Specifications' Influence on Composition and Tribological Characteristics of Industrial Gears Lubricants

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The main drivers that lead to changes in lubricant formulations for industrial gears are specifications of international organizations and original equipment manufacturers (OEM). Changes in gears design, such as: smaller dimensions, new materials and coatings, new ways of surface treating, and trend for lowering manufacturing costs with prolonged use, sets a new set of demands for lubricants. New oil formulations for industrial gears are developed with carefully selected and balanced chemical composition of additives and base oils. In this work are shown analyses results of four generations of gear oils developed in the last thirty years, starting with oils that fulfilled basic specifications' demands by its characteristics, and up to the most modern oils that meet the most stringent requirements of additional tests imposed by OEM. The aim of the study was to investigate how improvements of other characteristics required by individual specifications affect the tribological characteristics of the gear oils.

Keywords: *industrial gears, gear lubricants, original equipment manufacturers, specifications.*

1. INTRODUCTION

Gears are an essential element of most machines. Numerous factors influence the choice of lubricants for industrial gears, such as: construction and type of gear, rotation speed, operating temperature, teeth surface quality, type of lubrication, tooth flanks specific pressure, sealing and conditions in which they work.

Of the total amount of spent lubricants for industry in Europe, lubricants for industrial gears are represented by about 8 %. From that, a significant proportion relates to the application in mines and quarries, transport equipment, agricultural machinery, steel mills, power plants and chemical industry. Gear lubricants, in addition to the basic functions of lubrication of bearings and gears in order to reduce friction and wear, must provide protection against corrosion, bear high pressure and low temperature, and prevent leakage.

Quality of lubricants for industrial gears is defined by specifications of national and international standardization organizations, such as: AGMA – American Gear Manufacturers Association; DIN 51517-1, -2, -3 – Germany; US Steel 224, now AIST 224, specification of the American Association of steel producers.

Original equipment manufacturers (OEMs) also define lubricants quality for their products based on standard tests, as well as some additional requirements. Equipment manufacturers are today key drivers in development of gear lubricants formulations, especially those used in wind turbines.

Changes in the gear design, such as smaller size, new construction materials and coatings, new technology, energy efficiency and extended periods of use, require new lubricant formulations.

Development of new formulations for industrial gear oils requires a careful choice of the individual components of base oils and additives, as well as the study of intermolecular interactions in new and used lubricant. In addition, modern gear lubricant must contribute to energy efficiency and protection of the entire system. Compared to the earlier formulation, improved are oxidation and thermal stability, resistance to micropitting, demulsibility properties, bearings wear and corrosion protection, coatings protection, and compatibility with elastomers [1].

2. EXPERIMENTAL PART

The aim of the research is to study the impact of specifications on chemical composition and tribological properties of gear lubricant formulations. In this paper, we examined four generations of industrial gear oils that are developed according to the requirements of the relevant specifications for the past thirty years.

For testing purposes the samples of gear oils are prepared in the laboratory, which are indicated by R1 to R4 by the rising level of quality and compliance with the specification.

Gear oils are formulated based on the same combination of mineral base oils in order to achieve a viscosity grade by ISO VG 220 and for testing to be reduced to the study of differences in the quantity and chemical composition of performance additives. In this

Received: March 2015, Accepted: July 2015
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doi:10.5937/fmet1503223D

way, the influence of origin and degree of base oils refining is excluded, or content and the relationship of basic hydrocarbon chemical structures and hetero-elements of base oils. Differences in tested formulations relate only to the quantity and composition of performance additive package.

In Table 1 are listed which specifications meet these test formulations of gear oils: R1, R2, R3 and R4.

Table 1. Specifications that test gear oils meet

R1	R2
US Steel 224 AGMA 9005-D94 DIN 51517-3	US Steel 224 AGMA 9005-E02 DIN 51517-3 ISO 12925-1 CKC/CKD
R3	R4
US Steel 224 AGMA 9005-E02 DIN 51517-3 ISO 12925-CKC/CKD GMLS 2 EP Gear oil	US Steel 224 (AIST 224) AGMA 9005-E02 DIN 51517-3 ISO 12925-1 CKC/CKD GMLS 2 EP Gear oil David Brown S1.53.101 Cincinnati Machine Gear Siemens/Flender/13

Each of the mentioned specifications prescribes certain characteristics with the limit values. The oldest and long time strictest specification is US Steel 224, recently called AIST 224 that has good anti-wear characteristics.

