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IMPROVING THE LUBRICATING PROPERTIES OF OILS BY CHEMICAL ADDITIVES.

By R. Glocker.

Continuing the work reported at the session of the Academy(1) of 7th May 1942, regarding the amorphous structure of metallic surface layers in the sliding process, and inspired by the reports of Beeck, Givens and Smith(2) on the wear-diminishing action of phosphorus-containing additives to oil, further investigations were carried out on the change in the sliding surfaces by the addition of organic phosphorus compounds to the oil. Preliminary experiments showed that the chief technical significance of these additives consists, not in the aforementioned lessing of wear, but in an appreciable increase in the admissible surface pressure, which is accompanied by a drop in the coefficient of friction. By forming a working group, it has been possible to study the present problem, not only as regards its scientific aspect, but also to put the conclusions drawn to some practical use for aero-engine construction. This working group,(3) in addition to my Institute, comprises: Dr. Ing. Brockstedt of the State Material Testing Institute Stuttgart, Dipl. Chem. C. Müller, of the Organic Chemistry Institute of the Stuttgart Technical College; Prof. Dr. Ing. Wewerka and Dipl. Ing. Dollhopf of the Research Institute for Thermo-Dynamics of the Technical College, Stuttgart; Dr. Wahl of the I.G. Farben-industrie, Leverkusen; Dipl. Ing. Anders of Daimler-Benz, Stuttgart-Untertürkheim; Dr. Wiedmaier of the Research Institute for the Motor Industry, Stuttgart; Dr. Seemann of Daimler-Benz Gaggenau

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1) No. 52 (1942) of the Schriften der deutschen Akademie der Luftfahrtforschung.

2) Proc. Royl Soc. A. 177 (1941) 90.

3) Individual reports by the Offices concerned are in process of publication.

Method of testing and results.

Engine tests occupy much time and are costly; moreover, for reasons of fuel economy, they can only be conducted for important test experiments. Pre-selection must be effected by means of a speedy laboratory process. The number of oil testing machines is large, and for certain fields of application, types of machine such as the four-ball apparatus of Boerlage (Engineering 136, 1933, 46) for gear oils, give very practical results. For assessing the behaviour of a lubricating oil in the aero-engine, however, it has not so far been possible to establish a clear relationship between the results of a mechanical testing apparatus and the effect on the friction processes in the engine bearings and the cylinder rubbing surface.

By a happy chance, the wear-testing machine of Siebel-Kehl which was used in earlier investigations with amorphous metallic layers, was first of all used experimentally for testing various oils with additives containing phosphorus. It was not foreseen, and could only be showed by later experiments with engines, that from the surface pressures and coefficients of friction measured, qualititative pronouncements as to the lubricating behaviour of the oil in the engine could be obtained, the various additives being strongly differentiated in their improving action on the lubrication. The amount of oil required for an experiment is small, about 100 ccm.

On a ring rotating at 1.0 m/s, with outer and inner diameters of 28 and 20 mm respectively, made of lead-bronze or the piston alloy EC 124, slide three sector-shaped pieces, each with a supporting surface of about 10 sq mm of a part made of steel St. 60. (cf. Fig. 5 on p. 4 of part 52 of the Schriften der deutschen Akademie der Luftfahrtforschung). The temperature of the oil used for lubrication, is kept constant at 120° by a regulating device. Before each experiment, the contact surfaces are carefully treated with feldspar powder, maximum grain size 10 μ. The load is stepped up by stages, every half hour 120, 180, 250, 350, 450 ...... kg/sq cm, and the surface pressure and coefficient of friction are measured.

