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POSSIBILITY OF BIODEGRADABLE BASE OILS APPLICATION IN NEAT METALWORKING OILS

Abstract

The main properties of neat metalworking oils: lubrication, cooling and chips cleaning and other properties are achieved by base oil and additive selection. The concern of people safety at work and ecological protection become leading factors in metalworking fluid development and application. Besides, the modern fluids should meet severe demands of machine constructions and also take place in total costs lowering of metalworking operation. Increased material disposal costs and also ecological concern lead customers to the selection of less harmful fluids and optimal procedures of their disposal. In metalworking fluids composition there is an influence of cutting down the harmful compounds as are chlorinated paraffines, nitrites, diethanolamine, compounds with aromatic nucleus, borates, etc. Base oils which are commonly of mineral origin can be changed with other types, especially with renewable origin.

The aim of this work was to create and examine several new formulations of metalworking fluids containing biodegradable oils as possible replacement of mineral base oils. The possibility of their applications in some metalworking operations was examined as well.

1. Introduction

There are three important groups of relevant requirements in the area of the metalworking fluids application: technical requirements, human and environmental protection requirements and economic requirements [1]. Technical requirements include lubrication, cooling, chips cleaning from the metalworking zone, corrosion inhibition, etc. Requirements on environmental protection and human health primarily include the selection of less harmful chemical compounds for base oils or additives, then fluid management through special attention paid during work, and disposal of used fluids, along with the fluid life extension. Economic requirements are the increase of work rates, productivity increase, reduced consumption, reduced tool wear, reduced number of fluid exchange, reduced costs of used fluids disposal, etc.

The development of lubricants is significantly influenced by different laws or recommendations, equipment manufacturers and branch associations [2-5]. The main concern is the harmfulness of particular products which could cause leakage in the environment during transport or improper disposal and the application along with losses. Therefore environmentally friendly lubricants or biolubricants are more acceptable with their toxicity, biodegradability, microbiological inhibition and bioaccumulation being evaluated [6, 7]. Based on these characteristics, if they comply with the requirements, they are given the eco-labels by particular countries: BLAU ANGEL (D), WHITE SWAN (DK), ECO LABEL (EU), PRIJATELJ OKOLIŠA (CRO), etc. There is a trend of developing metalworking oils without chloroparaffin which is replaced by phosphates, sulphonates, and metalorganic compounds [8]. In the field of base oils, mineral base oils with lower aromate content, or even without aromates with sulphur content as low as possible [9]. The use of natural oils and greases of plant or animal origin in their original or refined form is becoming more popular [10].

Generally, the requirements for metalworking fluids are more and more stringent and the quantity of lubricants is getting smaller.

2. Classification of metalworking fluids

The most important international norm for the classification of metalworking fluids is ISO 6743/7, M (Metalworking) by which products are classified into two groups according to the predominating requirement of using cooling or lubrication. The first ISO L-MA group consists of watermiscible fluids with the predominating property of cooling, and in the second ISO L-MH group are lubricants with the predominating property of lubrication. That norm defines guidelines for the composition of fluids and their application in specific metalworking procedures such as cutting, grinding, forging, rolling etc. The Table 1 shows the classification of metalworking lubricants based on composition and properties in the operations requiring lubrication and which involve oils and special lubricants.

There is also the norm DIN 51385, (Kuehlschmierstoffe) which classifies products according to their watermiscibility: SN are fluids which are not watermiscible, SE (SEM, SES) are watermiscible fluids or concentrates and SEW (SEMW, SESW) are already prepared working fluids based on water. In general, metalworking fluids are classified into two groups: oils, neat or cutting oils, and watermiscible fluids. Furthermore, there is a classification in which their specific property is emphasized, for example chlorineless, amineless, high temperature, high pressure, high viscosity fluids, etc. Metalworking oils can be devided into two groups: active and inactive. This classification is done according to the behavior of additives based on sulphur to copper which make copper sulfide. Active oils contain sulphur additive in an active form. The reaction of active additive is very intense and undesirable in the case of treating copper and yellow metals. Therefore, for their working inactive oils, containing sulphur in an inactive form, are used.

Table 1: Classification of ISO-L-MH metalworking lubricants based on their composition and properties

Symbol ISO-L	NAME	COMPOSITION AND PROPERTIES	PARTICULAR APPLICATION
MHA	cutting oil, normal	refined mineral oil or synthetic fluid with anticorrosion additive	metal removal by cutting and metal rolling, operations primarily needing lubrication
MHB	cutting oil, mild EP	MHA type with friction reducing additive AW	metal removal by cutting, metal stamping, deep drawing, forging and rolling, operations primarily needing lubrication
MHC	cutting oil EP non-active	MHA type with extreme pressure (EP) additive, non-active	the same operations as MHB but at severe conditions, metal grinding and forming
MHD	cutting oil EP, active	MHA type with extreme pressure (EP) additive, active	the same operations as MHC, grinding and forming metals which do not contain copper
MHE	cutting oil special non-active, EP	MHB type with extreme pressure (EP) additive, non-active	the same operations as MHD at severe conditions, metal grinding, forming and ironing
MHF	cutting oil special, active, EP	MHB type with extreme pressure (EP) additive, active	the same operations as MHE at severe conditions metals which do not contain copper
MHG	lubricating grease for metalworking operations	grease, paste, wax, applied pure or diluted with a fluid of MHA type	contact surfaces lubrication in some specific operations as sheet metal forming or wire drawing
MHH	soap for lubrication at metalworking operations	soap, powder, solid lubricant, etc., and blends thereof	contact surfaces lubrication in some specific operations, wire drawing

3. Content of metalworking oils

Metalworking oils, neat or cutting oils, mainly consist of oil component (60-98%) along with functional additives: lubricating polar component up to 10 %, anti-corrosion additives cca 5 % and AW/EP additives to 25 % mass which is shown in the Picture 1. Additives for improving oxidation stability, flowability, foaming, and others are also added.

