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Non-Aqueous Metalworking Lubricants

1. Introduction

A decade ago, one could have been forgiven for believing that Non-Aqueous Metalworking Lubricants (NAMWLs) were destined for extinction, or at best, to occupy specialist niche applications. But, this article will show that non-aqueous products have important attributes with relevance now and in the future for the metalworking production industry.

As in many industries, theory has followed practice; engineers knew that sulphur and fats assisted in cutting and forming metals before lubrication regimes and formation of low-shear surface films were understood. Progressive improvements in lubrication technology have enabled significant advances in metalworking production. In this article emphasis is placed on relating the properties and composition of NAMWLs to performance in metal removal and deformation operations.

Experience is vital in the successful supply and servicing of metalworking lubricants. It is crucial to accumulate detailed and accurate information on the performance of products in practical applications. This is not always easy because feedback from the shop floor can be confusing at times. Metalworking lubrication calls on the knowledge and experience of the development chemist and the production engineer. When these two disciplines work together to evaluate and optimise performance, remarkable advances can be achieved.

2. Comparisons with water-based products

In recent years the range of applications of water-mix fluids has been extended by developments in formulation and engineering technology. Many operations which were traditionally carried out with neat oils can now be successfully accomplished with water-mix fluids. However, where superb lubrication and powerful extreme pressure properties are required, NAMWLs generally out-perform water-mix fluids. Conversely, heat removal by oil in water emulsions is far better because of the excellent cooling power of water and low viscosity which facilitates access to the cutting/forming zone. In certain special products used in metal deformation processes the emulsion is of the "invert" type i.e. water in oil, and because the continuous phase in this case is oil, the overall viscosity and lubricity are much more "oil-like".

NAMWLs are used in preference to water-mix fluids for certain very arduous operations and also where the machine tool depends on the metalworking fluid for lubrication. However non-aqueous products can also demonstrate other advantages over their water-based counterparts. They do not support the growth of micro-organisms unless water contamination is present. NAMWLs are also arguably easier to maintain in metal removal applications than water-mix fluids and are capable of being recycled many times before disposal becomes necessary. These factors will be examined more closely in the following sections.

The cost per litre of emulsion prepared from a water-mix fluid concentrate is generally much lower than that of a NAMWL which is used as supplied. Even if the concentrate costs much more per litre than a NAMWL, the dilution factor of 10 to 50 times means that the cost of the ready-for-use emulsion is much lower. On the other hand, a fair comparison must also take into account working life and the costs of maintenance and disposal.

3. Metal removal

The properties of neat cutting and grinding lubricants must be accurately matched to their applications and the formulator makes many choices in the development process.

Base stock selection must take into account viscosity, volatility, resistance to oxidation, composition and solvency for additives (naphthenic oils can be valuable especially at high additive concentrations). Synthesised hydrocarbon base stocks such as poly alpha olefins can offer significant advantages over conventional mineral oils.

Esters derived from vegetable sources are also effective base stocks. Their inherent molecular polarity imparts boundary lubrication. However, it is important to ensure adequate resistance to oxidation.

The significance of oxidation resistance, whether in mineral or vegetable derived base stocks, is often overlooked. Increased ambient and high localised temperature, together with dissolved metals, such as iron and copper, acting as catalysts, can accelerate the rate of oxidation. The situation is further aggravated by plentiful access to atmospheric oxygen as oils are sprayed and broken into fine droplets in the machining operation. Oxidation can result in development of acidity and formation of gums and lacquers which seriously interfere with the operation of machine tools. Such deposits are difficult to remove and prevention (through careful formulation) is definitely better than cure.

Perhaps surprisingly, flash point is an important characteristic. If volatile fractions are present, there is increased risk of fire in machine tools and extraction systems. This is an especially important consideration in formulation of products where low viscosity is necessary for the metalworking operation. Well-refined low viscosity base stocks, free from volatile fractions, are preferable to "dumbbell" blends containing low flash point constituents.

Extreme pressure agents include additives containing sulphur, chlorine and phosphorus as well as the passive extreme pressure agents (PEPs).

Sulphur may be in the form of a polysulphide or sulphurised natural or synthetic ester. Different degrees of sulphur activity are available as evidenced by the tendency to stain copper test pieces. Highly active sulphurised additives are used mainly in the formulation of heavy duty oils for cutting and grinding of steels. They are unsuitable for work with yellow metals because of the risk of staining. Sulphurised additives with controlled activity can be successfully used for operations on yellow metals and provide a formulation route for general purpose neat oils.

Chlorinated paraffins are extremely effective additives for a wide range of metal removal operations, especially arduous slow speed processes such as broaching of difficult alloys. However, chlorine-free products have been developed for many metalworking applications, driven by concerns regarding hazards associated with certain types of chlorinated paraffins.