AGMA specifications (from the initial AGMA 250-04, AGMA 9005-D9 to AGMA 9005-E02) had in its development a lot of changes, which were related to the tightening of foaming characteristics, and oxidation and corrosion stability, FZG test, and it serves as a starting specification of lubricants for industrial gears.

As the main specification for lubricants for industrial gears is considered DIN 51517-1, -2, -3, which together with the specifications AIST 224 and AGMA 9005-E02 covers the broadest set of quality requirements of a multifunctional industrial gear lubricant.

Table 2, comparing industrial gear oil standards, shows the comparison of the required characteristics of the three basic specifications that ensure the quality of the multifunctional oil for use in industrial gearboxes [2].

Table 2. Comparing industrial gear oil standards

	US Steel 224	AGMA 9005-E02	DIN 51517-3
Timken D2782	+		
Four-ball EP D2783	+		
Four-ball wear D4172	+		
FZG D5182		+	+
Demulsibility D1401			+
Cooper strip D130	+	+	+
Rust D665	+	+	+
Oxidation D28938	+	+	+
Demulsibility D2711	+	+	
FAG FE8 bearing			+
Seal test D471			+
Foam D892		+	+

The structural group composition of the gear oil is shown in Table 3. Analysis of the chemical composition of gear oil is shown in Table 4.

The results of the analysis of physical-chemical and tribological characteristics of gear oil samples are shown in Table 5.

Table 3. Results of FTIR analysis of the structural composition of tested gear oils, according to the method Brandes, CEI IEC 590

	R1	R2	R3	R4
C_A [% m/m]	6.53	6.80	7.12	7.85
C_P [% m/m]	52.35	52.77	52.69	52.88
C_N [% m/m]	41.11	40.42	40.19	39.25

Table 4. Analysis of the chemical composition of the oil samples R1, R2, R3 and R4

	Method	R1	R2	R3	R4
S [%]	ISO 8754	0.392	0.345	0.345	0.547
P [ppm]	ASTM D5185	170	99	337	500
N [ppm]	ASTM D5185	126	72	208	155
Ca [ppm]	ASTM D5185	–	–	–	25
B [ppm]	ASTM D5185	–	–	–	20

Table 5. Results of the analysis of physical-chemical characteristics of the oil samples R1, R2, R3 and R4

	R1	R2	R3	R4
Viscosity at 40 °C [mm^2/s]	220	220	220	220
Flash point [°C]	245	245	247	249
Pour point [°C]	– 9	– 9	– 9	– 9
Acid number [mg KOH/g]	0.26	0.18	0.42	0.48
Cu corrosion	1b	1b	1b	1b
Demulsibility [minutes]	10	15	18	6
Foaming	100/0	50/0	0/0	0/0
FZG, A/8.3/90	10	12	12	> 12
FAG FE-8 Roller wear [mg] Cage wear [mg]	–	1.8 108.4	–	1.5 64.5

Gear oils during the application may be exposed to water penetration, which can cause hydrolysis of certain components or lubricant degradation and loss of basic functional properties.

Only 1 % of water present in the gear oil for a longer period of time can reduce the life span of roll bearings up to 90 %.

The ability to separate water from oil, or demulsifying properties of gear lubricant, is very important characteristic [1]. Newer specifications stipulate a shorter time to separate water from oil in standard tests at various temperatures.

One of the latest OEM specifications, Siemens/Flender limits the water content in the lubricant at 300 ppm.

The penetration of impurities and degradation of oil can cause increased foaming and these characteristics must be kept under control.

At the request of some OEM, new tests for the foaming characteristics are introduced.

Micropitting, characteristic in question in recent specifications, is difficult to be detected with gear teeth.

It can be a result of many factors (improperly selected viscosity, insufficient EP and AW additives, water penetration, increased operating temperature) [3].

Anti-wear (AW) and extreme pressure (EP) characteristics of gear oils are an important parameter in determining their application. Load carrying capacity of oil can be determined using several tests, but the most common is the FZG test.

Test FAG FE-8 was carried out on samples R2 and R4 and weight loss was measured that occurred as a result of roll bearings wear.

Investigation of tribological characteristics of gear oils in this study was performed using four-ball machine.

2.1 Weld point

Tests for determining the point of welding (weld point) and the determination of the index load (load wear index) were performed by the ASTM D 2783 [4].

Table 6 shows the results of the last load before welding (Fig. 1). Using the same method under different loads were measured traces of wear and the load wear indexes are calculated, whose results are listed in Table 6. Figure 2 is a graphical representation of the value movements of load wear index.