Base oils are mostly of mineral origin and they can be paraffin, naphtenic, deeply refined, white, without aromates, etc. There is a tendency to use synthetic oils and natural oils-vegetable and animal oils or refined, even used cooking oil which can be easily refined and usefully graded [11, 12]. Table 2 shows categories of base oils according to the API (American Petroleum Institute) classification and their basic properties. Table 3 presents compared properties of basic groups of ester oils where it is shown that saturated esters have the most of preferable properties [13].

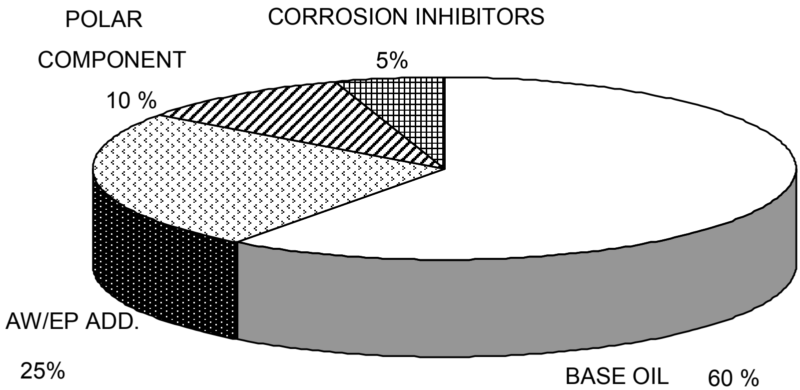


Figure 1: Composition of metalworking oil, *w* / %

Table 2: Base oils categories and their basic properties

API GROUP	Saturated hydrocarbons, *w* / %	Sulphur, *w* / %	Viscosity index
GROUP I solvent-refining	< 90	> 0,03	80 – 110
GROUP II hydrotreatment	≥ 90	≤ 0,03	80 – 119
GROUP II+ hydrotreatment *	≥ 90	≤ 0,03	110 – 119
GROUP III deep hydrotreatment / wax isomerization	≥ 90	≤ 0,03	>120
GROUP IV polyalphaolefins (PAO) polymerization, hydrogenation	defined formula $R-CHCH_3-/CH_2-CHR/_X-H$	-	>130
GROUP V	Other base oils not containing in I-IV including also synthetic: esters, glycols, natural oils and fats		
GROUP VI*	PIO (polyinternalolefins)		

*not contained in API classification but accepted by industry ATIEL (Technical Association of the European Lubricants Industry) [14]

Table 3: Comparison of ester base oils properties

PROPERTIES	PLANT OIL natural	DIESTERS petroche-mistry	UNSATURATED ESTERS oleochemistry	SATURATED ESTERS oleochemistry	COMPLEX ESTERS oleochemistry
Viscosity interval at 40 ^0C / mm^2s^{-1}	45 - 70	8 – 30	4 - 80	2 – 100	> 40
Viscosity index	very good	good	excellent	very good	excellent
Pour point	bad	excellent	low	very good	good
Oxidation stability	bad	good	good	excellent	very good
Hydrolytic stability	bad	excellent	good	good	very good
Lubrication	very good	sufficient	excellent	good	very good
Biodegradability	excellent	sufficient	very good	very good	good
Renewable source	yes	no	yes	yes	yes

For most of metalworking operations the properties of lubrication and pressure sustaining properties of oil component are not sufficient for prevention of friction and wear at contacts of real surfaces which are more or less rough [15]. For that reason when formulating the metalworking oils different compounds-additives are used in order to improve lubricant properties [16]. The use of that kind of an additive extends tool edge validity, improves the quality of metal surface and reduces power consumption. Additives for improving lubrication properties of metalworking oils can be classified into two groups: polar additives and antiwear and high pressure additives (AW/EP additives) [17]. The Table 4 shows main additive types for improving lubrication properties, compounds which generate at contacts with metal surface and approximate temperature of activation.