Boundary lubricants, used to improve lubricity, include natural and synthetic esters and fatty acids. Some less arduous metal removal operations can be carried out with oils containing boundary additives without the need for extreme pressure agents.
Natural esters may have poor oxidation resistance and this must be taken into account when formulating metal removal oils for applications where high temperature will be encountered.

Specialised additives include antioxidants, corrosion inhibitors and polymers which suppress the formation of oil mists.

Considering applications, one of the many puzzling facts to those who visit machine shops is that an apparently similar metalworking production operation is carried out in one company using a water-mix fluid and in another with a neat oil. There are many factors to be considered, but the following operations are frequently carried out using NAMWLs:

Grinding the flutes in drills and threads in tapping tools gives rise to high localised temperatures and it is essential to achieve a good surface finish combined with dimensional accuracy. Neat oils with viscosity in the range 28 - 32 cSt at 40 deg C and Class 1A copper corrosion, based on sulphur and phosphorus additive chemistry are typical, although oils of lower viscosity are sometimes used for similar form grinding operations.

Vertical broaching of alloy steels is a slow, but arduous operation. The lubricant must have low viscosity for easy access to the cutting zone and to ensure effective chip flushing, as well as extreme pressure properties and high lubricity. A typical broaching oil with viscosity of 15 cSt at 40 deg C contains chlorinated hydrocarbon combined with fatty ester. The limiting factor on the effectiveness of extreme pressure additives is the melting point of the film formed on the metal surface. In this type of application, speeds are reduced to control work hardening and the relatively low melting point of chloride films (compared to those formed by sulphurised additives) is not a limitation.

Severe deep hole drilling operations are often carried out using neat oils. A deep hole is generally defined as having a depth of 4 to 5 times its diameter, although a depth to diameter ratio of 300:1 is possible. The techniques include gun drilling, BTA and ejector drilling. In ejector drilling, cutting oil enters the drill between inner and outer tubes and exits, carrying the chips, through the inner tube. The operation generates high localised temperature due to the powerful cutting action, so that continuous cooling of the cutting oil is often necessary. Low viscosity is essential for access to the cutting zone and effective chip transport, combined with powerful extreme pressure properties and high lubricity. Active sulphurised esters are typically used as additives in oils for ejector drilling of steels. Although chlorinated hydrocarbons are often included in the formulation, in some very severe operations the localised temperatures result in decomposition with release of acidic material, causing corrosion which cannot be readily controlled using inhibitors. In such situations, a chlorine-free formulation has been found to solve the problem. It would seem that a water-based fluid would be preferable for such an operation due to its high cooling ability combined with low viscosity, and water-mix metalworking fluids can be successfully used for ejector drilling. However, for very arduous operations, the need for high extreme pressure properties and lubricity often tips the balance in favour of neat oil.

NAMWLs are also widely used for honing and in gear production and finishing operations including hobbing, shaping, shaving and grinding.

4. Metal deformation

The processes range from light presswork, where a “vanishing oil” may be the only lubricant required, to severe deep drawing, tube, rod and bar drawing, heading, cold pilgering and hot forging. The metals subjected to deformation range from copper, brasses, aluminium, carbon steels, through to nickel alloys and titanium. Generally deformation processes produce less waste than metal removal and enable specific metallurgical properties to be achieved. On the other hand many deformation processes require long production runs to justify the costs of capital plant and tooling. Metal forming lubricants call on similar additive technologies to those used in metal removal; however, some deformation processes require formulations containing solid lubricants such as graphite, molybdenum disulphide or zinc oxide. Less conventional lubricants include plastic film for pressing operations and even molten glass for hot extrusion.

When selecting a lubricant for metal deformation, it is advisable to consider the process as a whole:

What are the nature and conditions of the deformation operation?
What are the composition and metallurgical condition of the workpiece?
What is the surface condition of the workpiece and is any pretreatment carried out?
How will the lubricant be applied?
Is the lubricant expected to provide post-operational protection?
Are any subsequent processes, e.g. annealing or welding, carried out while the lubricant remains on the workpiece?
Will degreasing be carried out and by what method?

Surface condition of the workpiece can be critical, for example a phosphated steel surface is capable of retaining lubricant as well as providing protection against corrosion. In sheet metal press working, deformation in specific areas may be particularly severe, requiring a higher degree of lubrication than the general area of the sheet. In such cases "stay put" properties achieved by tackiness, viscous invert emulsion or gelled nature may be needed.

