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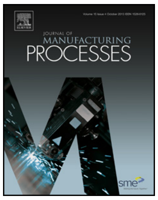

Technical Paper

Bio-based lubricants for forming of magnesium

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ABSTRACT

For a number of reasons, magnesium is being used increasingly often in applications where weight savings are desired. However, magnesium is difficult to form, so that warm or hot forming are generally necessary. Lubricants are recognized as essential in these processes, but the lubricants used to date for magnesium forming have environmental drawbacks. This paper evaluates the tribological behavior and rheology of four types of bio-based metal working fluids. Using an elastohydrodynamic lubrication apparatus, their traction behavior was measured and their piezoviscous behavior was determined by applying the well-known Hamrock–Dowson equation to measured film thickness profiles. The results showed that the investigated bio-lubricants have good ability to generate lubricant films in forming of magnesium. Traction tests showed low friction values, indicating the investigated bio-lubricants are suitable for metal forming applications where effective lubrication is desired.

1. Introduction

For a number of reasons, magnesium is receiving increased attention in design, but mainly because of its low density and the desire to attain lightweight designs. Most of the existing applications of magnesium involve die casting or thixocasting [21]; it is estimated that magnesium transmission casings cast in AZ91D offer up to a 25% weight savings over aluminum. Automobiles like the GM Savanna use up to 26 kg of magnesium. It is expected that the use of this lightweight material will continue to increase as automobile manufacturers strive toward meeting established Corporate Average Fuel Economy (CAFE) standards. The increased uses of magnesium are expected in structural components, instrument panels, intake manifolds, and assorted smaller parts. Many applications require features that cannot be economically cast, so forging and sheet forming operations are receiving increased attention. Unfortunately, magnesium is extremely difficult to form. Many alloys of interest (AZ series) have limited ductility, and the more ductile AM50B and AM60B alloys have low formability. For this reason, magnesium alloys are often formed hot or warm, as increasing temperatures by 150 °C can lead to high formability, even superplasticity [14,7,11]. Forming at 100 °C has been found to be beneficial [22], which is a moderate elevated temperature that does not overly complicate the lubricants that can be used.

Metalworking fluids (MWFs) increase productivity and the quality of manufacturing operations by cooling and lubricating during metal forming and cutting processes. Magnesium sheet formability and appropriate MWF selection issues remain a concern [8,26]. Solid lubricants are commonly used, such as polytetrafluoroethylene [14], grease, soaps or wax [1], colloidal graphite or boron nitride [11], or solid graphite without a carrier [30]. Mineral oils are often used; Matsumoto and and Osaka [21] blended mineral oils with sulfur and phosphorus-based extreme pressure additives; they also evaluated molybdenum disulfide in a ring compression test. Whenever lubricants are used, they are immediately removed from the magnesium surface because of corrosion concerns, especially the colloidal solid lubricants [1].

In 2010, about 5.3% of the worldwide lubricant consumption was MWFs, or about 197 million tons [29]. Despite their widespread application, they pose significant health and environmental hazards throughout their life cycle. There are many environmental concerns and new legislation regarding metal forming lubricants, a good summary of which is given by Bay et al. [5]. There is a strong goal to use environmentally-friendly and biodegradeable lubricants in greater amounts. Currently, biodegradability lubricants are around 25% of those used, and about 50% of all lubricants sold worldwide end up in the environment [24]. Due to extensive use of mineral oil based lubricants, several environmental issues such as surface water and groundwater contamination, air pollution, soil contamination, agricultural product and food contamination are emerging very rapidly [13].

In sheet metal forming, there are a number of dry film systems that have become popular [6], because of improved cleanliness

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and reduced requirements for recycling and disposal. Altan and his coworkers have carried out several large investigations on new lubricants for automotive sheet metal forming as substitutes to petroleum based oils [6,17,16] based on a system of laboratory tests emulating the varied conditions in sheet metal forming. Testing was performed on mild steel AKDQ 1008, HSLA steel, ASTM A1011 [6,15], Advanced High Strength Steel (AHSS), DP 500, DP 600, with and without zinc coating, with straight mineral oil, water based oil emulsions, dry films, chlorinated water emulsions and polymer films [17,16].

Several papers have been published recently investigating the tribological properties of bio-based lubricants for steel or aluminum forming. Wichmann and Bahadir [27] investigated the potential application of bio-based ester oils for use as lubricants in steel sheet metal working. Based on the results, ester oils produced from plant fats performed very well as cooling lubricants. Tall oil derived from pine trees has been developed for deep drawing operations and has good lubrication and antiwear properties [5]. Klocke et al. [18] report the development and application of a new tool coating which allows chlorinated paraffin oil to be replaced by a new environmentally benign, biodegradable, rape oil based lubricant. Bantchev and Biresaw [3] used polyalphaolefin to make binary blends of varying compositions with soy bean and canola oils. Tribological properties of lubricants with different compositions were investigated and pressure–viscosity coefficients were determined. Bantchev and Biresaw [4] investigated the film forming properties of oil-soluble polyalkyl glycols high oleic sunflower oil and their 50/50 (wt.%) blends. Winter et al. [29] studied the frictional properties of a novel biocide-free MWF on the basis of glycerol/water in comparison to conventional mineral oil based MWFs. The results indicated comparable and partially better results of the glycerol fluid in comparison to the conventional mineral oil based fluids.

