave inclusions on the surfaces of worked parts. Consequently, straight oils need to be filtered regularly to remove metal fines. Water-miscible MWFs require substantially more maintenance than straight oils do.

Because water-miscible MWFs are invariably less viscous than straight oils are, transferring chips from the tool-workpiece point of contact is more challenging. The challenge of transporting chips to chip-removal hardware increases with system size. In many machines served by individual sumps, the distance between the point of cut and the sump is 1 m (3.2 ft) to 2 m (6.4 ft). In large central systems, the distance can be more than 100 m (328 ft). Return sluices (trenches), in which recirculating MWF moves at high velocity (typically at least 570 L/min^{-1} or 150 gal/min^{-1}) and under turbulent flow conditions, transport chips to centralized MWF conditioning systems. Typically, these systems include a settling tank, chip-drag conveyer, tramp oil skimmer, and either disposable or permanent filter.

Disposable filters are typically fabrics produced from synthetic fibers. The medium is supported by a perforated plate so that fluid can pass across the filter without damaging it. Typically, disposable filters are designed to remove particles that are 100 m. Smaller pore-sized media – down to 10 m – are also available. As particles accumulate on the filter, the pressure differential across the medium increases. When it reaches a critical level, the filter will index (i.e., advance) so that fresh medium is in the flow path. Permanent filters are typically wedge wire drums. Like disposable media, wedge wire filters can be designed to remove particles of various sizes. For example, a 160-mesh filter will remove particles^3 96 m and a 1340-mesh filter will remove particles^3 10 m. When the pressure differential across a wedge wire filter exceeds its control limit, the filter unit will start a back-flush cycle to clean the filter's surface. For metalworking operations with very tight surface finish specifications, primary filters are often augmented with bag filters that can remove particles that are 1 m or smaller. For more details about MWF filtration see Brandt (2018 – Brandt, R. H., 2018. Chapter 12 – Filtration Systems for Metalworking Fluids. In J. Byers. Ed. Metalworking Fluids, 3rd Ed. CRC Press, Boca Raton, pp: 285-308. ISBN: 9781498722223).

Because water-miscible MWFs are typically complex formulations, diluted in water, and recirculated at high speeds, they are susceptible to deterioration processes that do not affect straight-oil fluids. Poor water quality is a major cause of MWF failure. Regardless of the quality of the make-up water, there's a tendency for water hardness to increase over time. As water evaporates from end-use diluted MWF and is replaced with fresh make-up water, hardness molecules such as calcium and magnesium carbonate concentrations increase. Moreover, the concentration of metal ions also increases. Calcium (Ca2+), magnesium (Mg2+), iron (Fe2+, Fe3+) and other metal ions are cationic (they have a positive electrical charge). Cations tend to cause oil in water emulsions to split. Consequently, to maintain emulsion stability, it is important to control water hardness. The large surface area to volume ratios of chips and swarf (micron to sub-micron size particles produced by grinding operations) make them nearly as reactive as dissolved metals. As noted above, removing chips and swarf from recirculating MWFs is essential to optimal fluid performance.

Well-aerated, aqueous fluids with water to oil ratios ranging from 90% to 97% provide an excellent environment for microbial life. The molecules used to formulate MWFs contain all of the essential elements of life: carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorous. As a result, without adequate control, microbial populations in MWFs can easily exceed 106 microbes/mL. Population densities on MWF system surfaces can range from 10x to 1,000x those found in the bulk fluid. Left uncontrolled, microbes can degrade MWF chemistry (fig 4), selectively consuming various functional additives. Microbes can also pose a potential health risk. When microbes, microbe fragments, or biomolecules become part of MWF mist they are called bioaerosols. Bioaerosol components can cause health issues ranging from mild allergies to sever pulmonary disease (for a detailed explanation of MWF microbiology and microbial contamination control, see Passman, F.J., 2018. Chapter 11 – Microbiology of Metalworking Fluids, In: J. Byers. Ed. Metalworking Fluids, 3rd Ed. CRC Press, Boca Raton, pp: 241-284, ISBN: 9781498722223).

