A review of the effect of sand dust and filtration on automobile engine wear

Article *in* Wear · January 1991

DOI: 10.1016/0043-1648(91)90279-4

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A review of the effect of sand dust and filtration on automobile engine wear

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(Received February 11, 1990; revised May 30, 1990; accepted June 22, 1990)

Abstract

The economics of operating internal combustion engines in cars, buses, trucks and other equipment is heavily affected by friction and wear losses caused by abrasive contaminants. This study is a review of the effect of sand dust, one of the main sources of foreign contaminants, on the wear of critical engine components, including the piston ring, cylinder sleeve and bearings. For each component, the mechanism of wear and the influence of dust variables on wear are analysed. The methods of engine protection and life extension are reviewed. Air and oil filtration are the primary methods for reducing the infiltration of dust into the internal engine components. The effectiveness of these is reviewed, together with the recent development of improved filters with higher efficiency.

1. Introduction

The economical running of tribological systems such as the internal combustion (IC) engines of cars, buses, trucks and construction equipment is heavily affected by friction and wear losses caused by particles getting into the system as contaminants, or generated within the system as wear particles. One main source of these particles is dust. Dust particles mostly contain silica because the solid crust of the earth contains 80% silica [1]. Silica particles are harder than the structural materials of engines, which is particularly important with piston rings and cylinder sleeves, since these are affected directly by the presence of small amounts of contaminants in the air intake. Following contamination, three-body abrasive wear occurs between the rubbing surfaces or else the foreign particles become embedded in the softer material causing two-body abrasive wear [2].

The cost of this abnormal wear is very high, particularly in dusty regions and construction sites. Koves *et al.* [3] discussed the cost of abnormal wear in the construction industry. They pointed out that the transport cost represents a significant portion of the total project costs in the construction industry. The transport cost consists of the purchase price of the vehicles and the

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0043-1648/91/$3.50

cost of operating them. The price of the engine constitutes a considerable proportion of the purchase price of a vehicle. Thus an increase in the performance life of a vehicle engine may bring about an overall reduction in cost. The service life of an engine may be increased by protecting it from normal as well as from abnormal wear, but especially from the latter. Tarnok [2] performed a study involving 2000 buses and 600 trucks aimed at reducing the abnormal wear and friction losses. This reduction was achieved through improvements in air, fuel and oil filtration and with the use of friction-reducing additives. Through tribological improvements in these trucks and buses, the annual savings amounted to the cost of 65 buses.

Fodor [1] stated that 80% of machine failures are due to wear. This means that engine life is mainly affected by the normal and abnormal wear of engine components. Wakuri and Ono [4], in an experimental study of marine diesel engines, reported the trends in normal and abnormal wear illustrated in Fig. 1. The figure shows the combined wear of cylinder liner and piston ring, and clearly illustrates that with time the abnormal wear increasingly exceeds the normal wear.

Different test methods may be used for determining the wear rate of an automotive engine caused by abrasive particles in general. The basic method consists of debris monitoring, which depends on the ability to detect the wear particles being generated by the rubbing components. Several techniques have been utilized to monitor and analyse wear debris in the past decade. These techniques, recently outlined by Ozogan *et al.* [5] may be divided into the following categories.

1.1. Lube oil sampling analysis method

This method depends on specimen extraction in the form of oil samples taken periodically to assess their debris content. The procedure is to take a sample from the lubricating oil; then the sample is filtered and the residue is reduced to ash and transformed by neutron activation into a mixture of radioisotopes. The quantity of wear debris and of extraneous matter entering the lubricating oil is then determined by γ-ray spectrometry [6].

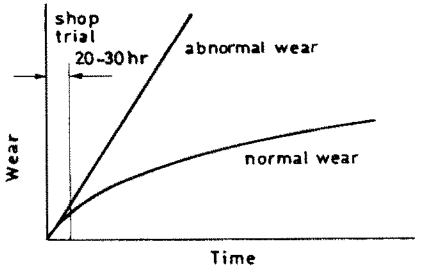


Fig. 1. The trends in normal and abnormal wear for marine diesel engines [4].