For a ring consisting of the aluminium alloy EC 124, the curve in Fig. 1 is obtained; to the Rotring reference oil 0.1% phosphenyl chloride was added. This reduces the coefficient of friction from 0.07 to 0.01. The wear cannot be measured as long as the coefficient of friction is so low. With a determined load, the "maximum admissible surface pressure" (in the present case at 750 kg/sq cm), the coefficient of friction exhibits a sudden rise, associated with noticeable wear. Conditions are similar with lead bronze (Fig. 2). The surface pressures tolerated are much greater, and the additive brings about a gain in the ratio of 1:6. The application of the index factor to the conditions of technical bearings is not permissible, since the smallness of the carrying surfaces favours the formation of a film of lubricant. The differences are to some extent "exaggerated" by the Siebel machine. In order to assess the lubricating behaviour of oils tested in like manner on the Siebel machine, the maximum admissible surface pressure is an important indication of practical utilization in the engine.

From the testing point of view, the alloy EC 124 affords certain advantages over lead bronze. Owing to the heavy loads supported, the latter requires protracted test periods, and is not well differentiated as regards its favourable emergency running properties. In the case of particularly active additives, the compressive yield point is reached, so that it is not possible to ascertain the maximum admissible surface pressure characterising the additive. On the other hand, it should be noted that many additives respond specifically to certain bearing materials (cf. Table 2). In all decisive experiments, therefore the determination of lead-bronze was also carried out.

The running-in test, given in Fig. 3, with 0.1% phosphenyl chloride additive, gives a preliminary idea as to the activity of the phosphorus compounds. The surface pressure was increased by stages to 550 kg/sq cm and then dropped to 450 kg/sq cm. After, with the machine running, the oil containing additive was replaced by oil free from additive, a surface pressure of 450 kg/sq cm, i.e. three times as great as with Rotring oil, was maintained during a running time of 70 hours, corresponding to a distance of 280 km. It was possible to increase the surface pressure still further; seizing only occurred at 850 kg/sq cm. Accordingly the sliding surfaces undergo a change owing to the additive, a change which remains for a long time after running has been continued in pure oil. We shall come back to this point later on.

In Table 1 a few figures are collated from the large number of experiments with various preparations with Rotring Oil (also with very thin oils, e.g. for hydraulic gears, the additives were active). The concentrations are between 0.05 and 1.5%, according to the activity of the additive. In most cases there is an optimum at a definite concentration, and an example of this is phosphenylous acid. The maximum surface pressure was attained with the preparation M. 100 (diparachlorophenyl phosphate).

Table 1. - <u>Maximum admissible load and coefficient of friction of Rotring oil with additives on the Siebel-Kehl apparatus (Brockstedt).</u>

Bt = Boiling temperature Dt = Decomposition temperature

The word "solid" or "fluid" refers to 20°C.

Type of Additive	Concentration	Kg/cm^2	μ
Phosphenylchloride Bt. 220°, fluid	0.05	750	0.01
	0.10	850	0.01
	0.20	800	0.008
	0.30	700	0.005
Phosphenylous Acid Dt. 200°, solid	0.2	600	0.01
	0.3	750	0.01
	0.4	700	0.01
	0.5	500	0.01
Dip-henyl phosphate Dt. 245°, solid	1.0	900	0.01
Diphenyl ester of phenyl phosphinic acid M.1. Bt 360° solid	1.2	800	0.02
Dicresylester of phenyl phosphinic acid M. 507 Bt. 390°, fluid	1.5	850	0.02
Diparachlorop henyl-phosphate M. 100 Bt. 250°, solid	1.0	> 1400	0.01
I.G. 891 Dt. 310° solid	0.8	> 1000	< 0.01
I.G. 1586/80 BS (J.7) Dt. 310°, fluid	2.0	1000	0.01
Sulphur (Junkers process)	(0.008)	450	0.01

The coefficients of friction are generally about 0.01% and show that mixed friction is present with considerable approximation to complete lubrication. It is worthy of note that the test apparatus of Heidebroek and Kluge, who worked in the domain of pure boundary lubrication, afforded no clear distinction between oil containing additive and oil without additive. Having regard to the engine experiments to be discussed later on, there appears to be some justification for stating that the behaviour of an oil in the state of boundary lubrication obviously does not possess the significance hitherto attributed to it for assessing the preservation in the engine.

