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Greased Lightning

Proper coolant lubricity helps smooth cutting performance.

The downtime associated with replacing cutting tools during a metalcutting operation is one of the most significant production costs. Cutting back on speeds and feeds can extend tool life, but it reduces productivity. To extend tool life without sacrificing production, machinists must reduce the friction and temperature in the cutting zone. Applying the right metalcutting fluid with the appropriate additives plays a major role.

To meet part specifications, the surface finish must not show symptoms of wear adhesion that can result when temperatures are too high. Moreover, dimensional tolerances must not be adversely affected by thermal expansion. The lubricating properties of a metalworking fluid reduce surface friction between the workpiece and the cutting tool and serve to contain heat generation and control temperature levels in the cutting area.

Water is an excellent heat conductor but provides poor lubrication. However, when water is mixed with a coolant concentrate designed to yield a high level of lubricity over a wide temperature range, the resulting emulsion can satisfy the requirements for high-speed machining of even difficult-to-cut metals. The most demanding applications, however, may require the higher levels of lubricity achieved with straight-oil formulations.

The deployment of cutting fluids designed to provide advanced lubricating characteristics has certain trade-offs. Water-miscible coolants and straight-oil formulations incorporating ingredients that increase lubricating performance may be costlier to purchase and use and may involve special disposal requirements.

In the Zone

The condition of the tool/workpiece interface dictates the properties required for the lubricating fluid. For example, in conditions characterized by low temperature and contact pressure, a film of lubricant may completely separate the contact surfaces of the tool and workpiece. In this hydrodynamic scenario, the lubricant's bulk properties, notably viscosity, provide the needed lubricity.

However, contact pressures when metalcutting are typically too high for fluid lubrication throughout the contact area. As the thickness of the lubricating film decreases, due to increased pressure between the metal surfaces and a loss of viscosity, the film's depth will eventually not exceed the microscopic roughness of the metal sur-

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To maximize the performance benefits from a metalworking fluid, a fluid's lubricating properties must be delivered throughout the tool/workpiece interface.

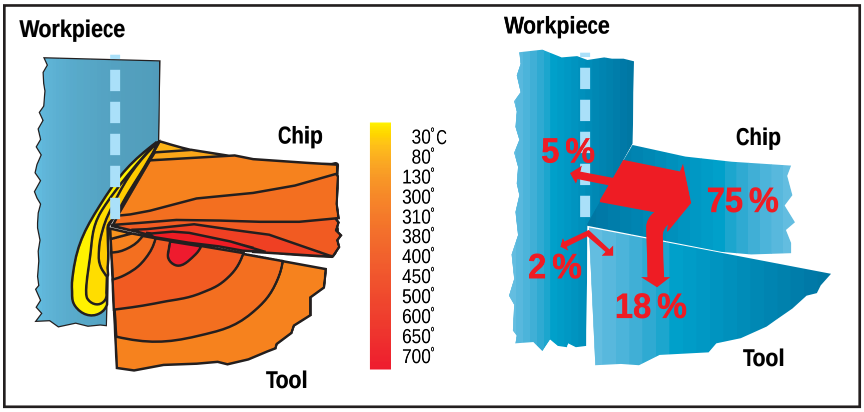
faces. The mechanical load, or pressure, between the surfaces increasingly becomes conveyed through partial metal-against-metal contact, raising friction and temperatures and further reducing the lubricating properties of the film.

This condition calls for boundary lubrication. Lubricating agents are added to the metalworking fluid that, on a molecular level, bond strongly to a metal surface through physical adsorption, providing a durable microscopic lubricating layer that maintains a low temperature and low coefficient of friction. At the high end of the temperature range where these additives are effective, through the process of chemical adsorption (chemisorption), molecules of these lubricants slightly penetrate the metal surfaces to further enhance lubricity.

As mechanical pressure, friction and temperature continue to increase, the low-to-moderate-temperature lubrication eventually gets removed from the metal surfaces. Full metal-to-metal contact then carries the entire mechanical load. At this stage, friction and temperature rise to a point where the microscopically rough metal surfaces begin to bond, causing "chunks" of material to be removed as the metal surfaces rub against each other.