1.2. *Debris collection methods*

Wear debris is collected from the flow path by a device such as a magnetic plug or a filter which is convenient to remove for debris extraction and examination [7].

1.3. *Direct detection method*

This method, described in detail by Jones *et al.* [8] and by Livonen and Aho [9], relies on monitoring the lubricant oil in the engine by on-line devices through which the oil flows. The presence of debris in the oil is detected directly by debris sensors. This system has many advantages of which the main ones are that it eliminates the need for regular human intervention and that it is very sensitive to small amounts of wear. This method also provides a means for evaluating the individual performance of critical engine components.

In this review, an attempt is made to assemble and analyse literature relating to abnormal wear of critical engine components caused by dust particles. For each critical part the mechanism of wear as well as available data on wear rates *vs.* dust particle variables are presented. Various measures reported for engine protection are discussed and their relative potential in reducing engine wear is outlined, with the emphasis on filtration.

2. Critical engine components

Abrasive particles entering the engine through the air filter or the fuel filter will cause extreme damage to engine parts. This damage occurs either by direct interaction of the dust particles entering the combustion chamber, or indirectly as the particles get carried away from the combustion area and mixed with the lubricating oil. This will cause wear in lubricated engine parts such as bearings, crankshaft journals and the bottom part of the cylinder bore (Baczewski and Jaroszczyk [10]). Therefore the critical engine parts which will be discussed here are

(1) Piston ring;
(2) Cylinder sleeve;
(3) Bearings (especially crankshaft and journal bearings).

Other engine components such as the fuel injection system (Koldonski and Wachal [11]) will not be discussed here since they are considered secondary in so far as engine wear is concerned.

3. Piston ring wear

Dust particles entering the combustion chamber with the hot mixture get into the gap between the piston ring and cylinder sleeve thus causing a three-body abrasive wear mechanism which affects the piston ring surface.

Wakuri and Ono [4] described the mechanisms causing normal and abnormal wear of the piston ring. They stated that under normal conditions,

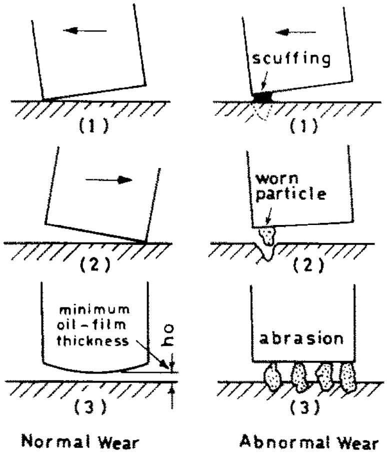


Fig. 2. Mechanism of abnormal wear [4].

wear at both edges of the piston ring is accelerated by edge loading and the ring surface is run in as shown in Fig. 2. Therefore the risk of scuffing is gradually reduced and ultimately the piston ring is separated from the cylinder by a hydrodynamic oil film. However, the risk of abrasion is increased in the presence of foreign particles. If scuffing begins, large particles are scraped off the metal surface by adhesion. Since the thickness of the hydrodynamic oil film between the ring and the liner is only a few microns, the middle part of the ring surface will be worn off by the large particles on the cylinder surface, and the ring surface will become flat, as shown in Fig. 2.

When the hardness values of the liner and of the ring are comparable, abrasive particles may dramatically increase the normal rubbing wear. Senholzi [12] suggested a mechanism in which abrasive particles roll between the two surfaces causing high local stresses and generating extensive normal rubbing wear. This will affect both piston rings and cylinder sleeve.