In deep drawing operations, substantial cold deformation of the metal workpiece occurs between the punch and die. Extreme

pressure agents, together with boundary additives, in a high viscosity base may be needed to avoid scoring and splitting of the piece. Unexpected variations in metallurgy of the workpiece can cause many puzzling times for the lubricant supplier, who sometimes seems to be in the front row when blame is apportioned.
Deformation of apparently softer metals is not always easy; for example in the drawing of sheet aluminium, uneven flow into the die can occur resulting in misshapen or broken pieces. Determining whether the problem arises from lubricant, metallurgy or tooling may not be easy, especially with production targets to be met.

The techniques used in tube drawing include sinking, mandrel drawing and plug drawing (the plug may be floating, tethered or fixed). Tube sinking is a relatively light process, because there is no internal constraint and a water-based lubricant may be adequate. However, drawing with an internal mandrel or plug often requires neat drawing oil because much greater demands are placed on lubrication between the exterior of the tube and the die and internally between the mandrel or plug and the tube.
As an example of applied lubrication technology, when drawing copper tubes with mineral oil based lubricants, degreasing is necessary prior to annealing in order to avoid deposition of carbon on the tube. Drawing lubricants based on polybutene can eliminate the need for inter-stage degreasing, because the polymer molecules break cleanly into small volatile hydrocarbon fragments in the non-oxidising atmosphere of the annealing furnace.

In the cold pilgering process, the diameter of tube is reduced in a large number of small steps by means of a fixed tapered internal mandrel and external ring dies with an oscillating rotary motion. Some cold reducing operations are carried out using aqueous lubricants; however, for nickel alloy tubes, neat oil with extreme pressure additives is normally required. Bench drawing of stainless steel tubes has traditionally been carried out using highly chlorinated oils, although chlorine-free lubricants are now available for this severe operation.

NAMWLs are also used in Schumag machines, which produce drawn, straightened, polished metal rod in cut-to-length sections from a hot-rolled coil feedstock. Neat oils are also used as outer lubricants in the hydroforming process which allows whole components to be produced in one operation, rather than fabricated.

The affinity of esters for heated metal surfaces is exploited in formulations for hot rolling and other hot deformation processes.

5. Health aspects

Oil Mists

When oils impinge on rapidly rotating machinery, as encountered in metalworking operations, aerosol mists can be formed. Health hazards are associated with breathing oil mists. The tendency to form oil mists increases with decreasing viscosity, and in the case of very low viscosity oils vapours can be formed. These effects are aggravated by increases in temperature. Very high localised temperatures, which can occur when the flow of oil to the cutting zone is obstructed, can also result in smoke formation.

Exposure to mineral oil mist in the workplace can be determined using a gravimetric method in which a measured volume of air is drawn through a sampler attached to the lapel of the machine operator. The method may give rise to an under-estimate of exposure with oils of viscosity less than 18cSt at 40 deg C, due to their increased tendency to form vapours which are not fully trapped in the sampling equipment.

Hazards to the skin

Exposure of the skin to mineral oils, especially when contamination is present, should be avoided. Very low viscosity oils can have a greater penetrating effect and are more likely to remove natural oils from the skin. The presence of swarf, metal fines and other particulates can cause minute cuts, the risk of which is increased by wiping the skin with rags, which may contain metal particles. Curls of swarf from metal cutting operations are obviously sharp; however, examination of grinding debris under magnification will also reveal tiny daggers.

Actions required

Whether using water-mix fluids or neat oils, employers are required to assess risks, monitor the condition of fluids, carry out health surveillance and implement appropriate corrective actions.

Information and advice

These topics are very well documented on the Health and Safety Executive (HSE) website and illustrated in the DVD on the Safe Use and Handling of Metalworking Fluids produced jointly by HSE and the UKLA Metalworking Fluid Product Stewardship Group.

6. Monitoring

Monitoring of metalworking fluids makes sound engineering sense as well as safeguarding the health of those who work with them. The types of tests generally applicable to NAMWLs in service include: -

- Viscosity.
- Flash point (highly chlorinated oils may emit hazardous decomposition products in this test).
- Infra-red analysis.
- Measurement of the concentrations of particulates and dissolved metals.
- Measurement of acidity.

Other tests e.g. to determine the potential for staining yellow metals, may be included depending on the specific product and application.

Monitoring should be planned and carried out following a pre-determined programme. One-off tests, although of some value, provide no information about trends. It is essential to set control limits for each parameter measured. If results fall outside of the control limits for particular systems or individual machines, an investigation should be made to determine the root cause of the variance and corrective actions implemented. The experience and advice of your lubricant supplier can be very valuable in formulating, implementing and operating the monitoring programme. Monitoring services may be available from your lubricant supplier; alternatively, external service providers are available.