Traditional strategies for maintaining microbial contamination control relied on the use of microbicides (ASTM E2169 Practice for Selecting Antimicrobial Pesticides for Use in Water-Miscible Metalworking Fluids explain how to select the most appropriate microbicide for a given MWF-related use). As regulations covering the use of MWF microbicides have become increasingly restrictive, MWF compounders have worked hard to replace older functional additives with biostable chemistries. Biostable additives must have well-demonstrated, non-biocidal, performance properties. If they do not, they might be considered to be unregistered microbicides. When regulatory agencies learn of unregistered microbicide use, they often impose stiff fines and occasionally start criminal proceedings.

The condition monitoring practices discussed above are used to determine whether the overall MWF concentration is within specified control limits. Tests such as pH, alkalinity, and conductivity can be used to signal when individual functional additives are being depleted. The balance of MWF components can be maintained through tankside addition. To ensure proper mixing and dosing, only qualified fluid managers should make these additions.

MWF performance also depends on good industrial hygiene practices. Workers must not use return sluices as open sanitary lines or waste receptacles. Although it is good practice to keep machine and shop floor surfaces clean, care must be taken to prevent washing solutions and debris from being rinsed into the MWF system. Floor cleaners are likely to split MWF emulsions. Dirt and debris are great sources of microbial contamination.

All MWFs are designed to work at specified concentrations. Fluid compounders define the optimal concentration for a given operation. For many operations, the optimal concentration is specified as X+2% (vol), where X is the optimal concentration. More is not necessarily better. When MWFs are used at concentrations greater than the specified range, they can become unstable. They can also lose their cooling properties and leave undesirable residues on both tools and finished parts. When microbicides are formulated to deliver the maximum allowable dose in end-use diluted MWFs, under-dilution can cause the final microbicide concentration to exceed the limits indicated on product labels. This can cause dermatitis, respiratory irritation, or both. Importantly, using inadequately diluted MWFs wastes money in unnecessary MWF concentrate costs. When used at concentrations less than those specified, MWFs lose their optimal performance. In particular, lubricity and corrosion inhibition performance is likely to be suboptimal [12]. Additionally, because alkalinity additives are not present at sufficient concentrations, pH control can become more difficult to maintain [12]. Similarly, if microbicides in the formulation are over-diluted, they will be ineffective and will possibly select for biocide-resistant microbes. Consequently, MWF condition is most easily maintained when MWFs are used at their specified end-use concentrations. Optimally, MWF concentrate is preblended with water (preferably deionized) before being added to in-use fluids. The MWF concentrate is added to a tank prefilled with the appropriate water volume and mixed to create a stable emulsion or well-mixed synthetic fluid.

As noted above, water evaporation is a major means for fluid volume loss. Consequently, unless MWF drag-out is greater than evaporation loss, MWFs tend to become more concentrated over time, and the amount of MWF mixed with water for make-up purposes is invariably less than that used when blending to fill an empty system. Fluid managers have equations for determining the correct MWF concentration for make-up fluid based on the system size, total volume of fluid needed to top-off the system, and the current MWF concentration in the system.

Historically, MWFs were simply thought of as consumables – no different from floor cleaners and paper towels. In the early 1980s, after MWF waste was designated as a hazardous waste, the concept of fluid management gained traction. Although the annual cost of MWF at a given metalworking facility accounts for a mere 1% to 2% of total manufacturing costs, effective MWF management can reduce manufacturing costs by 10% to 25%. This savings reflects increased tool life, reduced part rejection rates, and elimination of unscheduled system outages needed when the system must be drained, cleaned, and recharged.

The bottom line is that MWFs have a substantial impact on a manufacturer's success. This means that MWFs should be viewed as an asset, not an unavoidable consumable expense item. MWFs are liquid tools. Failure to keep MWFs in optimal condition will decrease manufacturing productivity and facility profitability. Plant managers ignore MWF management best practices at their own peril.

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