Fodor [1], in an extensive study aimed at improving IC engine life, discussed the effect of air filtration on piston ring wear. His results are presented in Fig. 3. This figure shows the wear rate under normal conditions (test run no. 4) compared with abrasive wear conditions at dust concentrations of 3 mg m^{-3} (test run no. 5) and 30 mg m^{-3} (test run no. 6). Under normal conditions dust concentration in the air intake did not exceed 0.01 mg m^{-3}. The catastrophic effect of abrasives (three-body wear) is apparent in run no. 6. Notwithstanding the difference in concentration between test runs 5 and 6, it is apparent that by decreasing the air filter efficiency* from 99.9% (run no. 5) to 98% (run no. 6), the amount of wear in the piston ring was increased fourfold. Kapuvary and Fodor [13] tested three types of air filters

*The efficiency of a filter is defined as its ability to retain dust passing through it. According to British Standards (BS 1701) the filter efficiency may be defined as the ratio of the weight of dust retained by the filter during a test to the weight of the dust fed to the filter.

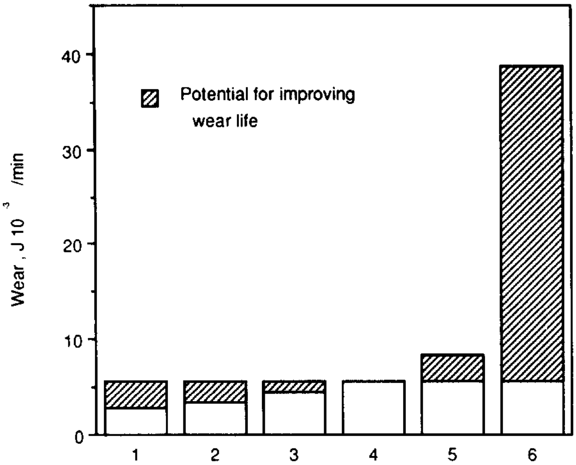


Fig. 3. Wear of cast-iron piston ring for 100000 km running period: 1, structural material quality; 2, lubricant oil quality; 3, fuel quality; 4, normal wear; 5, abrasive wear: air filtration, 99.9%; dust concentration, 0.003 g m^{-3}; 6, abrasive wear: air filtration, 98%; dust concentration, 0.03 g m^{-3} [1].

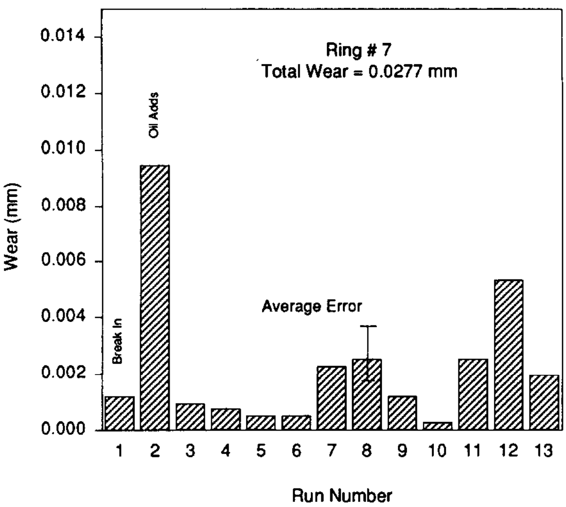


Fig. 4. Ring test results by Jones *et al.* [8]: run 10, 80 gm added dust, with air filter; run 11, 8 gm added dust, no air filter; run 12, particle size 0–5 μm; run 13, particle size 0–40 μm.

and obtained similar results. In general, filtration affects the dust concentration in the intake as well as the particle size of dust passing into the engine.

Jones *et al.* [8] studied the effect of increasing the concentration of dust in the inlet manifold. Their results are shown in Fig. 4. It is clear that when the dust concentration was increased from 0.1 g per manifold (run no. 5) to 0.8 g per manifold (run no. 8) the amount of piston ring wear also increased. This observation is corroborated by the work of Baczewski and Jaroszczyk [10]. The results of their experiments indicate that the abrasive wear increases with increasing concentration of contaminants in the air, as shown in Fig. 5. This effect has also been indicated by Dahl and Rhodes [14] and by Kapuvary and Fodor [13]. Jones *et al.* [8] also showed that when an air filter was installed the ring wear was markedly reduced. In Fig. 4, run no. 10, in which 80 g of dust was added with an air filter, may be compared with run no. 11, in which 8 g of dust was added without an air filter. It is clear that 80 g of dust with an air filter in place produced much less wear than 8 g without an air filter.