7. Maintenance, recycling and disposal

The results from the monitoring programme will provide a vital

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input to your maintenance plans. Control of particulates is essential for protection of operators, to ensure the quality of finished components, reduce tool wear and prolong the life of machine tools. Magnetic filters are fitted to many machines to continuously remove ferrous particles. Sump cleaning machines offer the facility of swarf removal coupled with fluid filtration. Some plants have facilities for oil purification including centrifuges which are very effective in removing metallic fines due to the great difference in specific gravity between oil and metallic fines. Unfortunately, in-house facilities often fail to achieve their potential. For example, a centrifuge, which has become filled to capacity will not remove any more solids. In line electrical heaters, if not properly maintained, can overheat and cause decomposition of the oil. It is essential for successful operation of in-house systems for the operators to understand their equipment and be allocated sufficient time to carry out the necessary tasks.

In certain applications, for example heading and cold reducing, the metalworking lubricants become very heavily loaded with fine metallic debris. Preliminary treatment may be required to remove gross contamination prior to fine filtration or centrifugation.

NAMWLs can be sent off-site to an external service provider for laundering. This is a quite different process from re-refining of used engine oils where all additives and contaminants are stripped out to produce re-refined base oils. In the laundering process, water and other contaminants are removed, whilst additives are retained in the oil. The service provider may offer the facility of correcting viscosity and replenishing depleted additive levels to produce "recycled" oil with equal performance characteristics to the original. There is no absolute limit to the number of times this procedure can be carried out.

The final limits on the life of a NAMWL are usually determined by contamination with a foreign material or extensive thermo-oxidative breakdown due to prolonged high temperature. Used mineral oils are classified as hazardous waste and must be disposed of by licensed contractor with appropriate documentation.

8. Conclusions

NAMWLs undoubtedly will continue to be needed for specialised metalworking applications. However, non-aqueous products are selected in some plants for applications which could also be carried out successfully with water-mix products. The reasons for such individual decisions are complex and include factors discussed in this article such as machine tool compatibility, service life, maintenance, recycling and disposal.

With a number of very notable exceptions, the metalworking production sector in UK has suffered from the effects of recession and international competition. Fortunately, many manufacturers of metalworking lubricants have long recognised the need for a global perspective when targeting markets for their specialised products. Practical experience of engineering production technology, knowledge of the performance of lubricants in specific applications and effective communication between marketing and development staff are essential ingredients of success found in our best companies.

David Neadle

Table 1.

GENERAL OVERVIEW OF METAL REMOVAL AND DEFORMATION OPERATIONS

Metal Removal
Turning, milling.
Threading, tapping.
Drilling and boring (including deep hole operations).
Gear production (including hobbing, shaping and shaving).
Grinding (including surface, cylindrical and centreless).
Form grinding (including thread, flute and gear grinding).
Broaching.
Honing, lapping, linishing and superfinishing.
Reaming.
Spark erosion (fluid has dielectric rather than cutting application).

Metal deformation
Presswork (including deep drawing).
Fine blanking.
Cold heading.
Wire drawing.
Rod and bar drawing.
Tube drawing.
Pilgering.
Extrusion.
Rolling (including section rolling, thread rolling, strip and sheet rolling).
Hot forming operations (including forging, extrusion and piercing).
Hydroforming.

Note : The table includes metalworking operations generally and is not limited to those carried out with NAMWLs.

Table 2.

CONSTITUENTS OF NON-AQUEOUS METALWORKING LUBRICANTS

Base fluids
Mineral oils - paraffinic and naphthenic.
Light hydrocarbons.
Polyalphaolefins.
Polybutenes.
Polyalkylene glycols.

Boundary additives
Natural and synthetic esters.
Fatty acids.

Extreme pressure additives
Sulphurised esters.
Polysulphides.
Chlorinated hydrocarbons.
Phosphate esters.
Passive extreme pressure agents (PEPs).

Oxidation inhibitors
Phenol derivatives.
Sulphurised olefins.
Zinc dialkyl dithiophosphates.

Corrosion inhibitors
Oil soluble sulphonates.
Benzotriazole derivatives.

Anti-mist additives
Hydrocarbon polymers.

Solid lubricants
Graphite.
Molybdenum disulphide.
Zinc oxide.
Polyethylene.
Polytetrafluoroethylene.
Metal soaps.
Silicates.

David Neadle worked in medical research and as a biochemist before joining Smallman Lubricants Ltd in 1968 (acquired by D.A. Stuart Ltd in 2000, which in turn was recently bought by Houghton plc).

His 40 years in the industry have included responsibility for product development, technical support and quality control of a wide range of industrial and automotive lubricants and ancillary products. Since 2003, he has worked in the industry as a consultant in health, safety and environmental areas.

David has been deeply involved with the work of the UK Lubricants Association and its predecessor the British Lubricants Federation, throughout most of his working life, with a strong interest in the health aspects of products.