Hindawi
Advances in Tribology
Volume 2024, Article ID 5997292, 12 pages
https://doi.org/10.1155/2024/5997292

Research Article

Experimental Comparison of the Effect of Using Synthetic, Semi-Synthetic, and Mineral Engine Oil on Gasoline Engine Parts Wear

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Received 15 February 2024; Revised 22 March 2024; Accepted 26 March 2024; Published 12 April 2024

Academic Editor: Mohammad Farooq Wani

This paper includes the laboratory and experimental methodology used to compare the effect of using mineral, semi-synthetic, and synthetic engine oil on the parts wear of a four-stroke gasoline internal composition engine (ICE). Three test platforms included three engines with identical, technical, and design specifications. They were operated under the same investment, ambient, and climatic conditions. The first engine was equipped with synthetic oil, the second with semi-synthetic oil, and the third with mineral engine oil. All of them had (SAE10W40 API: SL/CF). All test platforms were operated through three stages with variable loads for up to 1,500 operating hours (hr). Oil drain intervals (ODI) were every 100 operating hours. Used oil samples were taken to analyze the physical and chemical characteristics of viscosity, total base number TBN, flash point, metals wear Irion (Fe), copper (Cu), chromium (Cr), and wear index (WI) to investigate the effect of all oils on the wear of engine parts and by comparing the changes in wear. The used oil analysis (UOA) results were drawn that showed the superiority of the use of synthetic oil over semi-synthetic and mineral. It prolonged the technical engine's lifetime.

1. Introduction

The great development in the design of internal combustion engines has led to minimizing these engines, which increases the stresses affecting the lubricating oils, and it is very natural that the specifications of the engine oil change because of investment and operation in difficult working conditions [1].

The operational life and reliability of internal combustion engines are limited by the breakdown of the engine components due to wear under boundary-lubricated conditions. It is very advantageous to know the condition of an engine and its components without disassembling the engine for examination.

Recently, oils and lubricants are much better than the ones used several years ago. The deterioration of oil is caused by many factors, such as heat, friction, chemical contamination, and oxidation. In recent years, petroleum companies, working hand-in-hand with carmakers, have developed stronger additive packages to produce new types and categories of oils that extend oil drain intervals because the oil can withstand tougher conditions.

This paper employs the chemical and physical analysis of SAE10W40 API: SL/CF crankcase oil to predict the condition of the lubricant and engine components worn during real operation.

2. Engine Parts Wear

Wear is the progressive loss of the material from the operating surface of the engine due to relative motion between surfaces. The successful design of engine elements depends essentially on the understanding of tribological principles like wear and friction [2].

Wear occurs as friction causes deformation and breakage in the materials in contact. Lubricants can serve to reduce friction and wear as well [3].

This can be related to the nature of wear. Wear can be separated into the following categories: adhesive, abrasive, fatigue, and corrosive [4].

Adhesive wear occurs when asperities contact and weld together. The metal around the adhesive contact becomes work hardened, thus making adhesive contact stronger than the cohesion of the base metal, which causes chunks to be ripped out of the base metal. Adhesion is the reason dissimilar metals are usually chosen to run together, as they do not weld together easily [4].

Abrasive wear is akin to sandpaper on wood. Relative hard particles rub against softer material and scratches are formed. During this form of wear, polishing can also occur, just like sandpaper on wood, which can lower friction and be favorable in some instances.

Fatigue wear occurs as asperities are repeatably deformed and eventually break like a paper clip being bent repeatedly.

Corrosive wear occurs as chemical reactions break down the wear surface. This can also have positive effects, as some light corrosion can reduce adhesion. Rarely do these forms of wear occur alone but usually all have a compounding effect on each other. Adhesive wear forms particles that cause polishing, which reduces the protective oxides on the metal surfaces, which can cause further adhesive wear, etc. The prevention of these compounding interactions is the most important role of the lubricant as it flushes away particles to filters where they are removed, and chemical compounds are added to the lubricant (additives) to replace the worn protective layers. For example, the effect of graphene nanoplatelets (GNP) as lubricant additives in SAE 15W40 oil on the piston ring wear was reduced by using GNP-filled nanolubricant. The characterization of the worn piston ring surfaces showed that the tribo-film formed on wear tracks resulted in the improved performance of the engine, thereby reducing abrasive wear and surface roughness [5].

In order to reduce friction losses and wear of the main components of an internal combustion engine, antiwear coatings are applied to the sliding surfaces. Another factor in reducing friction losses in internal combustion engine associations is the continuity of the oil film, which is ensured by the proper shape of the sliding surfaces [6].

3. Engine Oils

Today engine technology requires a lubricant of higher performance due to longer drain intervals, higher temperature, and improved after-treatment durability and fuel economy. To meet those new requirements, new oil formulations are using more and more hydrocracked and synthetic base oils together with new additive packages. We can, therefore, wonder how this will affect the life cycle assessment of those lubricants whose objective remains to lubricate engines during a certain period [7].

The lubricating oils are the blood of the engine's operation, and the service life and economic effectiveness of the engine are relative to the quality, performance, and reasonable use of the oils. In recent years, many scientific researchers have dedicated themselves to studying lubricating oil additives as an important project. Typically, lubricants contain 75%–85% base oil (most often petroleum fractions, called mineral oils) and less than 25% additives. Oil is a general term used to cover all liquid lubricants, whether they are mineral oils, natural oils, synthetics, emulsions, or even process fluids [2].

However, improved lube oils can be quickly implemented in existing vehicles to have an immediate effect, whereas new vehicle and engine designs will take time to be introduced into the market [8].

Also, It is likely that new engines will be designed to use lower-viscosity oils to reduce friction losses, i.e., lowering lube oil viscosity from 10W40 to 0W10 has shown a 4% improvement in fuel economy [9].