The resulting level of friction is termed "adhesive friction," and the loss of material from the metal surfaces is called "adhesive wear." Adhesive wear prematurely shortens tool life and adversely affects the workpiece surface finish and, because of the high temperatures, its ability to maintain dimensional tolerances.

Another type of lubrication agent—a high-temperature one—must be added to the fluid instead to meet part specs. Through chemical reactions with the metal surfaces, high-temperature lubrication agents form thin layers of solid-lubricant film with low shear resistance, despite their exceptional tolerance for high mechanical pressures. Chlorine, phosphorus and sulfur are common agents—each active within a specific temperature range.



The approximate degree (left) and percentage (right) of heat that enters the tool, workpiece and chip during the metalcutting process.

Understanding Lubricant Types

Selecting a lubricant involves making two fundamental decisions: Should a cooling emulsion (a mix of oil and water) or a straight-oil formulation be used, and what lubricating additives should be included? These two decisions are interrelated, because some additives can only be deployed in a straight-oil formulation.

Oil lubricates significantly better than water, but water cools up to 10 times better than oil. Because most applications—particularly roughing—benefit from water's cooling properties, an emulsion that combines cooling and lubricating properties is usually the first choice. However, water, which comprises 90 to 95 percent of the emulsion, can complicate the use of lubricating agents, introducing unwanted side effects such as odors and other symptoms of biological instability.

Straight-oil formulations, on the other hand, accommodate a wider range of lubricating additives. They also form a thick layer that exhibits a hydraulic cushioning effect at moderate temperatures, yielding significantly higher levels of lubricity than water-based coolants.

The base oil in a metalworking fluid—whether a cutting oil or coolant concentrate—can be derived from petroleum, plants or animals. The most common are two types of mineral oil: naphthenic and paraffinic. Without additives, these mineral oils are not exceptional lubricants, being suitable only for easy-to-machine metals such as brass, aluminum and some steels. However, mineral oil is an excellent carrier of a range of additives used to lubricate the cutting zone at increasingly higher temperatures.

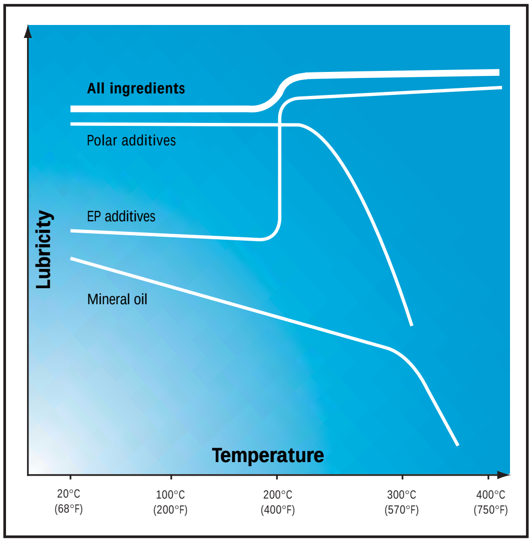
Vegetable oils extracted from a variety of seeds and nuts provide high levels of lubricity. They are an effective ingredient in neat cutting oils as well as water-miscible emulsions, both as a base stock (the carrier) and as an additive.

A fluid's ability to deliver lubricating properties evenly throughout the contact surfaces between tool and workpiece is essential. In coolants, this puts a premium on the drop size of the emulsion. The emulsion must be able to release the lubricant in sufficiently small droplets to reach the tip of the cutting tool, meaning droplet diameters in the submicron range.

Boundary Additives

Polar additives in cooling emulsions, which provide lubrication under boundary-pressure conditions, are added to the base stock in the form of oils, saturated fats or wax. They are derived from animal sources—such as lard and fish oil—and from plants—peanuts, castor, canola, tropical oils and others—especially cultivated to yield properties suitable for cutting metal.

The lubricating properties of polar additives derive from their chemical composition. Polar molecules consist of long carbon chains with functional head groups that yield an uneven distribution of electrons over the molecule and produce an elevated chemical affinity for metal surfaces. At temperatures below 400° F, the head groups attach themselves to the metal surface. They become packed closely together, with their long carbon chains symmetrically



The relationship between lubricity and temperature for polar additives, EP additives and mineral oil.

orienting themselves perpendicular to the metal surface.