In Fig. 4, the results of the Siabel machine for the I.G. preparation 891, which contains phosphorus and was very much used in engine tests, are compared with a Rotring oil, sulphurised in accordance with the Junkers process. At low pressures, the coefficient of friction of the sulphurised oil is greater than that of pure oil, but the surface pressure tolerated as far as the steep rise in the coefficient of friction, and the appreciable increase in wear, is, however, essentially higher. Increasing the sulphur concentration up to about 10 times the amount only makes things worse. With 891, the coefficients of friction are far lower; the maximum admissible surface pressure, even at 0 .4 , is greater than with sulphurised oil, and attains at the normal concentrations of 0.6 to 0.8% some 1000 kg/sq cm. Judging by the course of the curves, the actions of the admixture of elementary sulphur and of organic compounds containing phosphorus are somewhat different.

Direct inferences as to the action of the p hosphorus-containing additives on the bearing capacity of bearings are afforded by experiments on a large bearing testing machine, Wewerka type, with an oil circulation of 30 litres. A nitrided steel shaft, 45 mm in diameter, runs at a sliding speed of 7 m/s in bearings 20 mm wide, with 0.0 9 mm play. The gain in carrying capacity by the oil additive is occasionally quite considerable, e.g. with lead bronze, 50 to 210% (Table 2). The influence of the bearing material is unmistakable; the preparations 891 and M.1 behave in the reverse manner as regards their activity, according to whether lead bronze or silver are used for purposes of comparison. The slight improvements in piston alloy EC 124 are probably to be attributed to the fact that the hard silican rich structural components, remain when the surface is worn and may penetrate the film of lubricant. For bearins with a high tin content, phosphorus-containing additives are not usable owing to decomposition; for lead-antimony interchangable bearings with about 10% tin, they may, however, be used without hesitation.

In order to test the after-effect observed on the Siebel machine, the steel shaft and lead-bronze bearings were first of all caused to run in oil with 0.6% 891 for two hours at 120 kg/sq cm. Then, after the oil had been changed for oil free of additive, the load was stepped up 40 kg/sq cm every 20 minutes, until seizing occurred at 680 kg/sq cm; this limiting load is 2½ times greater than when running in pure oil. Improvements in the carrying capacity was also observed if the shaft only or the bearing only had run-in oil containing additive. In practical engine operation it is thus sufficient to use the additive for the running-in period only, if by adequate oil filtering care is taken that the running film formed is not later destroyed by extraneous substances.

Table 2. Increase in the carrying capacity of steel shafts with bearings of different materials, by the use of additives with the Oil (Wewerka & Dollhopf).

Diameter of shaft 45.0 mm, peripheral speed of the journals 7 m/s, medium-heavy steam turbine oil (4.5 E at 50° C).

Type of additive	conc. %	lead bronze %	Silver %	Special brass %	Light metal EC 124 %
Phosphenylchloride	0.05	-	-	50	-
Phosphenylous acid	0.3	65	90	20	20
Diphenylphosphate	1.0	100	-	-	-
Diphenyl-ester of phenyl phosphinic acid (M.1)	1.2	180	20	230	30
I.G. 891	0.6	50 - 75	210	50	30
I.G. 1586 / 80 BS	2.0	-	-	30	20

Points of view for chemical development.

Organic chemical materials, which are to be used as additives to lubricating oils for aero-engines, must satisfy a number of conditions, which are difficult to comply with in their entirety. To the forefront of these is a high temperature stability, as much as possible over 300°C, and resistance to decomposition in the presence of water vapour. Great activity is usually associated with ease of decomposition and low temperature stability (cf. Table 1). On this account the highly active phosphenyl-chloride, for example, is unsuitable for use in engines. Furthermore, the preparations must not react chemically with lead tetraethyl and accelerate the ageing and resinification of the oil, because otherwise the piston rings will stick. This difficulty has caused the failure of a number of additives suggested in technical literature, e.g. tricresyl phosphate + oleic acid. On top of this comes the practical requirement of good oil solubility, so that the addition may be made if possible without warming the oil. The most favourable substances in this respect are those in liquid form, such as dicresyl ester of phenylphosphinic acid. Solid preparations may be used with the help of solvents, e.g. lauryl alcohol for diphenyl phosphate. The I.G. preparation 891, which is widely used for engine tests, requires the oil to be heated to 160°C. By the addition of a solution acid, preparation 1586/80, the result is achieved that the preparation can be supplied in the liquid form in a mixture of benzene and ethyl alcohol (Designation 1586/80 BS). This solution is to be mixed cold with 50 times the quantity of Rotring oil.