The lubricant used in an engine is vital as it serves many functions, such as separating surfaces in relative movement, flushing away particles, cooling the engine, and reducing wear and friction [10].

The lube oil must perform all these functions while remaining stable for long durations. The performance of the oil is optimized through complex oil formulations, fitting the correct viscosity range for the engine application and understanding how the oil performs over the range of engine conditions expected. Because of all these demands, engine lubricants have become complex over the past 100 years.

The operation of the engine, type of service, type of fuel, and the characteristics and age of the engine can change oil properties [10]. Engine oil properties are not inherently constant and change for a variety of reasons, including the shear of polymers in the oil, which lowers viscosity, fuel diluting the oil, additives being used, and various forms of deposits. Oil can also nitrate from nitrogen in the air or nitrogen reaction products. Lower molecular weight molecules in the oil can evaporate, thereby thickening the oil [10].

The many functions of a modern lubricant are the result of the careful blending of chemical additives and carefully refined base stocks [10].

Additives are used extensively in lubricants to improve their lubricating properties. One of their roles is to enhance the mechanism of hydrodynamics to increase the resulting protective lubricant film thickness. However, another important function of an additive is the formation or enhancement, by either a chemical or a physical activity, of a boundary layer on the opposing surfaces: this acts both to protect the surfaces from degradation and, most importantly, to reduce the shear or frictional force required to slide them over one another [11].

Engine base oils are typically mineral oils, synthetic or partial synthetic. Mineral oils are produced from crude oil in a distillation process that separates the hydrocarbons in the crude oil by molecular weight.

Synthetic oils are lubricants primarily developed from a chemical process to build up low-molecular-weight hydrocarbons whose molecular-weight distribution range is small and whose chemical structure is resistant to degradation [10].

Table 1: General overview of base oils and viscosities.

API group	Classification	SAE viscosity	Cost
Mineral base oils			
Group I	Mineral oil	15W40, 20W50	Low
Group II	Mineral oil	10W40, 15W40	Low
Group III	Mineral oil/hydrocracked	5W20, 5W30, 5W40, 10W40	Moderate
Synthetic base oils			
Group IV	Synthetic oil	0W20, 0W30, 0W40, 5W20, 5W30, 5W40, 10W40	High
Group V	Synthetic ester	2W20, 0W30, 0W40	Extremely high

Semi-synthetic oil is produced by mixing mineral oil with synthetic oil, provided that the latter does not exceed 30%. The heat transfer properties of synthetic base oils can be very different from mineral oils, with synthetic oils being able to sustain higher oil temperatures [10].

Almost every lubricant used in plants today started as just a base oil. The base oil category defines what the oil is made of, how it is manufactured, and how the lubricant handles certain environments, such as extreme heat. The American Petroleum Institute (API) has categorized base oils into five categories. The first three groups are refined from petroleum crude oil [12]. Although made from crude oil, Group III base oils are sometimes described as synthesized hydrocarbons. Like Group II base oils, these oils are also becoming more prevalent.

Group IV base oils are full synthetic polyalphaolefins (PAOs). These synthetic base oils are made through a process called synthesizing. They have a much broader temperature range and are great for use in extreme cold conditions and high heat applications. Oils Group V is for all other base oils not included in Groups I–IV. Before all the additives are added to the mixture, lubricating oils begin as one or more of these five API groups [12].

Table 1 shows the API grouping of the base oils. Table 1 also gives an overview of how oils are created for a specific viscosity and a general indication of the costs associated with differing oils. The higher cost of synthetic oils is mostly due to the much higher complexity and cost of production [13].

Table 1 is an approximate guide as to which oil viscosities belong in which group and shows that there is a significant overlap between Group III hydrocracked oils and Group IV oils. Table 1 also clearly illustrates that oils using less refined mineral-based oils only have a limited range of applications, as they cannot meet the demands of modern engines.

To base oils, additives are added which serve a variety of purposes. Antioxidant is the most important oil additive [14]. This sacrificial agent reduces the tendency of the engine oil to oxidize, thicken, and form varnish. Antiwear additives, like zinc dialkyl dithiophosphate (ZDDP), in the oil react with the physical surfaces within the engine to create protective layers, which prevent wear and corrosion. ZDDP dissociates, and its dissociation products have better properties that reduce friction, wear, and oxidation [15].

When graphene nanoplatelets (GNP) and graphite nanoflakes (GNF) were used as lubricant additives in SAE15W40, the friction coefficient and specific wear rate reduced with increasing load, sliding speed, and sliding distance for both nanolubricants in comparison with base oil 15W40 [16].

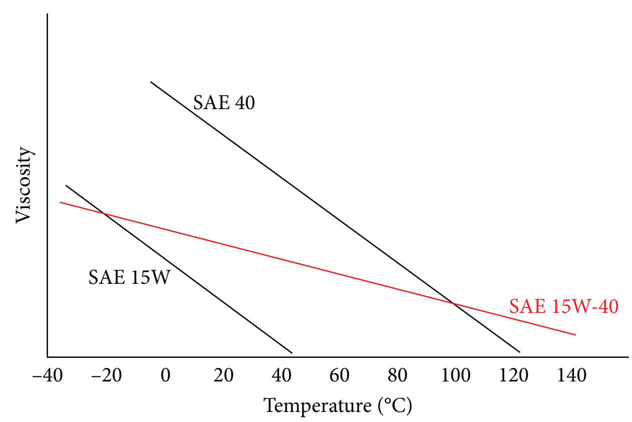

Figure 1: Polymer-thickened oil viscosity changes [18].

There are detergents added to the oil that neutralize acids formed during combustion or overheating of the oil, protect engine components from corrosion, inhibit deposits from forming, and help keep surfaces clean [17].