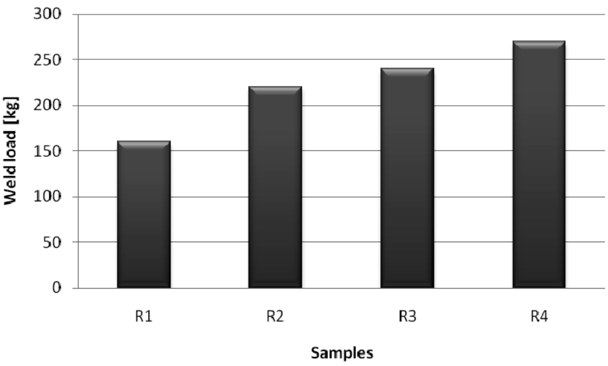

Figure 1. Weld load of gear oils

Table 6. Weld point and load wear index

	R1	R2	R3	R4
Weld point [kg]	160	220	250	280
Load wear index [kg]	45	48	49	62

Coefficient or load index is defined as the ability of the lubricant to prevent wear for a given load [5]. The next step is to use the data obtained by this analysis to calculate the coefficient of friction, as many researchers have done and used the results in their works [6]. Described below are the results of testing of these characteristics for four studied formulations of gear oil.

2.2 Wear test

Anti-wear properties (wear test) of gear oils were determined by ASTM D2266 at four-ball machine [7]. The test for determining the wear diameter of gear oils was made by the extended and modified methods. Most AW tests are carried out under a load of 20 and 40 kg. With the aim of establishing a more reliable anti-wear properties over a wide area load method is modified, so that the tests were carried out under different loads.

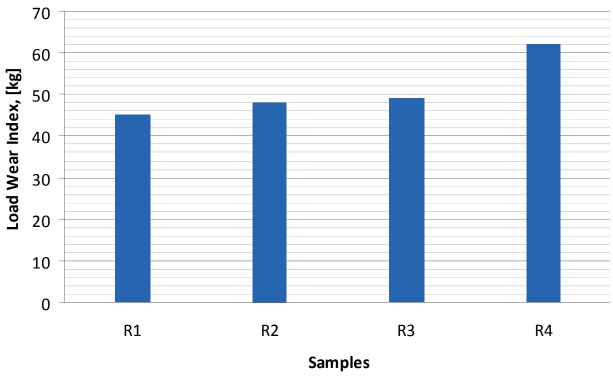

Figure 2. Load wear index

For each sample of gear oil test was performed for 1 hour, 1800 rpm, under loads of 20, 40, 80, 120, 160 and 200 kg and mean diameter of wear was measured, as shown in Table 7.

Table 7. Results of wear diameters measured after wear test made with different loads

Time: 1 hour	R1	R2	R3	R4
Load [kg]	Scar diameter [mm]			
20	0.30	0.35	0.35	0.30
40	0.33	0.40	0.38	0.42
80	0.80	0.88	0.86	0.80
120	at 5' end	1.64	1.70	2.16
160	–	2.30	1.87	2.17
200	–	2.37	2.94	2.94

Visual grades are given for wear and appearance (score: regular or irregular) on balls and oil condition after the test. Figure 3 shows trends in the value of wear diameter with increased loads.

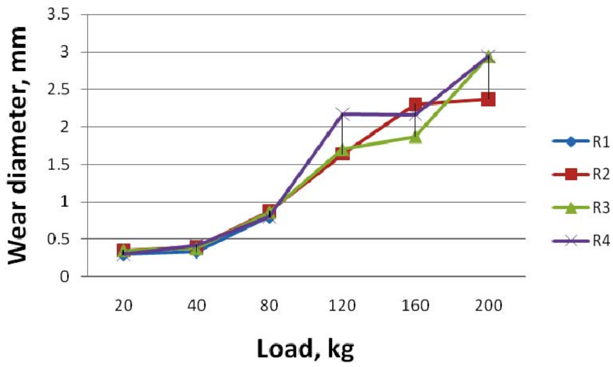

Figure 3. Dependence of wear diameter of gear oils load in four-ball test

2.3 Discussion

First tested formulation of gear oil, R1, met only three basic specifications, then valid AGMA 9005-D94, US Steel 224 and DIN 51517-3.

Anti-wear characteristics of the sample R1 was possible to test only to load of 120 kg, when it came to oil degradation after only 5 minutes of the test (Fig. 3). Traces of wear on balls (sample R1) were irregular in shape, with a thickening of metal removed by wear, as shown in the photograph in Figure 4. Since the requirement of specifications US Steel 224 for anti-wear characteristics for wear diameter was 0.35 mm, that characteristic was also met. Welding point is measured at 160 kg.