Bio-based MWFs are an attractive alternative that have not been applied regularly to magnesium forming. Bio-based oils possess certain advantageous frictional properties such as good lubricity, low volatility, high viscosity index, solvency for lubricant additives, and easy miscibility with other fluids. However, it must be recognized that magnesium is corrosive in an aqueous or acidic solution, so water-based lubricants and emulsions must be used with care. Padmanaban et al. [23] developed a bio-based semi-synthetic MWF from algal oil and found the critical tribological performance influencing properties such as higher shear stability, low temperature stability and corrosion resistance are higher in chemically modified algal oil as compared to vegetable oil based metalworking fluid. Zulkifli et al. [31] studied the effect of temperature on tribological properties of chemically modified bio-based lubricants using a four-ball tribotester and compared the results with additive-free paraffin oil.

In this paper, four types of bio-lubricants were subjected to tribological tests in an elastohydrodynamic simulator and their pressure–viscosity coefficients were determined based on film thickness data. The frictional behavior was also investigated using traction tests for contact between highly polished steel and magnesium discs and steel balls. These green lubricants showed promising properties to justify themselves to be an excellent substitute to conventional oil based lubricants.

To assess functional applicability of bio-based MWFs in manufacturing processes, the dependency of the interaction between the tool-workpiece-MWF has to be investigated. For engineering calculations of a Newtonian concentrated contact film thickness, the rheological properties of the liquid lubricant have always been described by two parameters, the ambient viscosity and the pressure-viscosity coefficient that is a measure of the piezo-viscous response. Film thickness generation ability is very important for lubricants, but the friction behavior is also critical. Bair and Winer [2] demonstrated that Newtonian lubricants have a limit to the shear stress they can support. Fluids that can support high shear stresses are useful as traction fluids, while those with limited shear stresses are suitable as lubricants because of their associated low friction values [20].

2. Lubrication theory and rheology

It is well-known that MWFs need to have a well-controlled range of viscosity at the desired temperature. In some applications, such as metal forging or rolling, a fairly inviscid fluid is desired to maintain some limited asperity-asperity contact between the workpiece and tooling to prevent gross surface roughening (orange peel). In other applications, such as sheet metal hydroforming or metal extrusion, the entrainment velocity is too low to result in hydrodynamic lubrication, and better film-generating properties are desired [20]. Lubrication effectiveness is quantified by the dimensionless film thickness parameter,

$$\Lambda = \frac{h_{\text{avg}}}{\sqrt{R_{qa}^2 + R_{qb}^2}} \tag{1}$$

where h_{avg} is the average film thickness, and R_{qa} and R_{qb} are the RMS surface roughness for the surfaces in contact. In boundary lubrication, the film thickness parameter is between 0 and 1. For mixed lubrication, it is between 1 and 3. Full film lubrication, which is sometimes further classified as thick or thin film lubrication, involves surfaces that are separated by a lubricant film, so that $\Lambda > 3$, In manufacturing operations, asperity roughening due to applied strain results in boundary or mixed lubrication being the most common regimes.

In metal forming operations, there are well-known and accepted approaches that illustrate the rheological importance of lubricants. For example, the well-known Wilson-Walowit [28] equation expresses the lubricant film thickness as

$$h = \frac{6\eta\gamma U}{\tan\theta\,(1 - e^{-\gamma\sigma})} \tag{2}$$

where h is the film thickness, U is the mean velocity, η is the lubricant viscosity, θ is the bite angle, and σ is the material flow strength. γ is called the pressure–viscosity coefficient, and appears in the Barus equation for lubricant rheology:

$$\eta = \eta_o e^{\gamma p} \tag{3}$$

where p is the pressure. Selles et al. [25] present a methodology for calculating the film thickness in a metal forming operation and allowing it to evolve using the Reynolds equation. Friction is partitioned between lubricant shearing and adhesion at contacting asperities. Results have been promising, allowing prediction of friction and heat transfer coefficients in non-isothermal forming operations, and allowing these coefficients to evolve during a process. However, in order to predict lubricant film thickness, the rheology must be well-characterized.

Therefore, the lubrication effectiveness in terms of film thickness generation can be gauged from direct measurement of the viscosity and pressure exponent. Viscosity measurement is straightforward, using a Saybolt universal viscosimeter and the approach described in Hamrock et al. [10]. Measurement of pressure–viscosity coefficient is much more difficult; there are approaches such as chambers that will pressurize while a viscosity measurement takes place, or jumping ball approaches [12]. However, it is recognized that there is a potential for shear localization and molecule ordering in rolling or sliding that may not be simulated properly in the pressurized chamber approaches.

This paper uses the elastohydrodynamic lubrication (EHL) theory of Hamrock and Dowson [9] to determine the pressure viscosity