Insoluble contaminants, varnish, and sludge are controlled with dispersants. Friction modifiers are added to reduce engine friction. Defoamers are added to reduce the foaming of oil, as foam can alter the oil's load-carrying and viscometric properties. Viscosity modifiers or viscosity index improvers change the base oils' viscosity-temperature relationship so that the oil remains sufficiently fluid when cold but does not become too thin when hot. Pour-point depressants help to keep the oil from solidifying at very low temperatures. All these additives work together to prolong the life of the engine while also seeking to improve efficiency.

Engine oils were originally a single SAE grade, but multigrade oils were developed to aid in cold start conditions. Thin oils have a slower rate of change in viscosity over temperature than thicker oils. It is advantageous for the thicker oil to have a flatter slope, like the thinner oil, so that the viscosity does not drop as drastically at lower temperatures.

This can be accomplished by thickening a thin oil with polymers, usually methacrylate [9]. This effectively shifts the viscosity-temperature profile of the thin oil upward along the viscosity axis to make a multigrade oil, as shown in Figure 1. The addition of a small amount of a long-chain polymer, the length of which may be a million times the diameter of a water molecule, to a Newtonian fluid gives the most desirable lubricant by increasing the fluid film pressure, and as a result, the load carrying capacity increases and the friction factor decreases [14].

Degradation and contamination of the lube oil are the major causes of failure in IC engines. Increases in contaminant levels and changes in fluid properties can be both an indicator of deteriorating component conditions and a cause of component failure. Environmental pollution by an IC engine is related and largely to the engine's condition, which in turn depends largely on its lubricating system [19].

3.1. Engine Oil Analysis. Wear has important, negative effects on the functioning of engine parts. Additionally, this situation is very difficult to evaluate accurately in oil analysis for engine condition monitoring. Original equipment manufacturers (OEM), lubricant suppliers, and oil analysis laboratories provide specific guidelines for wear metal concentrations. These limits provide good general guidelines for interpreting oil analysis data but do not take into account common factors that influence the concentration of wear debris and contaminants in an oil sample. These factors involve oil consumption, fresh oil additions, etc., and particular features such as engine age, type of service, environmental conditions, etc. [20].

Oil analysis is a series of laboratory tests used to evaluate the condition of lubricants and equipment components. By studying the results of the oil analysis tests, a determination of equipment/component condition can be made. Primarily, this is possible because of the cause-and-effect relationship between the condition of the lubricant to the condition of the component sampled [21].

The inspection or analysis of lubricating oil has been used to check and evaluate the internal condition of oil-lubricated equipment since the beginning of the industrial age. Early methods included smelling the oil to detect the sour odor of excess acidity, rubbing it between fingertips to check lubricity, and observing its color and clarity for signs of contamination. Today, oil analysis programs use modern technology and laboratory instruments to determine equipment condition and lubricant serviceability. Oil analysis uses state-of-the-art equipment and techniques to provide the user with invaluable information, leading to greater equipment reliability [21].

The degree of physical and chemical deterioration, i.e., the degree of contamination and degradation, can be evaluated using a set of standard and specialized tests, such as measuring certain properties and comparing these with a baseline value (new oil) [22].

Analysis can measure several properties of the lubricant and evaluate its degradation. These include antifreeze; appearance; fuel; content water; soot; nitration; oxidation; sulfation; viscosity; viscosity index; total base number (TBN); wear metals (Al content, Cr, Fe, Mo, Na, Ni, Pb, Si, Sn, V); particles [22].

Particle quantification (PQ Index) is also called wear index (WI). It is the measurement of total ferrous (iron) particles present in the sample. PQ does not take into account the size of particles. The ferrous is detected via magnetic fields and is dependent on the type of laboratory equipment used. They will determine how the measurement is taken. Regardless of this, the generated reading will report the total concentration of the magnetic particles in that sample [22].

PQ Index can be used to measure ferrous wear metal particles in oil, grease, and coolants. PQ analyzers have no units and can be thought of as mass ferrous particles per mass of oil (mass/volume). PQ does not take into account particle size; we need to use the iron (Fe) readings of the elemental analysis to figure out when the concentration level is above 10 μm. This is where the PQ information can be very useful, especially in components that are starting to show fatigue signals or have large internal wear indicators starting to appear rapidly [22].

This paper will only focus on those that were considered the most important for the monitoring of the degradation of mineral, semisynthetic, and synthetic oil, which are metals wear (Fe, Cr, Cu), wear index, viscosity, TBN, and flash point. It is the aim and scope of this research.

Adopted allowed precautionary limits of oil analysis are illustrated in Table 2 [23]. Test results values should not exceed it.

Table 2: Precautionary values adopted criterion for the validity of oil.

Specifications	Allowed precautionary limits
Kinematic viscosity at two degrees: 40 and 100°C	±35%
Total base number (TBN)	<2
Iron content	<200 ppm
Copper content	<40 ppm
Chromium content	<20 ppm

Table 3: Experimental materials.

Specifications	Unit	Qty
Gasoline generator set	Piece	3
Unleaded gasoline octane 90	Liter	2,250
Mineral engine oil SAE10W40 API: SL/CF	Liter	12
Synthetic engine oil SAE10W40 API: SL/CF	Liter	12
Semi-synthetic engine oil SAE10W40 API: SL/CF	Liter	12
Light projector 450 W	Piece	3
Lamp 140 W	Piece	9
Timer	Piece	1
Electrical contactor	Piece	1
Voltage gauge	Piece	3
Current gauge	Piece	3
Frequency gauge	Piece	3
Temperature gauge	Piece	3
Operation hours counter	Piece	3
Electrical cable 3×2 mm^2	Meter	6
Electrical socket	Piece	6

Table 4: Tests instruments.