According to Fodor [1], the particle size which has the maximum wear effect on piston rings is 15 μm. However, Jones *et al.* [8] reported an opposite trend in the effect of dust particle size, showing that 0–5 μm dust produced more wear than 0–40 μm dust. This is illustrated in Fig. 4 where the two relevant runs are no. 12 for a particle size of 0–5 μm and no. 13 for a particle size of 0–40 μm.

The effect of particle size was also discussed in detail by Baczewski and Jaroszczyk [10]. They stated that the maximum wear in the top compression ring is caused by particles of sizes from 30 to 35 μm (Fig. 6). This conclusion contradicts the findings of Jones *et al.* [8] but it is in line with Fodor's findings [1]. They also mention that all the results given in the literature, independently of engine type and method of test, show that the wear in engine parts increases with increasing particle size and that maximal wear appears for different ranges of particle dimensions.

According to the reports in the literature, there appears to be a disagreement on the particle size which causes maximum wear. While the trends reported by Baczewski and Jaroszczyk [10] show a clear peak for the wear

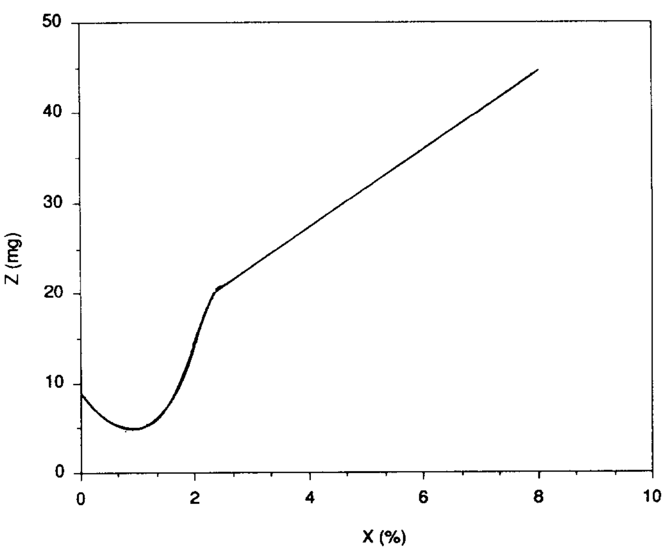


Fig. 5. The wear dependence (abrasive wear) *vs.* concentration of contaminants [10].

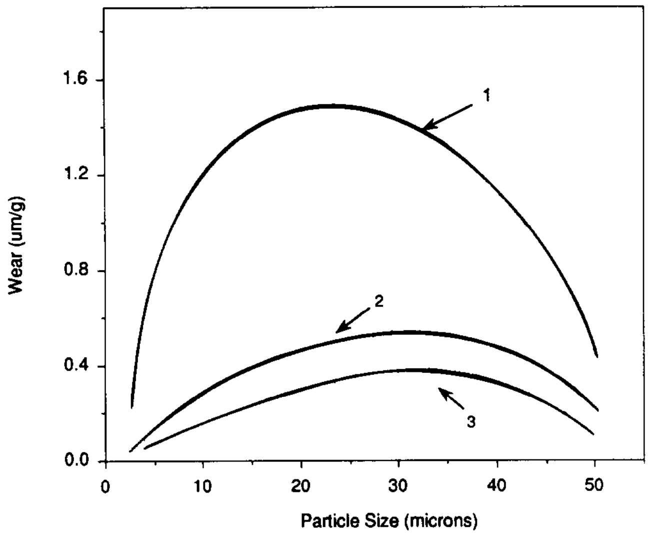


Fig. 6. Individual wear of engine elements as a function of abrasive particle size: 1, cylinder sleeve; 2, bearings; 3, piston [10].