Altogether about 50 organic substances, mostly containing phosphorus, were made; of these 18 phenyl derivatives were prepared for the first time by Dipl. Chem. G. Müller. In this connection, the following points of view have been formulated: In addition to phosphorus, the molecules must contain a further active group, e.g. Cl or OH, also an aryl or alkyl group. The phosphoric acid itself is not active. In phosphenyl chloride the benzene nucleus has attached to it an atom of phosphorus to which two chlorine atoms are linked. In phosphenylous acid, the phosphorus atom is associated with two O H groups and an oxygen atom. In diphenyl ester of phenylphosphinic acid, the OH group is etherified with phenol (Fig. 5). By the introduction of halogen into the nucleus of aryl esters of the phosphoric acid, its activity is appreciably enhanced, e.g. diparachlorophenylphosphate. The introduction of alkyl residues into the nucleus improves solubility in oil. The acidity of the preparations does not play a decisive part as regards their activity. For large-scale work, regard must be paid to the basis of raw material. In this respect, it is recommended in practical cases to provide several preparations with the most varied possible basis of raw materials.

Special care has been bestowed upon the reaction of the additive on the oil. The Technical Experimental Station of Oppau of the I.G. Farbenindustrie carried out ring seizing experiments which showed, for the fluid I.G. preparation 1586/80 BS with 2% concentration, no shortening at all of the running time compared with Rotring oil without additive (the low wear on the piston rings was quite remarkable), while for 1.2% of the preparation M1, the running time amounted to only 80% of the figure for pure oil. It is worthy of note that the laboratory experiments with the various test methods for the affect of ageing of both preparations have just the opposite effect; the additive M 1 behaves better than 1586/80 BS. This observation forms a new chapter in the non-agreement between laboratory and engine ring sticking tests.

Experiments on the action of oil additives.

The increase ascertained in the load capacity when using oil with additives containing phosphorus may be based fundamentally on two different causes, on an increase in the pressure stability of the oil film by improving the adsorption, or else on the levelling off of the points of the sliding surfaces by mechanical and chemical processes. The second viewpoint is adopted by Beeck, Givens and Smith; the unevennesses are first removed at the points of greatest load and therefore of maximum heating and speed of reaction; the action consists of "chemical polishing".

Experiments directed towards a direct determination of the adhesive ability of the oil film with the aid of a rotating metal disc and weighing of the oil coating did not lead to satisfactory results. On the other hand, a chemical process (after Kadmer, Schmierstöffe 1940, p. 286) for ascertaining the wetting capacity furnished clear distinctions. Iron powder is mixed with oil and benzene the amount of iron dissolved by a given action with sulphuric acid enables the wetting capacity (z) to be measured. For Rotring alone, z=2, for 1% M.1 z=26 and for 1% 891, z=29. According to this, the wetting capacity is considerably enhanced by the additives.

Observations on the Siebel and Wewerka machines regarding the stability of the changes brought about by the additive in the sliding surfaces, when further running takes place in oil without additive, favour the view that the unevenesses in the surfaces are smoothed out. This can readily be proved by optical methods. On the Siebel apparatus there were running three rings of EC 124 and three opposite numbers of steel St 60, total distance 8 km at 120 kg/sq cm, the first pair in Rotring oil free from additives, the second in Rotring oil with 1% of the I.G. preparation 891 and the third in a Rotring oil sulphurised in accordance with the Junkers process (sulphur content about 0.008%). The photographs of sections made by the Schmaltz method will be found in Fig. 6 for the rings and Fig. 7 for the steel parts. The differences in action are surprisingly large. The surfaces operated with sulphurised oil are less rough than the corresponding surfaces where pure oil was used. Smoothing by the additive 891 is extraordinarily intense. With oil free from additive, the unevennesses in light metal and steel amount to 14μ, with sulphurised oil 10μ in light metal and 6μ in steel, and with 891 only 2μ for both metals. In the treated initial state, the values were about 4 and 6μ. These findings are in perfect agreement with previous measurements of the coefficient of friction.