Equipment	Type	Manufacturer	Tests	Method
Viscometer	Manual/Ostwald	Cannon/Fenske	Kinematic viscosity at 40 and 100°C	ASTM D445
Potentiometer	Automatic	Metrohm	Total base number (TBN)	ASTM D 2896
Atomic absorption spectroscopy	Automatic	Pye Unicam SP	Determine the concentration of metals iron, copper, and chromium in the oils	ASTM D2788–D3605
Ferrograph DR-5	Direct reading	PREDICT	Wear index (WI)	Instrument manufacturer's instructions
Cleveland open cup flash point test meter	Manual/Cleveland open cup	SUR-Berlin	Flash point	ASTM D 92

Table 5: Experimental gasoline generator set data.

Item	SUNSHOW SS1800
Phases	Single
Max power	1.1 kVA
Rated power output	850 VA
Rated frequency	50 HZ
Rated voltage	220 V
Rated current AC	4.6 A
Operation hours	4.8 hr
Manufacture	Shanghai Sunshow Mechanical and Electrical Co. Ltd.
Origin	China

4. Experiment

4.1. Materials. The materials used in this research are shown in Table 3.

5. Equipment

Table 4 provides information about the instruments used in this study.

6. Method

6.1. Tests Platforms and Engine Oils. The actual and laboratory experimental method was adopted in this research. Three identical test platforms were equipped and operated. Each platform includes a gasoline generator set, which has the technical specifications shown in Table 5, in addition to electrical loads, a set of gauges, a timer, an electrical contractor, etc., as illustrated in Figure 2.

In addition, they included three stationary engines identical in technical and design specifications, as shown in Table 6. They were operated in parallel with the same investment, ambient, and climatic conditions at the same time. The first sump engine was filled with mineral oil, the second semi-synthetic oil, and the third with synthetic oil. All of them (SAE10W40 API: SL/CF). The three platforms were operated in three stages with different loads up to 1,500 operating hours.

6.2. Operation and Sampling of Test Oils. The three platforms were operated in parallel with different loads in three Stages to achieve different operating conditions for the experimental engine, normal, heavy-duty, and very heavy-duty conditions to derive results in all cases. These stages will be explained as follows:

The first stage: Operating the platforms in parallel with a constant and stable load equal to 50% of rated power @ 3,000 rpm up to 900 hr. Thus achieving normal operation conditions at this stage.

The second stage: The platforms are operated in parallel with a variable electrical load via the timer and the electrical contactor, as shown in Figure 2. According to the schedule shown in Figure 3, the platforms are operated sequentially with 50% of rated power for 15 min, then 100% of rated power for 5 min, and so on, up to 1,200 hr @ 3,000 rpm. Thus, the load changes six times during one operating hour, which achieves heavy-duty conditions at this stage.

The third stage: The platforms are operated in parallel with a variable electrical load according to the schedule, as shown in Figure 4. The platforms are operated sequentially with 100% of rated power for 5 min, then 92% of maximum power for 5 min, and so on, up to 1,500 hr @ 3,000 rpm. Thus, the load changes suddenly 12 times during one operating hour, which achieves very heavy-duty conditions at this stage.

During the three stages of the actual experiments, oil drain intervals every 100 hr immediately after the engines stop. They are placed in sterile plastic bottles to be laboratory samples. They are sent to the laboratory to perform eight analyses for each oil sample: kinematic viscosity @ 100°C, kinematic viscosity @ 40°C, TBN, flash point, wear index WI, and metal wear Fe, Cu, and Cr.

7. Results and Discussion

7.1. Viscosity, Flash Point, and TBN. It is necessary to note that the purpose of viscosity, flash point, and TBN analysis is to verify and deny that any of them have not collapsed or decreased, which may be a cause of abnormal wear or defect in actual experiments and the validity of the results.

Tables 7 and 8 show their results and illustrate that viscosity at all stages fluctuates for all tested engines and remains within accepted precautionary limits. The reason for this behavior is that viscosity change is a result of many different factors and conditions of the engine.