Table 4: Additive types and compounds formed on contact with metal surface

ADDITIVE TYPE	COMPOUND FORMATION WITH METAL SURFACE	APPROXIMATE TEMPERATURE OF ACTIVATION, t / ^0C
Polar compounds:		
Vegetable and animal glycerides	Me-soaps	room temperature to 200
Organic fatty acids	Me-soaps	to 200
Synthetic fatty compounds	Me-soaps	to 200
Polymer esters	Me-soaps	to 400
AW/EP additives:		
Chlorine compounds	Me-chlorides	110 – 420
Organophosphorus compounds	Me-phosphydes, Me-phosphates	150 – 800
Sulphur compounds	Me-sulphides	450 – 900
Sulphur, pure	Me-sulphides	to1000
Overbased petroleum sulfonates	Me-carbonates, ferit structure	to 950

Polar additives cause physical adsorption at metal surface by forming a layer of metal soaps. This soap layer has an intense slipping ability and it improves the pressure resistance. Additives with AW/EP properties are compounds made of chlor, sulphur, phosphorus, overbased petroleum sulfonates and the other. There is a chemical reaction on the metal surface producing a layer of inorganic compounds (chlorides, sulphides, phosphates, carbonates, etc.) with a general formula $FeS_xP_yO_z$ [18, 19]. These compounds have lower melting points than metal itself and low friction coefficients. Furthermore they also have separating asperities at contacting metal surfaces. Fig. 2 shows two metalworking surfaces in relative motion and additive activity under particular conditions of contacting metal surfaces [20].

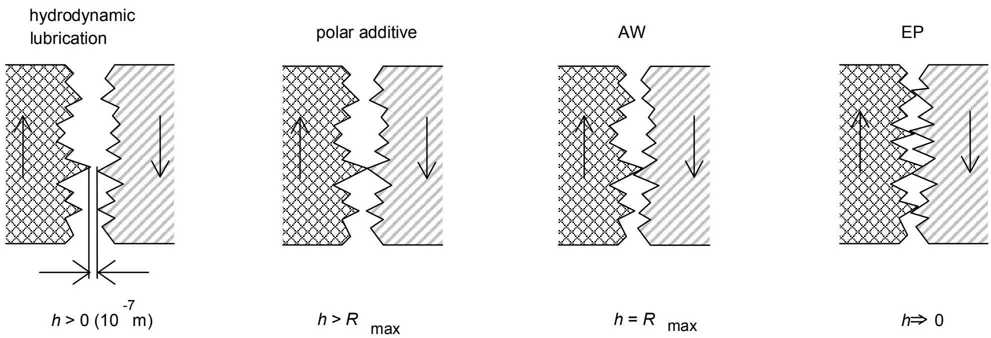


Figure 2: Additive activity in separating asperities of opposite contacting metal surfaces
(h = thickness of lubricating fluid, R_{max} = the highest asperity on the metal surface)

In the area of hydrodynamic lubrication the thickness of lubricating fluid (h) is bigger than the largest asperity on both contact surfaces. When increasing outside pressure and speed, the thickness of fluid is reduced and it reaches the size equal to the height of the largest asperity on metal surfaces (R_{max}). The activity of polar additives is sufficient in that area. The thickness of fluid layer is reduced by further increasing of pressures and relative speeds of contacting surfaces. Metal surfaces have contact in several places. Local temperatures are high enough for activating AW additives. EP additives are emphasized by pressure increase. There are very fast reactions between lubricating fluids, i.e. their additives and metal surfaces. All these types of lubrication come into use with most operations at the same time.

4. Experimental part

4.1. Aim

The aim of the test is to produce new metalworking fluids, i.e. oils which will be less harmful for the environment and the employees by using ester type and biodegradable base oils.

Oils must have appropriate lubrication properties for the application in different metalworking operations. Different viscosity grades (5, 10 and 30 $mm^2\ s^{-1}$ at 40 ^0C) are required and they have to show better properties when compared to the existing products and provide stability during their application.

4.2. Test methods

For the determination of physical and chemical properties of test fluids we used the conventional test methods for these additive or oil types according to standards ISO, ASTM, DIN. [21]. The basic properties metalworking oil test and appropriate methods are shown in the Table 5. The Table 6 shows the conditions of dynamic and mechanical properties test performed with three laboratory machines which are mostly used for examining and evaluating metalworking lubricants [22].

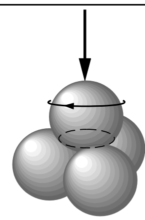
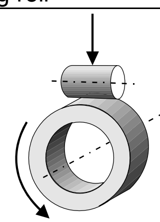
Table 5: Properties of metalworking oils and methods for their examination

PROPERTY	Method	
Viscosity kinematic at 40 ^0C / $mm^2\ s^{-1}$	ASTM D 445	ISO 3104
Density at 15 ^0C (or 20) / $g\ cm^{-3}$	ASTM D 1298	ISO 3675
Flash point / ^0C	ASTM D 92	ISO 2592
Pour point / ^0C	ASTM D 97	ISO 3016
Corrosion on copper, 100 ^0C, 3h	ASTM D 130	ISO 2160
Foaming at 24, 94 & 24 ^0C	ASTM D 892	ISO 6247
LUBRICATION PROPERTIES:		
Weld point / N 4-Ball EP machine	ASTM D 2783	DIN 51350
Wear scar diameter / mm 4-Ball Wear machine	ASTM D 4172	-
Wear scar area / mm^2 Reichert balance machine	REICHERT	-
Specific surface pressure / MN m^{-2} Reichert balance machine	REICHERT	-

4-Ball EP Machine determines the lubricant mechanical properties or, in other words, the hardness of lubricating layer in boundary lubrication conditions (EP properties). The basic test element consists of four balls in the form of equilateral tetrahedron dipped in a test fluid. An upper ball rotates at the constant speed around the vertical axis at the same time touching the other three balls in the base of tetrahedron. Under the load the ball test lasts for 10 seconds. The load is increased until the balls are welded. The load of welding is a test result expressed as the weld point in N. When the value of weld point is increased, the hardness of lubricating layer is also increased.