In order to follow optically the running-in process of bearings, the interference method has proved of better service than microscopic or electron microscopic photographs, which do not indicate so clearly any differences that may be present. Two photographs with the Zeiss interferometer of the surface of a hardened steel shaft in the treated condition and after running-in pure Rotring oil (surface pressure increased every twenty minutes by 40 kg/sq cm, up to 120 kg/sq cm) are shown in Fig. 8. At the bearing points of the shaft, the interference curves begin to flatten. Photographs of two shafts loaded up to 200 kg/sq cm, whose interference aspects were the same in the lapped state, are compared in Fig. 9. The interference curves of the shaft operated with 0.6% 891 are very much flatter. The running-in process is thus accelerated by the additive, and even improved, probably owing to the fact that the surface points, which are the points of maximum pressure and temperature, are levelled by chemical reaction with the phosphorus. This is also borne out by the occurrence of a strongly adhesive, insoluble, brownish surface coating on the bearing run with the additive. This coating makes the interferometric investigation of the sliding surfaces of the bearing impossible.

Additives for gear oils.-

Since the situation with regard to raw materials has made it necessary to abandon the use of fats for gear oils, investigations were carried out to study the effect of additives containing phosphorus under the conditions occurring in the gears. According to the previous experience, the behaviour in Boerlage's four-ball apparatus could be taken without hesitation as a standard for testing. The load is measured at which the steel balls are welded together. A few results from a large series of experiments are given in Table 3. Army engine oil (Summer grade) with the various additives does not attain, with normal, hardened steel balls, the figures obtained with gear oil. On the other hand, gear oil is surpassed if, in accordance with Bokemüller's suggestion, bonderised balls are used. In this case, the compressive strength is approximately as great as that of the best hypoid oil with normal balls.

Table 3. Welding point load of various oils on the four-ball apparatus. (W. Seemann).

AEOS = Army Engine Oil Summer Grade

Type of oil	Type and concentration of additive %			Steel balls Normal	Bonded
Gear Oil	-		-	260 kg	600 kg
AEOS	-		-	140	300
"	I.G.	891	0.5	180	950
"	"	"	0.2	-	850
"	M	100	0.5	190	850
"	M	100	0.2	180	800
"	M	401	0.5	180	1000
"	M	401	0.2	180	1000
"		"	0.1	160	950
"		"	0.05	160	800
Hypoid Oil	Sulphur		?	1000	-

A particularly active additive for stress in the gears is M. 401; even concentrations of 0.05% suffice to obtain a welding point of 800 kg with bonded balls. An undesirable property of the present uncompounded fatless gear oils is the drop in their pressure resistance at high temperatures. When heated for one hour to 200°C with a constant stream of air, the compressive strength drops to about 3/4 of the amount, while in engine oil with the phosphorus containing additives given in Table 3, it is maintained. This superiority is particularly well marked in measurements of wear with toothed gear, which were extended at 150°C up to 112 hours. (Glaubitz, MPA , Stuttgart). With engine oils containing 0.5% additive M. 100, the wear remains within moderate limits, but with gear oil it exhibits a rapid rise, even after about 30 hours.

For use in rear axle gears, the important question is whether the additives attack the usual packing material. According to original experiments by Messrs. Carl Freudenberg at Weinheim, the normal packing material may be used with 0.2% M. 100 or M. 401. Higher concentrations call for Simrit packing. There are therefore no difficulties in this respect.

Experiments with automobile engines.