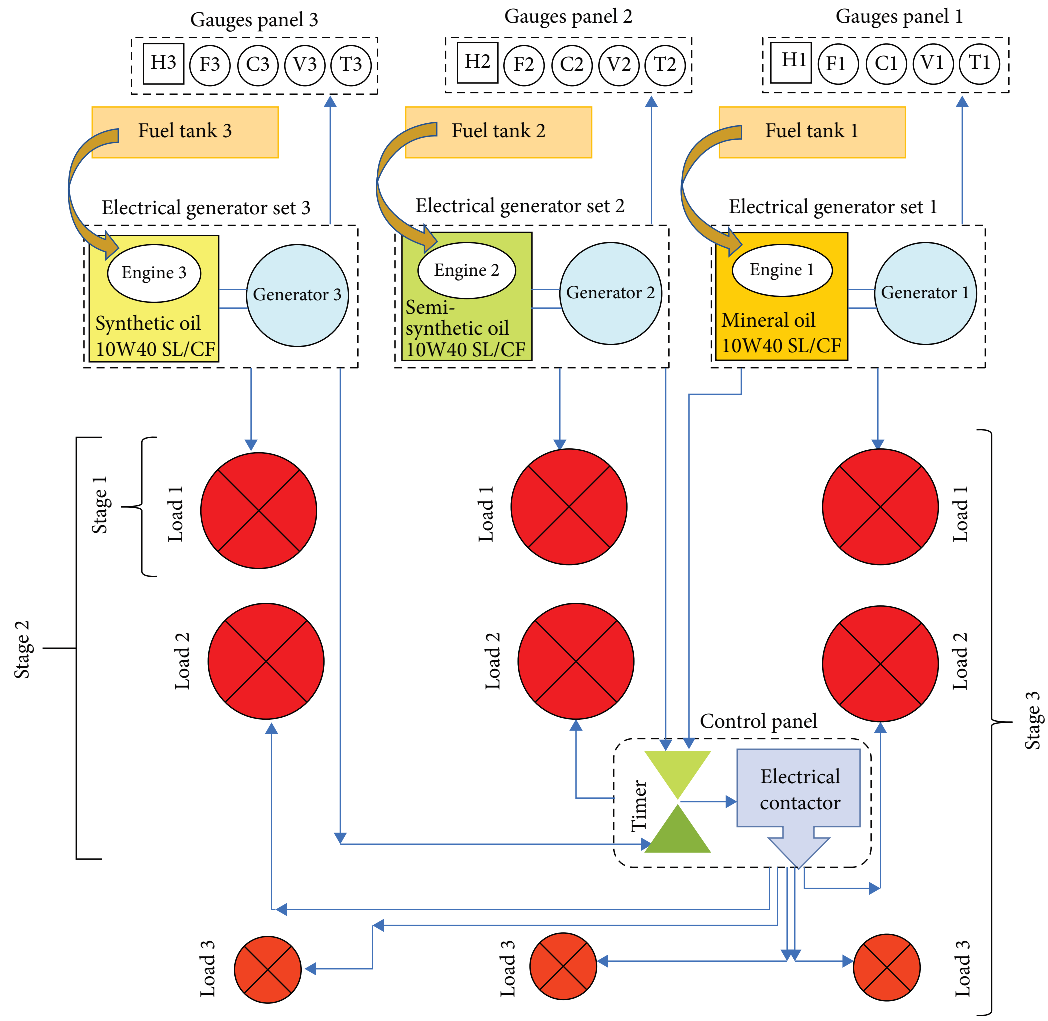

Figure 2: Schematic diagram of the test setup. H: operation hours counter, F: frequency gauge, C: current gauge, V: voltage gauge, T: temperature gauge, Load 1 = 50% rated power = 450 W, Load 2 = 50% rated power = 420 W, Load 3 = 140 W. Load 1 + load 2 + load 3 = 1,010 W = 92% max power = 119% rated power.

Table 6: Engine experimental data.

Item	SS154FO
Type	Inclined, 1 cylinder, air cooled, 4 strokes, OHV
Displacement	87 cm^3
Bore × stroke	54 × 38 mm
Revolution speed (constant)	3,000 rpm
Fuel	Unleaded gasoline
Sump capacity	0.4 L
Engine serial number 1	EA01765
Engine serial number 2	EA01398
Engine serial number 3	EA01722

Alkaline and antioxidant additives deplete in oil with time allowing the oxidation, polymerization, and disintegration of oil and the formation of acids so viscosity increases and oil thickens. On the other hand, polymeric additives are exposed to shearing because of stress, thereby causing a decrease in viscosity. Therefore, the resultant viscosity may increase, decrease, or may cancel out.

TBN decreases with traveled operation hours, which began at the high value of the new oil, which expresses the amount of alkaline additives in the oil to neutralize the

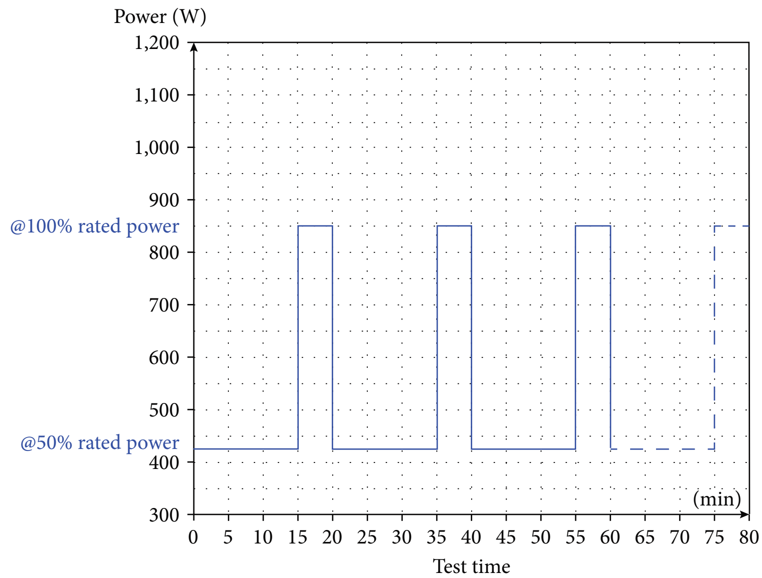

FIGURE 3: Experimental schedule for variable loads at the second stage.

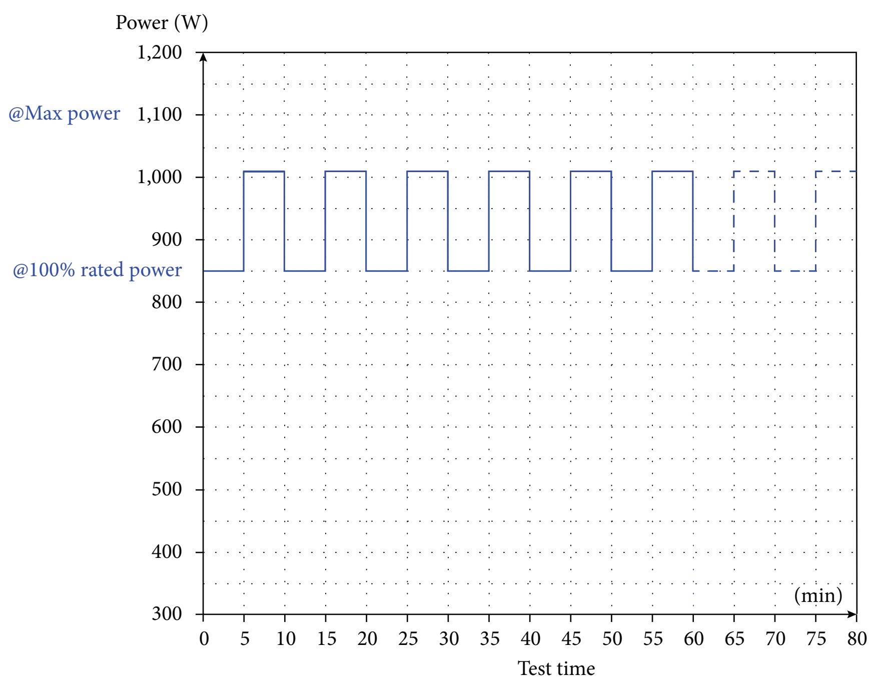

FIGURE 4: Experimental schedule for variable loads at the third stage.

acidic products formed during operation; these products will reduce the alkalinity additives percentage in the oil as indicated by the decrease of TBN. It remains at the allowed precautionary values.