4-Ball Wear Machine for determining wear is based on the same principle. It is used for determining resistance of lubricating layer in mixed and mild boundary conditions. The test lasts for an hour with constant balls load and increased temperature. Wear scar of three lower balls is measured and the result is expressed as wear scar diameter in mm. Wear scar of balls is a direct indicator of the resistance of lubricating layer against loading; when the value of wear scar diameter is smaller, the resistance of lubricating layer is higher.

Table 6: Operating condition of test equipment for evaluation of lubricant mechanical properties

Test equipment	4-Ball EP Machine	4-Ball Wear Machine	Reichert balance machine
Method	ASTM D 2783	ASTM D 4172	REICHERT
Metal	STEEL AISI-E-52 100		Steel, 100 Cr6
Diameter / mm	12.7 balls'		12.0 roll's
Speed / s^{-1}	upper ball: 29.5	upper ball: 20	ring, 15
Load of test elements / N	up to 8000	400	300
Test temperature / ^0C	20 ± 5	75 ± 1	20 ± 5
Test time	10 ± 0.2 s	1 h	60 s/ or 100 m sliding contact
Measured properties	Weld point / N	Wear scar diameter / mm	Wear scar area / mm^2 Specific surface pressure / N m^{-2}
Test elements	4 balls		ring-roll
Tribological elements (schematic)			

Reichert balance machine is a device for determining sustainability of specific surface pressure of lubricating layer between contacting metal surfaces. The basic test element of this device consists of a roll and a ring. A roll is a static element and a ring is a dynamic element. Lubrication of test elements is performed in the way that the ring is partially dipped in a test fluid and it carries a certain amount of lubricant during rolling. The test includes 100 m of sliding contact of a ring in the conditions of constant selected loading of test elements. Wear scars left on a test roll are in the form of ellipse. Wear scar area in mm^2 is expressed as a test result on the Reichert balance machine. Specific surface pressure (with specific load) in N m^{-2} is calculated from wear scar area. The test result is better with smaller wear scar area since the specific surface pressure which fluid can sustain is higher.

4.3. Test additives, base oils and metalworking oil formulations

Raw materials available at the market and produced by their own are used for the new metalworking oil formulations. The additives include overbased petroleum sulfonate which replaces harmful chlorparrafin as an EP additive, sulphurised and phosphorus additive. Their properties are shown in the Table 7. As base oils we have selected monoesters produced by the transesterification procedure of vegetable oils and greases such as rapeseed oil, coconut oil and used cooking oil. Their properties are shown in the Table 8. All the esters are well biodegradable (biodegradability is determined by the CEC-L-33-T-82 method).

Table 7: Physical and chemical properties of tested additives

ADDITIVE	COMPOSITION	Sulphur content, *w* / %	Phosphorus content, *w* / %	Density at 20 ^{0}C, ρ / g cm^{-3}	Acid number / mg (KOH) g^{-1}, ISO 6618
AD-VIS	Overbased petroleum sulfonate, calcium	1.27	-	1.21	- (TBN)
AD-Sa	Sulphurised natural esters and olefins, non-active	15.0	-	0.975	-
AD-PE	Phosphorus ester of an ethoxilated fatty alcohol with 5 EO	-	4.8	1.025	144

*TBN = total base number

Table 8: Physical and chemical properties of tested base oils

BASE OILS	Viscosity at 40 ^{0}C / mm^2 s^{-1}	Flash point / ^{0}C	Biodegradability / %
E1= monoester, saturated	2.5	138	97
E2= monoester, saturated	4.0	180	
E3= monoester, saturated	4.9	170	
E4= monoester, saturated	9.0	220	
E5= monoester, saturated	16.1	230	

5. Test results and discussion

For examining basic properties of test additives we prepared compounds in ester type base oil; the Table 9 shows the compositions and test results. The compounds of all additives were prepared in different percentages (1, 2.5 and 5 % w). It needs to be emphasized that AD-VIS compounds in this base oil are turbid and that were not tested afterwards.

The Figure 3 shows test results of additive compounds in base oil on 4 ball machine, ASTM D 2783. Higher weld point values were achieved with AD-S additive and they were getting higher by increasing additive concentration. Weld point is not changed by AD-PE, so the results remain the same regardless of any concentration.

Table 9: Composition of tested additive mixtures in base oil and examination results of basic properties

COMPOSITION Formulation	REF.	FS1	FS2	FS3	FP1	FP2	FP3
Ester E1/E2/E3/E4	+	+	+	+	+	+	+
AD-Sa, w / %	-	1	2.5	5	-	-	-
AD-PE, w / %	-	-	-	-	1	2.5	5
Appearance and colour	clear	clear	clear	clear	clear	clear	clear
Corrosion Cu, 3h,100 ^{0}C	1b	1a	1b	1b	1a	1b	1b
Weld point / N	1260	2500	3150	5000	2500	2500	2500
Wear scar diameter / mm	0.63	0.82	0.57	0.58	0.43	0.48	0.61
Wear scar area / mm^2	37.7	7.9	5.2	2.8	13.9	12.1	10.2
Specific surface pressure / MN m^{-2}	7.95	37.97	57.69	107.1	21.5	24.7	29.4

The Figure 4 shows the results of testing antiwear property of test formulations on a 4-ball wear machine according to the ASTM D 4172 method. Lower values are obtained with AD-Sa at lower additive concentrations and with concentration increase to 5 % of wear scar diameter values are equal.