The result is a dense layer of large molecules, creating a thick and durable lubricating film between the tool and workpiece. The formation of "metallic soaps" along the metal surfaces extends the polar agents' lubricating performance. Fully ester-based fluid formulations—that is, straight oil and coolant formulations relying on vegetable oil as the carrier—usually improve on the cutting performance of polar agents added to a mineral-oil base.

The film of polar additives also serves as a barrier against corrosion, effectively sealing off the metal surfaces from atmospheric oxygen. However, these organic additives can affect the biological stability (the proliferation of microorganisms) of water-miscible coolants. Moreover, the other ingredients present in the cutting fluid can impact the lubricating effectiveness of the polar agents. The molecules of emulsifiers, corrosion inhibitors, biocides, stabilizers, anti-oxidants, defoamers, odorants and other agents all, in a sense, compete with the polar molecules for space on the metal surfaces.

Under Pressure

At a critical temperature threshold (approximately 400° to 500° F), the polar agents begin to desorb—detach from the metal surfaces—or simply become worn off by the abrasion resulting from excessive mechanical stress. At this point, the extreme-pressure (EP) chemical additives begin to counter the severe conditions: chlorine at around 400° F; phosphorous at 500° F and sulfur at 1,100° F.

Layers of solid lubrication (salts) formed in chemical reactions with the metal surfaces will sharply reduce the total amount of friction and heat produced in the cutting area—upwards of 50 percent or more—with consequent favorable implications on surface finish, tool life and BUE formation.

The most common EP lubrication agents added to oil formulations and coolant concentrates are chlorine or sulfur or a combination of the two. Phosphorous can also be effective, but for many applications its effective thermal operating range is overlapped by lower-range chlorine and higher-range sulfur additives. Phosphorous is also generally considered a mild EP additive.

EP additives are inactive at room temperature, so they have a neutral effect on machines, operations and the environment. They become chemically active with metal surfaces only at the elevated temperatures prevailing in the cutting zone.

The selection of EP additives for a specific application is driven by factors such as machining requirements, corrosion potential and other side effects, usage, fluid maintenance and disposal, universality, and cost reduction and productivity targets.

The Chlorine Controversy

Chlorine is the most widely used EP additive and is the most practical option for coolants. Yet some controversy and confusion surround its use in metalworking fluids, and it's become the subject of supervision and some restrictions by regulatory agencies in several countries (see sidebar).

Chlorine is incorporated into coolants and oil formulations via a chlorinated carrier, typically a chlorinated paraffin. It is activated at the metal contact points in

Regulated chlorine usage

Chlorine is one of hundreds of chemicals whose manufacture and application are monitored by regulatory agencies in most countries. When used as a metalworking lubricant, chlorine is "bound" in a hydrocarbon of some type. Any number are appropriate. Paraffins are commonly used.

As molecules, hydrocarbons form chains of different lengths. Their hydrocarbon-chain length and chlorine content characterize different grades of chlorinated paraffins. They have similar physical and performance characteristics, but regulatory agencies in several countries are concerned about health issues and environmental side effects associated with some paraffins.

For regulatory purposes, the compounds have been classified as having short, mid-length and long chains. Differences in regulations on usage and manufacture with regard to some of the products can easily lead to confusion about all of them.

Short-chain chlorinated paraffins (SCCP) are of concern. In the U.S., with one exception, there are no restrictions on the manufacture and use of any chlorinated paraffins. The EPA has included a SCCP grade (the C12 short-chain variety at 60 percent chlorinating concentration) among the approximate 650 chemicals whose production and use are monitored through the Toxic Release Inventory.

Internationally, there are no restrictions with regard to mid- and long-chain compounds, and the metalworking industry, for the most part, relies on paraffins with mid-length chains. In Canada, all short-chain products are classified as toxic, although permissible to use. In Europe, both the manufacture and use of short-chain products are restricted.

Using chlorinated paraffins as an EP additive will not turn spent coolant into hazardous waste in the eyes of the EPA. But the waste fluid is subject to the EPA's "refutable presumption" policy. The EPA assumes waste oil with a chlorine content exceeding 1,000 ppm is hazardous. But the agency allows the user to demonstrate that the chlorine originated from a source not considered hazardous, such as chlorinated paraffin.

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the cutting zone at temperatures above 400° F and remains reactive with the metal surfaces beyond 1,100° F, forming solid lubricating films of metal chlorides.