The flash point gradually decreases slightly and is within acceptable limits, indicating no fuel leakage into the engine lubricant.

The changes of the flash point (degree) in a slightly gradual manner and within acceptable limits indicate that there is no fuel leakage into the engine lubrication circuit.

The decrease in the flash point by more than 30% is evidence of this and an indication of the technical condition of the engine.

8. Metals Wear

Analysis of wear metal Fe, Cr, Cu, and WI indicates the effect of using different oils on the wear of engine parts for small-power stationary engines according to the methodology of this research. This refers to comparing the effect of synthetic,

Table 7: Oil analysis results for viscosity, TBN, and flash point at the first stage.

Oil statues		Fresh oil	Used oil								
Stages			Stage 1 @ load 1 = 50% rated power								
Operation hours × 100		0	1	2	3	4	5	6	7	8	9
Mineral oil	Viscosity@40°C ST (cSt)	109.9	116.8	86.4	93.7	102.6	103.9	108.3	105.3	108.3	105.3
	Viscosity@100°C ST (cSt)	13.8	14.2	11.6	12.2	13.4	13.2	13.9	13.6	14.1	14.6
	TBN (mg KOH/g oil)	13.5	12.0	10.5	10.1	9.9	9.6	8.9	8.6	8.9	8.6
	Flash point (°C)	220	228	205	200	200	190	204	198	200	202
Semisynthetic oil	Viscosity@40°C (cSt)	125.6	95.5	82.7	84.6	97.5	94.0	92.2	98.3	99.2	99.7
	Viscosity@100°C (cSt)	15.2	12.7	11.8	11.4	13.1	12.7	12.5	13.4	14.3	14.9
	TBN (mg KOH/g oil)	13.2	11.9	13.2	11.8	11.6	11.2	10.4	10.0	10.1	10.0
	Flash point (°C)	250	222	220	219	216	204	216	200	190	180
Synthetic oil	Viscosity@40°C (cSt)	103.33	78.3	78.6	81.4	78.3	78.6	80.0	81.4	87.1	85.5
	Viscosity@100°C (cSt)	15.46	14.2	13.4	12.7	14.2	13.4	13.0	12.7	13.7	13.3
	TBN (mg KOH/g oil)	13.19	12.4	12.0	11.7	12.4	12.0	11.8	11.7	10.0	8.2
	Flash point (°C)	228	190	204	205	190	204	203	205	206	200

Table 8: Oil analysis results for viscosity, TBN, and flash point at the second and third stages.

Oil statues		Fresh oil	Used oil					
Stages			Stage 2 @ variable load 2			Stage 3 @ variable load 3		
Operation hours × 100		0	10	11	12	13	14	15
Mineral oil	Viscosity@40°C (cSt)	109.9	89.0	79.5	106.4	107.3	134.4	115.9
	Viscosity@100°C (cSt)	13.8	13.3	12.5	13.6	15	16.42	14.64
	TBN (mg KOH/g oil)	13.5	8.1	7.3	6.9	6.7	6.4	6.1
	Flash point (°C)	220	180	164	210	210	222	222
Semisynthetic oil	Viscosity@40°C (cSt)	125.6	79.2	78.8	78.2	81.43	93.04	91.69
	Viscosity@100°C (cSt)	15.2	12.3	12.2	11.6	12.01	13.32	13.1
	TBN (mg KOH/g oil)	13.2	9.4	8.7	8.3	7.6	7.1	6.4
	Flash point (°C)	250	190	205	196	178	212	218
Synthetic oil	Viscosity@40°C (cSt)	103.33	87.6	74.4	73.9	74.19	84.31	79.82
	Viscosity@100°C (cSt)	15.46	14.9	13.2	12.1	9.98	12.28	12.9
	TBN (mg KOH/g oil)	13.19	8.1	7.9	7.6	7.4	7.1	6.8
	Flash point (°C)	228	194	180	192	172	206	212

semi-synthetic, and mineral engine oil on gasoline engine parts wear. It is the topic and goal of this research.

9. Iron (Fe) Wear

It is clear from Figure 5 that the change in the rate of wear of Fe for synthetic oil is less than for mineral and semi-synthetic oils over the entire operating period of 1,500 operation hours, where the curves linearly began in the first stage with a relatively high value until the first 100 operation hours, which is justified by the break-in period.

First, the wear Fe increased at 100 operating hours linearly for all oils, which is explained by the break-in period of the new engines. The wear Fe increases gradually and steadily relatively in the first and second stages, to increase more in the third stage where the engine operating conditions are very heavy duty during the third stage, but the wear increase for mineral oil was greater than for the other two oils. All values for all oils remained within the precautionary limits adopted globally and allowed.