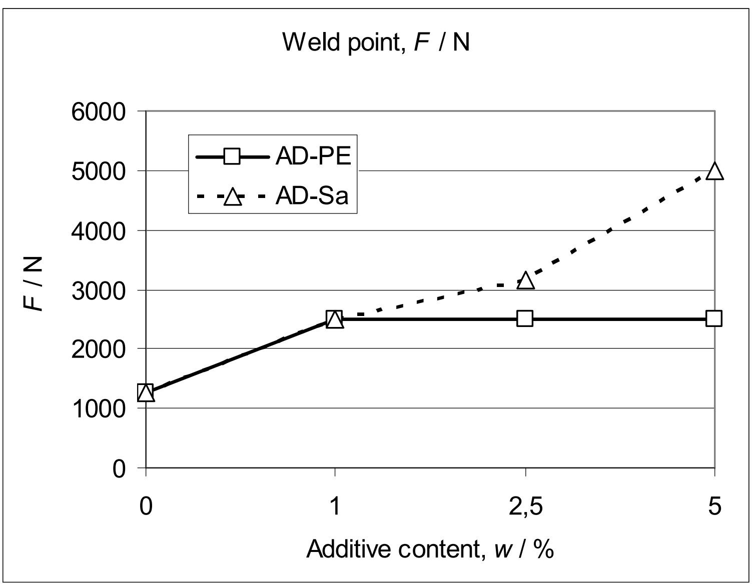


Figure 3: Weld point of tested additives at their various amounts in base oil, *F* / N

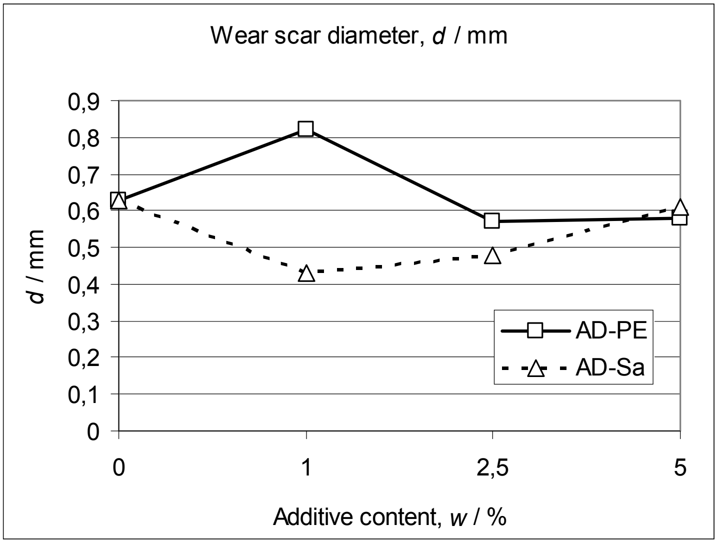


Figure 4: Wear scar diameter of tested additives at their various amounts in base oil, *d* / mm

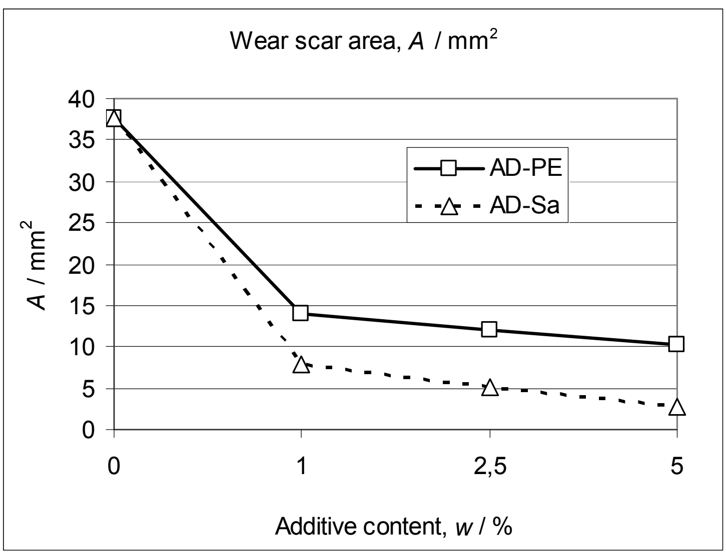


Figure 5: Wear scar area of tested additives at their various amounts in base oil, A / mm^2