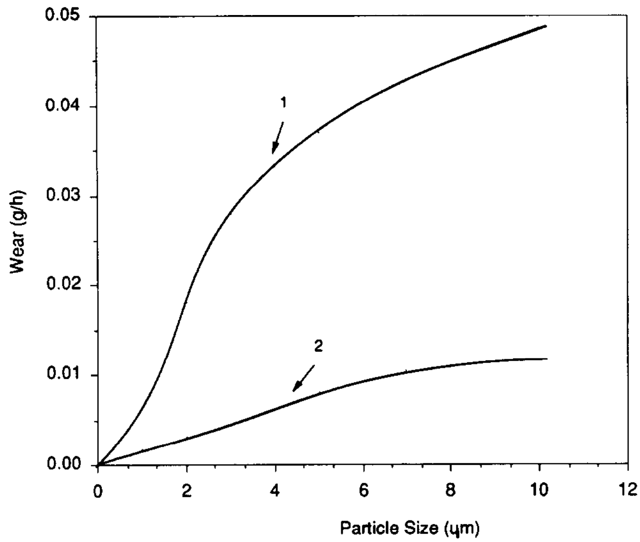


Fig. 7. Effect of different sizes of mineral particles on the wear of piston rings using 1, corundum; 2, silica [10].

rate, it is difficult to reconcile their findings with those reported by other investigators.

The type of dust, or more precisely its hardness, has a major effect on piston ring wear. Baczewski and Jaroszczyk [10] reported on the influence of the type and particle size distribution of dust on the wear of piston rings, as shown in Fig. 7. They concluded that when the hardness of the particles increased from 7, for silica, to 9, on Mohs' scale, for corundum, the wear in the piston ring increased by 300%–400%. However, in the absence of data on different values of particle hardness, and considering that Mohs' scale is not linear, it is difficult to generalize from these findings. Further experiments will be required to establish the effect of dust type and hardness.

4. Cylinder sleeve (liner) wear

Astashkevich [15] stated that abrasive particles which are introduced in the friction zone, sand dust being one source, initiate wear by microseizure of unhardened surfaces. He also reported the effect of air filtration on cylinder liner wear caused by the passage of mineral abrasive particles which are present in the air, when they are larger than the minimal film thickness.

Evidence of this microseizure is provided by operating experience using engines which were run in a very dusty atmosphere during accelerated rig laboratory testing (Astashkevich [16]).

Larin and Astashkevich [17] made tests on a friction machine with reciprocating motion imitating the operation of engine cylinder components, with a pressure of 77 kgf cm^{-2} and a sliding speed of 3 m s^{-1} using heavy duty diesel oil. They showed that the addition to the lubricant of finely divided abrasive powder, with a particle size of about 5 μm, intensifies seizure and reduces the load-carrying capacity of frictional pairs and their resistance to scoring.

On both surfaces micro-investigations revealed large regions of metallic interaction and also roughness with greater dimensions than those of the abrasive particles introduced into the lubricant. Therefore wear products in the form of unoxidized over-work-hardened solid metal particles can, under certain conditions, be active abrasives which move between the frictional surfaces and do not always decrease in size, as mineral abrasives do, but can interact with the metal surface and grow many times, with destructive effects. This was observed during the operation of chromium-plated cylinder liners with aluminium alloy pistons (Larin and Astashkevich [17]).

Tarnok [2] made a more exact study of the effect on the cylinder wear of improving the air filtration. His results are given in Fig. 8 and show that the cylinder failure rate is decreased with improved air filtration, *i.e.* particle size and concentration. It is also shown in this figure that the reduction in the frequency of cylinder sleeve failure is greater than that of the bearings. This is because the cylinders are affected directly by dust particles; so increasing the filter efficiency will decrease the amount of dust as well as the size of particle passing to the engine, causing a reduction in the frequency of failure. This is also borne out clearly by the results of Baczewski and Jaroszczyk [10]. Figure 6 suggests that the most severely affected component of the engine (by dust particles) is the cylinder sleeve. It also shows that the greatest degree of wear is caused by dust particles ranging in size from 20 to 25 μm.