10. Chromium (Cr) Wear

As Fe wear, the wear started at 100 operating hours dna increased linearly for all oils, which is explained by the break-in period of the new engines, as shown in Figure 6. The wear rate of Cr changes by very small values compared to Fe; this is explained by the fact that chromium is harder than iron, which resists wear more. The increase in the second stage was steadily increased for all oils due to the engines working in difficult conditions, and the values of synthetic oil remained lower than those of semi-synthetic and mineral oils. The wear increased clearly in the third stage because the engines were working in very difficult conditions. All

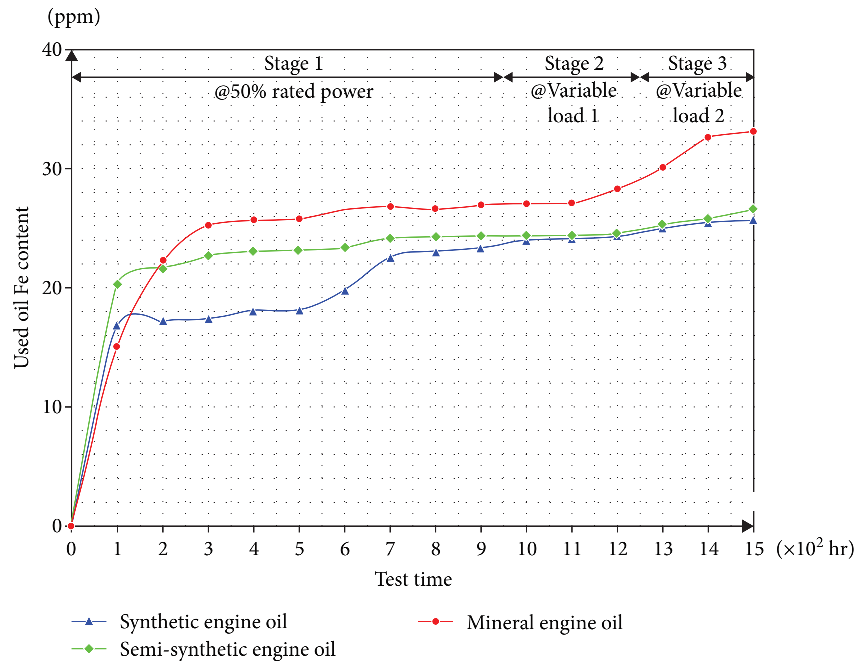

Figure 5: Fe content changes in terms of the number of operation hours.

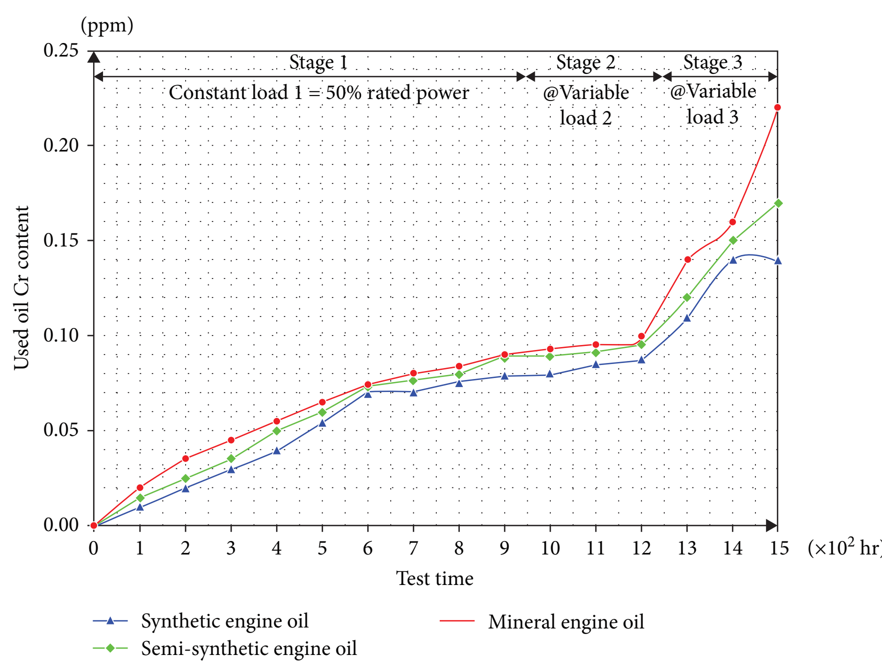

Figure 6: Cr content changes in terms of the number of operation hours.

values remained within the internationally accepted precautionary and permissible limits.

11. Copper (Cu) Wear

Figure 7 shows that Cu curves are similar to Fe. The increase in wear is evident as it is simple in the first stage under normal operating conditions for the engines, increases in the second stage due to a change in the load to achieve heavy-duty operating conditions for the engines, and then increases in the third stage more due to the variable load according to the schedule and to achieve very heavy-duty operating conditions for all engines.

12. Wear Index (WI)

WI does not take into account the size of particles. The direct reading ferrograph = DR-5 measures the density of large

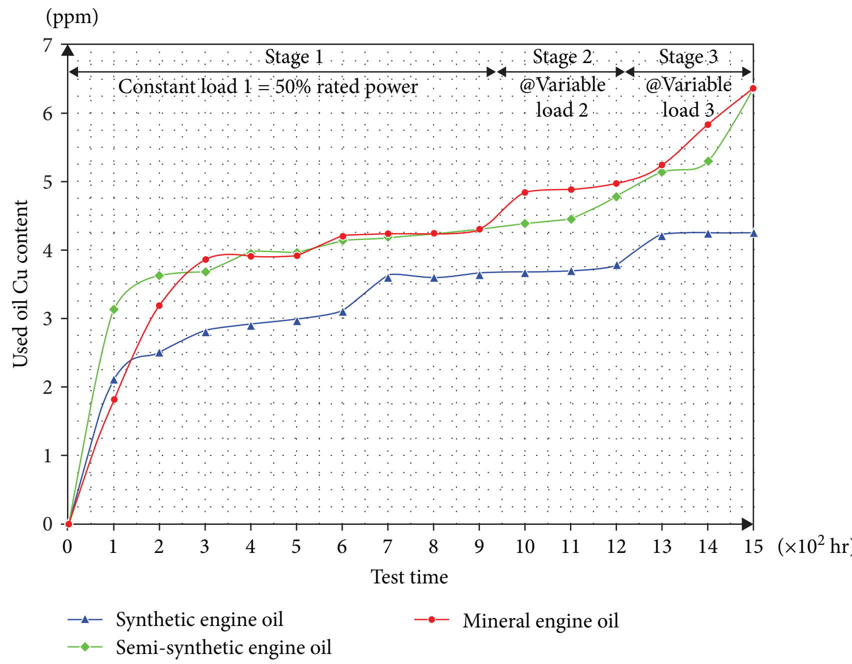

Figure 7: Cu content changes in terms of the number of operation hours.