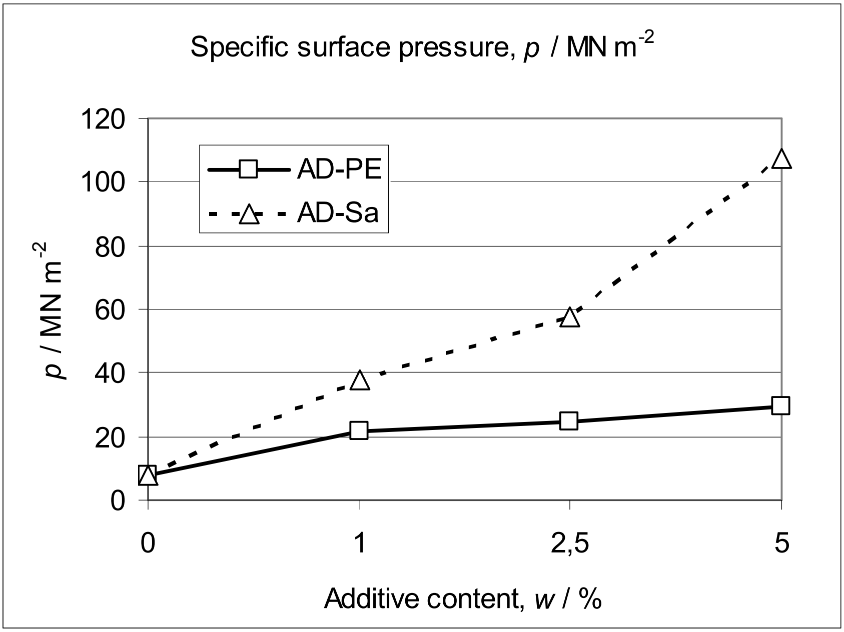


Figure 6: Specific surface pressure of tested additives at their various amounts in base oil, p / MN m^{-2}

Test results on the Reichert balance machine, which determines the wear scar area, are shown in the Figure 5. It is obvious that wear scar area are reduced by increasing concentrations for both additives. AD-Sa additive prevents wear in all the concentrations.

The Figure 6 shows determining property of sustaining specific surface pressure by the Reichert balance machine. The results show that increasing of concentration of both additives enhances this property, while AD-Sa provides better hardness of lubricating layer.

In a complete comparison of the properties at all the test machines AD-Sa showed a larger influence on lubricating properties when compared to AD-PE.

Additive compounds are used in metalworking oils in order to obtain the optimal lubrication properties under different working conditions which are mostly characteristic in particular treatment processes. A number of tests on laboratory machines proved that the combination of additives contributes to improved properties when compared to using separate additives.

The Table 10 shows the compositions of test formulations and examination results of basic properties. The REF.Min formulation is based on mineral oil of paraffinic type. The R-BIO 1-4 formulations consist of a combination of esters for achieving desirable viscosity grades of oil and additives AD-Sa and AD-PE. Formulations with

AD-VIS were also prepared in equal concentrations, but they were turbid (a) which is a result of incompatibility with esters so they were not further tested. Compatibility of conventional additives which are used in formulations with mineral oils is a critical property in formulations with ester, synthetic or natural oils [23]. The REF.BIO formulation is biodegradable oil from the market which was used for comparison of test properties. The Table 10 shows the basic properties of stability, Cu corrosion and dynamic-mechanical properties. All the formulations are clear which is an indicator of compatibility of all the components in the composition. Formulations are inactive towards Cu which means that they can be applied at yellow metal machining.

Table 10: Composition of tested metalworking oils their basic properties

COMPOSITION / Formulation	REF.Min	R-BIO1	R-BIO2	R-BIO3	R-BIO4	REF.BIO
Mineral oil	+	-	-	-	-	-
Ester E1/E2/E3/E4	-	+	+	+	+	+
AD-VIS	+	- (a)	- (a)	- (a)	- (a)	-
AD-Sa	+/-	+	++	+++	+	-
AD-PE	+/-	+	++	+++	++	+/-
Appearance and colour	clear	clear	clear	clear	clear	clear
Corrosion Cu, 3h,100 ^{0}C	1b	2b	2b	+2b	1b	1a
Weld point / N	1600	2000	2500	3150	2500	1260
Wear scar diameter / mm	0.69	0.50	0.51	0.57	0.57	0.63
Wear scar area / mm^2	37.4	21.4	10.7	6.3	9.7	37.7
Specific surface pressure / MN m^{-2}	8.02	14.01	28.03	47.6	30.92	7.95

a = formulation turbid,
Additive content, *w* / %: +++ = 3 - 5, ++ = 2 – 2.5, + = 1

The Figures 7-10 show the results of determining lubrication of test BIO formulations in comparison with referent oils of mineral origin and biodegradable fluids. By determining the weld point, the Figure 7, formulation R-BIO 3 showed the best property or, in other words, the hardest lubricating layer.

The results of determining wear scar diameter, the Figure 8, show that almost all the formulations have good values of sustaining pressure under mild lubrication conditions. The least wear scars were made with formulation R-BIO 1.

The results of determining wear scar area, the Figure 9, show huge differences among properties. All the R-BIO formulations have considerably smaller wear scar areas from the other formulations.