In order to obtain information as to the stability of the oil containing additive in en gine operation, trial trips were carried out with a 2 l BMW-car of the Institute. After certain distances, samples of oil were taken and tested on the Siebel machine. The oil supply in the crank case was not topped up. The preparations behaved in very different ways. By way of comparison, a few figures are given for distances of 800 kilometers; the original activity had dropped to 40% with phosphenylous acid, 60% with diphenyl phosphate, 70% with preparation M.1 and 80% with preparation M. 507. Even after a distance of 1300 kilometres, slight activity was noticed.

Qualitative observations with fuel consumption and engine performance led to the question as to what extent a reduction in the internal frictional resistances of the engine has a practical effect. Such a reduction may certainly be expected to take place owing to the action of the additives, in accordance with the results of the Siebel engine. For such experiments, engines that have not yet been run-in are particularly suitable. A new engine, ex works, was built into a passenger car of FKFS. With the throttle valve kept in the same position, a distance of about 5 km in both directions was traversed on the arterial road, and the mean speed was measured as a distance: time ratio; the fuel consumption was also measured. By averaging the figures for the outward and return journeys, interference by wind could be eliminated to a large extent. First of all the run was carried out with Essolube 40, then warmed Essolube 40 with 0.6% 891 was substituted. The accuracy attained will be seen from the curves in Figure 10 . Apart from the first outward and return journey, the speed is higher and the specific fuel consumption (consumption per unit of distance, divided by speed. Consumption rises with speed) is lower than with oil free from additive. The exceptional case provided by the first trip with oil containing additive shows that a certain time is required until the effect reaches its full extent.

Altogether three series of measurements were carried out with the passenger car. At the first filling with oil containing additive after a distance of 380 km since leaving the works, an 8% rise in speed and a 14% drop in the specific fuel consumption were established. Between 600 and 1800 kilometres, the car was run on pure Essolube 40. Unused Essolube 40 with 0.6% 891 was then inserted and an improvement of 4% in both speed and specific fuel consumption was attained (Fig. 10). With renewed use of the additive after a distance of 15800 km, the action of the additive could not well be detected. Experiments with a 2 l BMW car which had done 70,000 km confirmed the finding that practically with a vehicle engine that has been well run in, the additive in the oil does not furnish any appreciable gain in performance. On the other hand, an improvement was noticed in accelerating from low speeds with normal gear. This agrees with the observation made in connnection with trial trips, that with a thinner oil - Essolube 20 instead of 40, with a viscosity ratio of 1 : 2 -, the improvement amounts to 5% in accelerating from a speed of 20 km/h over a measured course of 100 m, with 2% gradient.

The additives make it possible to use thinner oils, without fear of seizing. Besides starting more easily at low temperatures, these possess the advantage that the lubricant reaches the various lubricating points more easily; furthermore, the temperatures of the bearings, which behave proportionately to the viscosity, remain lower. For these reasons, thin oils are recommended abroad for automobile engines (C.G. Williams, Research Inst. of British Autom.Eng. 1941).

Tests in the aero-engine.

One of the main points of interest is whether, at the high cylinder temperatures, the stability of the additives will be adequate. Durimg a 10-hour run of a single-cylinder ring of engine type DB 605, oil samples were constantly taken. The result of the test on the Siebel apparatus is shown in Fig. 11 for the preparation 891. There first of all occurs an appreciable consumption of the additive, until, in the course of normal toppings up, a constant figure prevails, which corresponds on the Siebel apparatus to a surface pressure of 500 kg/sq cm. The second danger point is the formation of residue and the seizing of the piston rings. On this account diphenyl phosphate must be discarded (According to a verbal statement by Dr. Zorn (I.G. Farbenindustrie Leunawerk), the U.S. Air Force apparently used diphenyl phosphate in 1938, but abandoned it after some time).