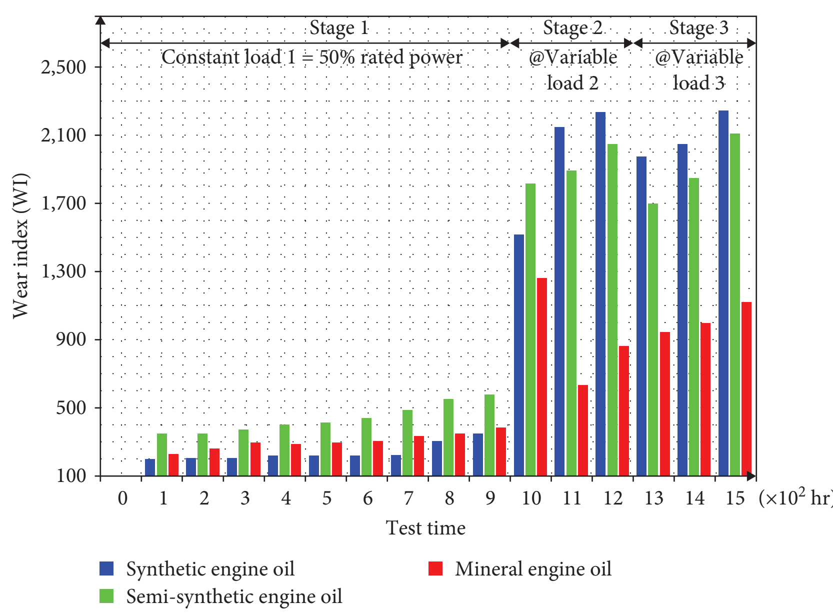

Figure 8: Wear index changes.

particles (DL) greater than 5 μm and small particles (DS) less than 5 μm. This test helps to determine the wear in the engine parts to see if it is normal or abnormal. Accordingly, it is recommended to repair faults to prevent engine failure and subsequent breakdown and failure. This is useful for predictive and preventive maintenance.

Figure 8 shows the increase in the WI values in the second and third stages, which expresses heavy-duty and very heavy-duty conditions in the operating conditions of the engines. A clear difference is observed in the lower WI of mineral engine oil than that of synthetic and semi-synthetic.

In general, the results of the practical experiment and laboratory analyses of the three stages of the experiments and for all the engines show that all values are within the accepted and permissible limits for the validity of the oil compared to the precautionary values adopted globally.

Synthetic oil outperformed semi-synthetic and mineral oil, as the metal wear values decreased for the synthetic oil compared to the semi-synthetic and mineral oil in different proportions for each of the wear metals studied.

The metal wear rate of synthetic oil decreased compared to semi-synthetic oil in proportion to the average values, respectively: Fe: 9.9%, Cu: 27%, and Cr: 11.4%. The metal wear rate of synthetic oil decreased compared to mineral oil by percentages of the average values, respectively: Fe: 22.5%, Cu: 28.3%, and Cr: 23.9%.

All these results are at the stages of practical experiments with different loads, normal, heavy-duty, and very heavy-duty, and for steady gasoline engines @ 3,000 rpm; thus, we have reached the goal and the desired goal of this research.

13. Conclusions

(1) The effect of using synthetic oil on engine wear parts is better than semi-synthetic and mineral oil for SAE10W40 API: SL/CF, small-capacity, steady gasoline engines @ 3,000 rpm, and variable loads, according to the methodology of this research. It prolonged the technical engine's lifetime.

(2) The metal wear rate of synthetic oil decreased compared to semi-synthetic oil in proportion to the average values, respectively: Fe: 9.9%, Cu: 27.9%, and Cr: 11.4%. The metal wear rate of synthetic oil decreased compared to mineral oil by percentages of the average values, respectively: Fe: 22.5%, Cu: 28.3%, and Cr: 23.9%.

(3) Ferrograph results showed a clear decrease for mineral oil than for synthetic and semi-synthetic oil, which indicates a lower wear index.

(4) This research contributes to the promotion of predictive and preventive maintenance of engines. Through tests of engine oils, we can know the technical condition of the ICE and its technical life without disassembly and determine the engine overhaul, which reduces maintenance costs and saves both time and effort.

Abbreviations

A: Ampere
Al: Aluminum
API: American Petroleum Institute
ASTM: American Society for Testing and Materials
C: Commercial
Cr: Chromium
cSt: Centistockes
Cu: Copper
Fe: Iron
GNF: Graphite nanoflakes
GNP: Graphene nanoplatelets
hr: Hour
ICE: Internal composition engine
L: Liter
Mo: Molybdenum
Na: Sodium
Ni: Nickle
ODI: Oil drain intervals
OEM: Original equipment manufacturers
OHV: Overhead valves
PAOs: Polyalphaolefins
Pb: Lead
ppm: Part per million
PQ: Particle quantification
Qty: Quantity
rpm: Revolutions per minute
S: Service
SAE: Society of Automotive Engineers
Si: Silicon
Sn: Tin
TBN: Total base number
UOA: Used oil analysis
V: Vanadium
V: Volt
WI: Wear index
ZDDP: Zinc dialkyl dithiophosphate.

Data Availability

Data are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

We would like to acknowledge the Faculty of Mechanical and Electrical Engineering at Damascus University and the Higher Institute for Applied Sciences and Technology in Damascus, Syria, for helping us without financial compensation, providing facilities for us to conduct tests on the devices available to them in order to encourage scientific research. The financing of this study was personal.

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