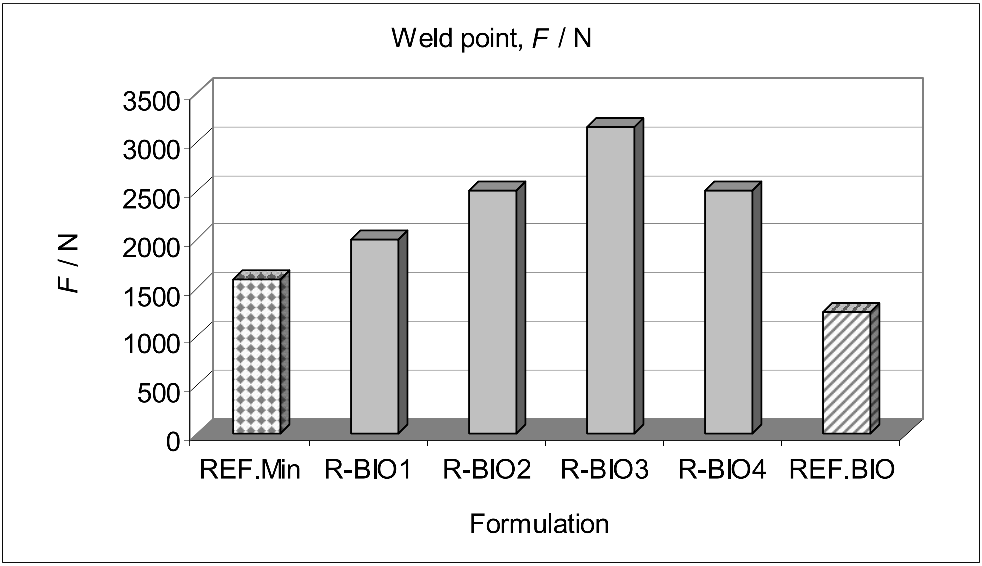


Figure 7: Weld point of tested metalworking oil formulations, *F* / N

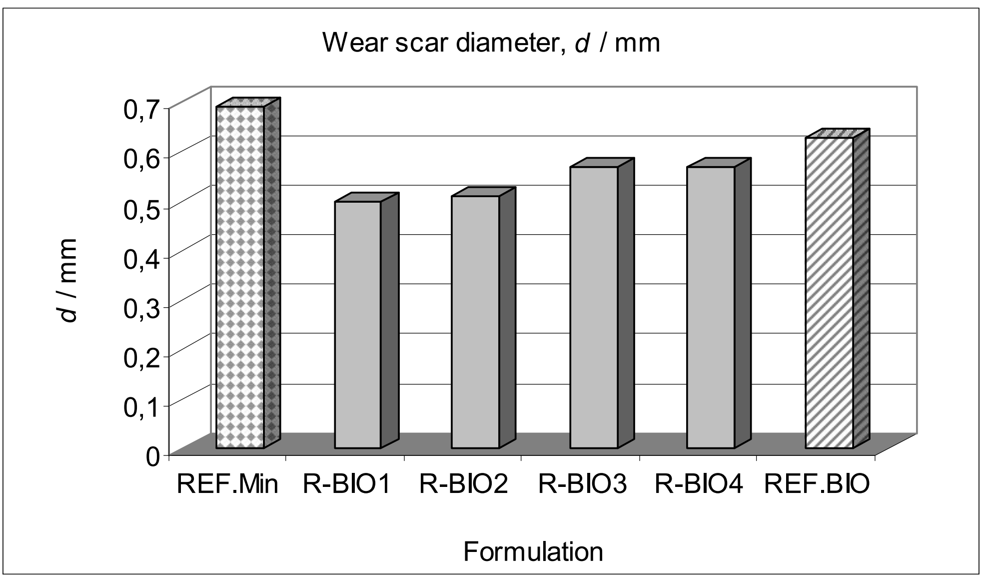


Figure 8: Wear scar diameter of tested metalworking oil formulations, *d* / mm

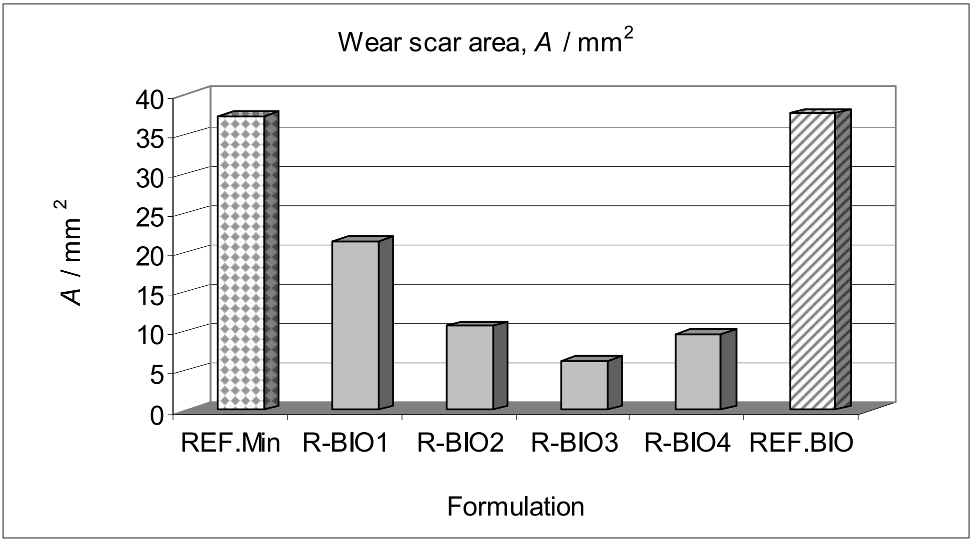


Figure 9: Wear scar area of tested metalworking oil formulations, A / mm^2

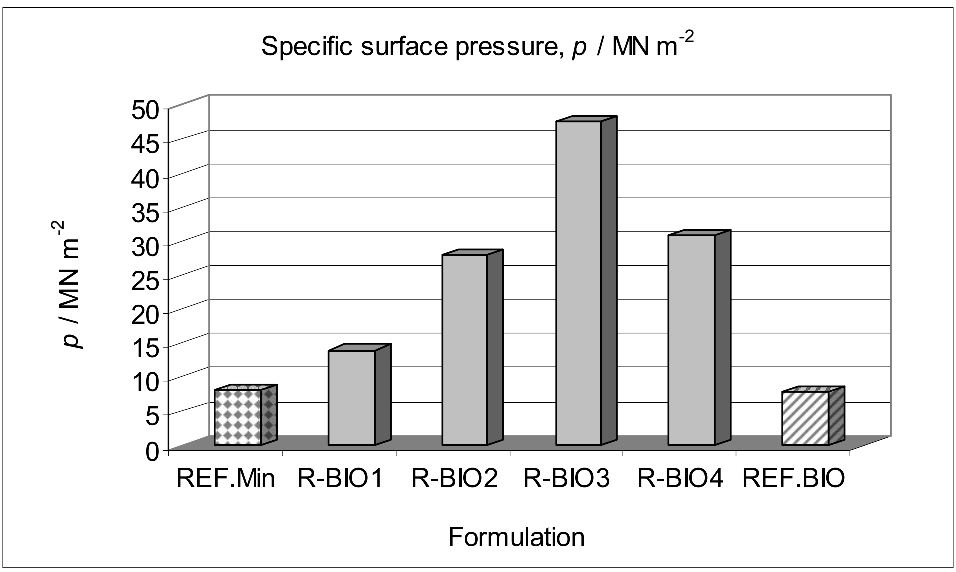


Figure 10: Specific surface pressure of tested metalworking oil formulations, p / MN m^{-2}

The results of determining the property of specific surface pressure on Reichert machine is shown in the Figure 10. It is obvious that the property of sustaining high pressures of all R-BIO formulations is better when compared to other lubricants. The R-BIO3 formulation produced the best results. The Table 11 shows the sum total of results of produced properties on a particular test machine for all the formulations of metalworking oils in a specific order. REF.BIO has the lowest lubrication properties and it is followed by REF.Min formulation.

Table 11: Total test results for all examined formulations

EXAMINED PROPERTY	Order of formulations' efficiency
Wear scar diameter, *d* / mm	R-BIO1<R-BIO2=R-BIO4<R-BIO3<REF.BIO<REF.Min
Weld point, *F* / N	REF.BIO<REF.Min<R-BIO1<R-BIO2=R-BIO4<R-BIO3
Wear scar area, *A* / mm^2	REF.BIO>REF.Min>R-BIO1>R-BIO2>R-BIO4>R-BIO3
Specific surface pressure, *p* / MN m^{-2}	REF.BIO>REF.Min>R-BIO1>R-BIO2>R-BIO4>R-BIO3
SUM TOTAL OF RESULTS	R-BIO3>R-BIO4>R-BIO2>R-BIO1>REF.Min>REF.BIO

Generally, the R-BIO 3 formulation showed the best properties when evaluating the results obtained from these three laboratory machines for testing dynamic-mechanical properties of lubricants. Accordingly, this formulation can be used for metalworking processes with more demanding work regimes, for example threading, while other formulations can be applied for easier operations such as turning, sawing or grinding.

Apart from dynamic-mechanical properties also other physical and chemical properties, required for all lubricant types, were determined. The highest viscosity of oil formulation blended for these tests was 16 $mm^2\ s^{-1}$, and the lowest viscosity was 4.5 $mm^2\ s^{-1}$ at 40 ^{0}C, which also contributes to excellent cooling properties of these oils. To continue this research other types of additives need to be applied together with more kind of esters, especially esters with higher viscosity which could be used for more demanding metalworking processes especially for low speed operations.