From the large volume of tests of the Daimler-Benz A.G., particularly worthy of mention is a 100 hours' run of a new engine DB 60 5 with 2% admixture of 1586/80 (liquid preparation). After 30 hours the concentration had been halved. The main bearings exhibited a good bearing surface, which was slightly matt, but under the microscope, very fine and even roughnesses could be detected. The bearing surfaces were pink in colour, and this gradually turned dark brown in the air. The non-bearing parts were dark brown to black. The coating could not be removed by wiping. Findings in the dark coloured big end bearings were likewise good.

On the gudgear pins the running in colours otherwise observed were lacking. The piston rings exhibited a good bearing appearance. There were no corrosion phenomena in any part of the engine. The sludge formation was normal. Sticking was observed in some of the piston rings, but this did not give rise to any trouble in running. By the use of the preparation in the normal concentration, any undesirable secondary phenomena are accordinly precluded during running in.

Fig. 12 shows the results of series experiments with 126 aero engines DB 605, of which half were run in with pure Rotring oil and half with the additive 891 or 1586/80 BS. The findings in the bearings were assessed by a point system; the best surface appearance being indicated by II.

Bearings with 6 points are passed by the Inspection. The improvement in the running-in process by the additive is unmistakable. The maximum occurrence is displaced in the direction of the high point figures, and the numerous bearings on the borderline of acceptance are eliminated. Furthermore, in operating with oil containing additive, there was not a single bearing rejected owing to seizing, while in the comparative series with pure oil, 14 bearings had to be rejected for this reason. In assessing the practical significance, care must be taken that this figure is spread over approximately the same number of engines, as generally only one bearing per engine is rejected.

A large series of 462 aero-engines DB 605 D, run in with the additive 1586/30, gives quite a clear picture: the number of rejected bearings has decreased to one fifth of the normal amount; in bearings affected by "carbon" particles, the grooving is considerably less than in oil without additive.

To summarise, it may be said that it is possible to make chemical additives for lubricating oil, which afford considerable improvement in the running-in process for aero-engines, without the occurrence of undesirable secondary phenomena. Whether those containing phosphorus are fundamentally superior to those containing sulphur and chlorine, must remain a subject for further research. In the present materials situation, it is important for practical use in aero-engines that operation should be adjusted to several preparations with the most varied raw materials possible.

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Fig. 1 - Surface pressure and coefficients of friction for the light metal EC 124 with the addition of phosphenyl chloride (Brockstedt).

Fig. 2 - Surface pressure and coefficients of friction for lead-bronze with the addition of phosphenyl chloride (Brockstedt).

Fig. 3 - Running-in test on the Siebel-Kehl-machine with the addition of phosphenyl chloride (Brockstedt).

Fig. 4 - Surface pressure and coefficients of friction for sulphurised oil and for the additive I.G. 891 with rings of EC 124 (Brockstedt).

Fig. 5 - Constitutional formulae of certain oil additives (G. Müller).

Fig. 6 - Photographs of sections of light metal surfaces (EC 124)
- a) Sulphurised Rotring oil according to Junker's process.
- b) Rotring oil with 0.6% I.G. 891 preparation.
- c) Rotring oil without admixture.

Fig. 7 - Photographs of sections of steel surfaces St. 60.
- a) Sulphurised Rotring oil according to Junker's process.
- b) Rotring oil with 0.6% I.G. 891 preparation.
- c) Rotring oil without admixture.

Fig. 8 - Interference photographs of a hardened steel shaft.
- a) in the lapped state.
- b) after running-in with Rotring oil without admixture at 120 kg/sq cm.

Fig. 9 - Interference photographs of two run-in, hardened steel shafts (at 200 kg/sq cm.)
- a) Rotring oil without additive.
- b) Rotring oil with 0.6% I.G. 891 preparation.

Fig. 10 - Effect of oil additive I.G. 891 on performance of a passenger car and fuel consumption. (Test runs together with Wiedmaier).

Fig. 11 - Testing the stability of the oil containing additive (0.6% I.G. 891) in aero-engine operation (Brockstedt).

Fig. 12 - Statistical comparison of action on bearings in aero-engines DB 605 after running-in with Rotring oil with and without additive (Anders and Halvor).