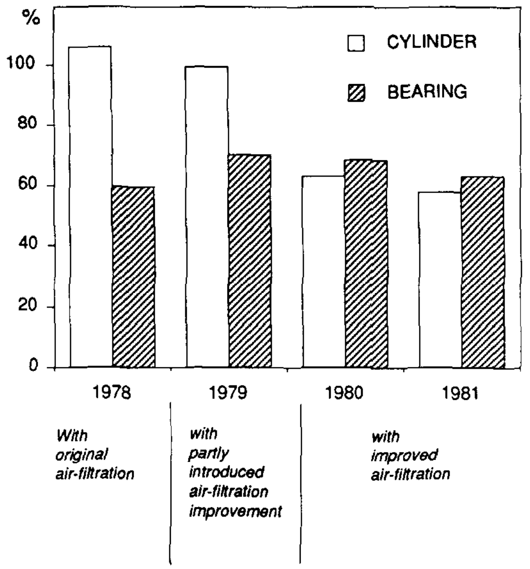


Fig. 8. The reduction of bearing and cylinder failures with improved air filtration [2].

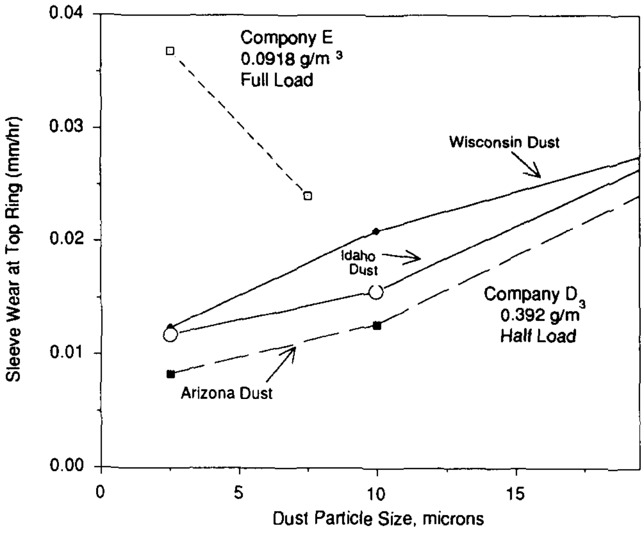


Fig. 9. Damage on the piston ring sleeve as particle size increased with various dust types [14].

The abrasive dust particle size has a major effect on the wear rate of the ring sleeve, which affects the performance of the engine. Dahl and Rhodes [14] showed that the damage to the sleeve increased, in general, with increased particle size and dust concentration as reproduced in Fig. 9. These two factors are affected directly by the air filter efficiency. They also showed that the amount of piston ring wear varies with the type of dust, *i.e.* the hardness of the dust particles. The results given by Dahl and Rhodes [14] indicate a continuous increase in wear rate for various types of dust, without any tendency to a peak, up to 20 μm in size. This contradicts later results by Baczewski and Jaroszczyk [10].

The effect of the hardness on the wear rate of the cylinder sleeve is also important. Fodor [1] showed, in his experiments on engine wear, that the wear characteristics of the cylinder can be improved by increasing the hardness of the cylinder sleeve. His results are shown in Fig. 3, run no. 1, where increasing the cylinder hardness from 250 to 450 HB appears to cause a proportionate reduction in the wear rate.

5. Bearing wear

Journal bearings including those of the connecting rods, camshaft and crankshaft are affected by dust particles. Dust particles which enter through the intake manifold do not affect the bearings directly (since most engine bearing parts are lubricated). However, some dust in the cylinders infiltrates into the lubricating oil and is carried away from the combustion region. Once this occurs the dust remains mixed with the lubricant in the oil lubrication cycle unless it is filtered by the oil filter.