6. Conclusion

Several types of biodegradable base oils, or in other words, synthetic esters from saturated plant oils from the market and our own production, were tested in the paper. Among additives used there were esters of phosphoric acid, sulphurated natural oil of inactive type and natural overbased petroleum sulfonate. Blended additive compounds in test base oils gave good stability properties except from overbased petroleum sulfonates which produced turbid compounds which is an indicator of its incompatibility with these oils.

Different types of biodegradable metalworking oils of different viscosity (4.5 - 16 $mm^2 s^{-1}$ at 40 ^{0}C) with lower and higher additive composition were made. A degree of additivation was as it follows: R-BIO1<R-BIO4<R-BIO2<R-BIO3.

Lubrication properties come in this order (from higher to lower): R-BIO3>R-BIO4>R-BIO2>R-BIO1, so that the optimal lubricant can be selected according to specific requirements of metalworking operations. BIO cutting oils can be widely used depending on the requirements of metalworking operations, lubrication methods and ecological awareness.

New BIO cutting oils can be applied for especial lubrication methods as are minimal quantity lubrication (MQL), by fogging, spraying, etc. For conventional treatment methods they can be applied when excellent surface quality is needed. BIO cutting oils can be used in cases when lubricant is totally lost in the environment (total-loss application) such as sawing grinding, threading and other metalworking operations on pipes and other constructions in open spaces.

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Ključne riječi	Keywords
Biorazgradljiva bazna ulja	Biodegradable base oils
Biorazgradljive tekućine	Biodegradable fluids
Ulja za obradbu metala	Metalworking oils
Podmazivanje, svojstva	Lubrication properties
Esteri iz prirodnih ulja i masti	Esters from natural oils and fats

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