Figure 4. Photo of ball loaded with 120 kg after 5 minutes of wear test with a sample R1

Demulsifying characteristics were good, and the results of the foaming test characteristics met the requirements of the then specifications, with allowed 100 ml foam that disappeared in 10 minutes.

Sample R2 meets the ISO 12925-1 CKC/CKD, which required value of FZG test of 12 degrees for all gradations of gear oil. Tests for FZG test and FAG test are conducted in laboratories by the manufacturer of additives. The test results were in accordance with the specifications.

Specification' requirements for sample R2 were stricter for the foaming characteristics. AGMA specifications in their audits strictened some features, such as with the foaming test the permitted foam volume was reduced from 100 to 50 ml.

The sample R2 showed good results in the wear test on four-ball machine. Oil showed greater signs of degradation only in the wear test under a load of 160 kg for 1 hour and changed the colour of the balls in the dark and had irregular wear.

From the sample R3 compatibility tests on plastics, elastomers, paints, and tests on the micropitting are done in additive manufacturers' laboratories. The test results were consistent with the values prescribed by specifications that sample R3 met [8].

The sample R3, in addition to good results in basic tests, showed slightly better EP features than sample R2, because the welding point was 250 kg, and the results of the modified wear test under increased load gave inferior wear diameter. Load wear index has only slightly bigger value. But the balls in wear test under a load of 120 kg had a bright, unchanged colour with the regular trace of wear (Fig. 5.).

Figure 5. Photo of ball loaded with 120 kg after 60 minutes of wear test with a sample R3

Sample R4 is formulated according to the latest specifications, Siemens/Flender, audit 13th. That specification, in addition to basic and performance characteristics, has required the following tests: micro pitting, compatibility with paints, elastomers, and static and dynamic tests on the elastomers used for gaskets. Endurance time to change the dimensions of the elastomer was extended from earlier 168 hours to 1008 hours. All those tests were done by the manufacturer of additives, and the results are in accordance with the requirements of the specification. Demulsifying characteristics were significantly better, which is especially important when used in gear units of wind turbines, which can lead to accumulation of the condensation of moisture.

The four-ball EP and anti-wear tests of sample R4 gave the best results. Load wear index is 62 kg, and weld point is 260 kg.

3. CONCLUSION

Based on the results of physical-chemical, extended performance and special tests on samples of four generations of industrial gear oils, one can see how specifications and their requirements developed.

As multifunctional gear oils, which find their application in industry, according to the specifications that meet the results of the analysis, we can evaluate samples marked R2 and R3. Performance characteristics that make it suitable for cement plants, steel mills, mines, and many industries, in terms of dust, temperature changes and moisture, are fulfilled.

The leader of OEM manufacturers, Siemens/Flender, formulated their demands within the frames of the new and very demanding Siemens/Flender specifications. The specification has gone through many revisions, whereby the scope of examination was expanded with new functional tests and limit values of certain parameters were significantly tightened. Given the complexity of the chemical composition of these formulations and a number of intramolecular interactions between the components of high polarity, product development is time consuming and requires extensive research. The formulation must be stable over a wide range of shear and thermal stresses, and the additive component resistant to hydrolysis. Gears of wind turbines with the tested oil R4 operate stably over 4 years.

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УТИЦАЈ СПЕЦИФИКАЦИЈА МАЗИВА НА САСТАВ И ТРИБОЛОШКЕ КАРАКТЕРИСТИКЕ МАЗИВА ЗА ИНДУСТРИЈСКЕ ЗУПЧАСТЕ ПРЕНОСНИКЕ

Перо Дугић, Марица Дугић

Основни покретачи који доводе до измена у формулацијама мазива за индустријске зупчасте преносние (редукторе) су спецификације међународних организација и произвођача оригиналне опреме (ПОО). Промене у дизајну редуктора, као што су: мање димензије, нови материјали и превлаке, нови начини обраде површина, те тежња ка снижавању трошкова производње и продужену употребу, пред мазива постављају низ нових захтева. Развијају се нове формулације уља за индустријске редукторе са пажљиво одабраним и уравнотеженим хемијским саставом и односом адитива и базних уља. У раду су приказани резултати анализа четири генерације уља за редукторе развијаних у протеклих тридесетак година; од уља која су својим карактеристикама испуњавала захтеве основних спецификација, до најсавременијих уља која испуњавају најстрожије захтеве додатних тестова уведених од стране ПОО. Циљ испитивања је био да се одреди колико су побољшања осталих карактеристика, које су захтевале поједине спецификације, утицала на триболошке карактеристике уља за редукторе.