Coolant concentrates for general machining applications usually have 3 to 6 percent of chlorinated paraffins by volume. Heavier-duty applications may benefit from concentrations of 6 to 12 percent. Most general machining applications show significant improvements in cutting performance following the introduction of a chlorinated paraffin as the EP additive. Tool life, for example, often increases by 20 percent or more.

There are virtually no restrictions in the U.S. on the use of chlorinated paraffins in metalworking fluids. The presence of these additives does not turn the fluids into hazardous chemical waste. However, the U.S. Environmental Protection Agency wants the fluids to be managed as though they were, which can make disposal an issue.

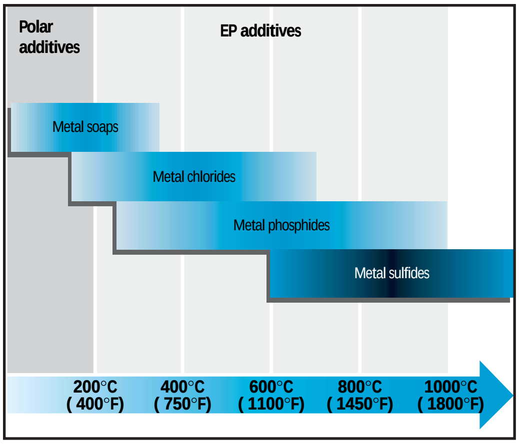
The best strategy is to recycle and reuse fluids as much as possible, which puts a premium on avoiding contamination, maintaining the sump and using quality formulations. The EPA (www.epa.gov) and the Chlorinated Parraffin Industry Association (www.regnet.com/cpia) provide publications describing fluid-management programs.

Reacting to Sulfur

The key advantage of sulfur as an EP additive is that it remains active at very high temperatures—higher temperatures than would be permissible in the cutting zone for reasons other than maximizing surface finish and minimizing tool wear. From around 1,100° F and up, sulfur reacts with the freshly cut metal surfaces to form solid-lubricant films of exceptionally pressure-tolerant metal sulfides. These characteristics make sulfur an almost indispensable additive in some heavy-duty operations.

Chemically, elemental sulfur is the simplest of the EP additives. It is typically added to the cutting fluid in the form of sulfured oil—such as mineral oil—or fat. Low concentration levels are usually sufficient even in demanding applications.

By itself, sulfur can be quite reactive. It tends to stain copper and steel. It is quite stable, however, when bound in fatty oils that have been sulfured at high temperatures. Any lingering tendencies to stain are usually easily remedied with antistaining agents added to the fluids.



The temperature ranges when polar and EP additives become chemically active.

Coolant formulated with sulfur often requires special attention because of sulfur's tendency to produce odors. Incorporating only small amounts of sulfur—perhaps 0.2 to 0.3 percent—will mitigate odor problems but still contribute good lubrication. Another successful strategy is to add sulfur in the form of a ZnDDP (zinc dialkyldithiophosphate) compound, although functional side effects on the fluid system may result.

Combining Reactive Elements

Combined, EP additives tend to yield better lubricating and cutting performance than when only one is used. A coolant emulsion incorporating polar agents combined with EP additives can provide the benefits of a universal cutting oil to an operation characterized by many disparate requirements. Or, the heavy-duty properties of a coolant may qualify it as a viable alternative to a straight cutting oil.

Chlorinated and sulfur additives, for example, combine to provide lubrication across the entire extreme-pressure temperature range. When used in conjunction with polar additives, the result is a lubricant meeting shop requirements for just about any combination of cutting applications.

Vegetable esters, phosphor and calcium are also effectively combined with chlorine in extreme pressure situations.

Next Step

Cutting performance is measured by many parameters. Among them are meeting customer part specifications, achieving profitable production rates, and minimizing the cost of cutting tools and the time needed to replace worn cutters. The lubricating properties of metalworking fluid are variables with significant impact on cutting performance metrics.

No two applications are exactly alike, and two coolants with similar specifications can yield dissimilar results. To optimize cutting performance, engineers should first establish baselines for their operations—gathering and assessing current measurements for each application and the coolant or cutting oil applied. Potential and actual improvements to be achieved with alternative formulations can then be documented in relationship to changes in costs and operating requirements.

About the Author

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