The mechanism of abrasive wear of bearings caused by dust particles is explained in detail by Senholzi [12]. He considered the mechanism of cutting wear. This occurs when one surface is significantly harder than the other, which is the case in journal bearings. The hard contaminant particles, which get into the clearance between the journal and the bearing, are pressed by the harder surface into softer surface. The soft surface then holds each abrasive particle in such a way that it behaves very much like a lathe tool and cuts away the harder surface. The cutting wear particles, which are generated, themselves look exactly like miniature pieces of lathe turnings, their length and thickness being determined by the size of the contaminant particles and the wearing surface material. This type of wear may also be observed in the final stage of machine failure without the presence of abrasive particles. If a hard wear surface has roughened (for many reasons such as surface fatigue and pitting) then the resulting hard sharp edges may generate cutting wear against the softer surface. For instance, a fractured element in a rolling contact bearing may generate cutting wear from the softer separator.

Jones *et al.* [8] did some experiments on wear in the connecting rod bearings. They studied the rate of wear on bearings by direct injection of dust into the oil. Their results are shown in Fig. 10, in which run no. 3 was with 0.8 g added dust, and run no. 6 was with 2.4 g added dust, both without an oil filter. The corresponding increase in wear was fivefold. It was shown that as the amount and the particle size increased (meaning low air filter efficiency and thus higher dust concentration), the wear rate increased on the connecting rod bearings.

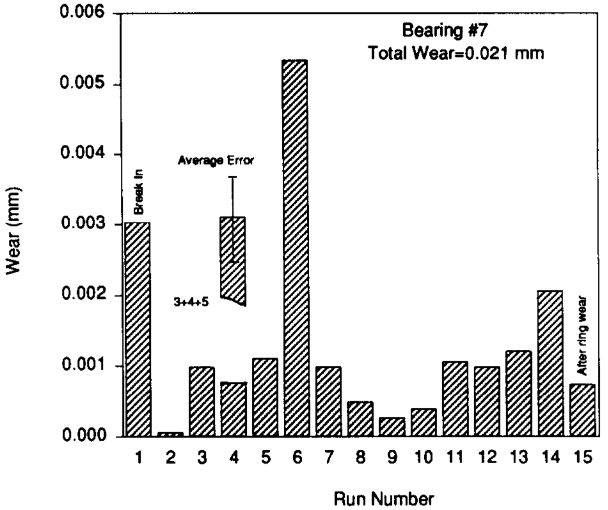


Fig. 10. Bearing test results [8] for several engine runs: run 3, 0.8 g, no oil filter; run 6, 2.4 g, no oil filter; run 8, 2.4 g, oil filter A; run 9, 2.4 g, oil filter B.

Particle size has a major effect on the wear of engine bearings. Baczewski and Jaroszczyk [10] studied the effect of dust particle size on the bearing wear rate. Their results are shown in Fig. 6. They mentioned that the most severe wear in the bearings they used was caused by particles with sizes in the range from 10 to 35 μm, and the peak occurred at 30 μm. Fodor [1] obtained results in the same range, although his experiments showed that a dust particle size of 15 μm gave the maximum bearing wear rate. This is half the size determined by Baczewski and Jaroszczyk [10].

Jones *et al.* [8] noted that the wear rate in connecting rod bearings is also affected by the bearing location. In Fig. 11, connecting rod bearings in two different locations are compared. The results for the initial average wear show that the bearing closest to the return line from the dust addition chamber, bearing no. 7, experienced twice the total wear compared with the farthest bearing, no. 1. The difference in the wear rate is due to the difference in the amounts of dust reaching the bearings.

The effect of air filtration efficiency (dust concentration and particle size) and improvement represented by a decrease in the number of bearing failures was discussed by Tarnok [2]. His results, shown in Fig. 8, indicate no significant decrease in bearing failure through improving the air filtration. This is because dust particles reaching the engine bearings must pass through two types of filters. The first is the air filter, and the second is the oil filter. It may also be suggested that the lower wear rate in engine bearings caused by dust is because the bearings have a high degree of hardness relative to any dust particles. Jones *et al.* [8] studied the same factor but from another point of view. They studied the effect of oil filtration on bearing wear rate and proved that the installation of an oil filter reduces the wear rate significantly. Among the results of their experiment, shown in Fig. 10, is a comparison

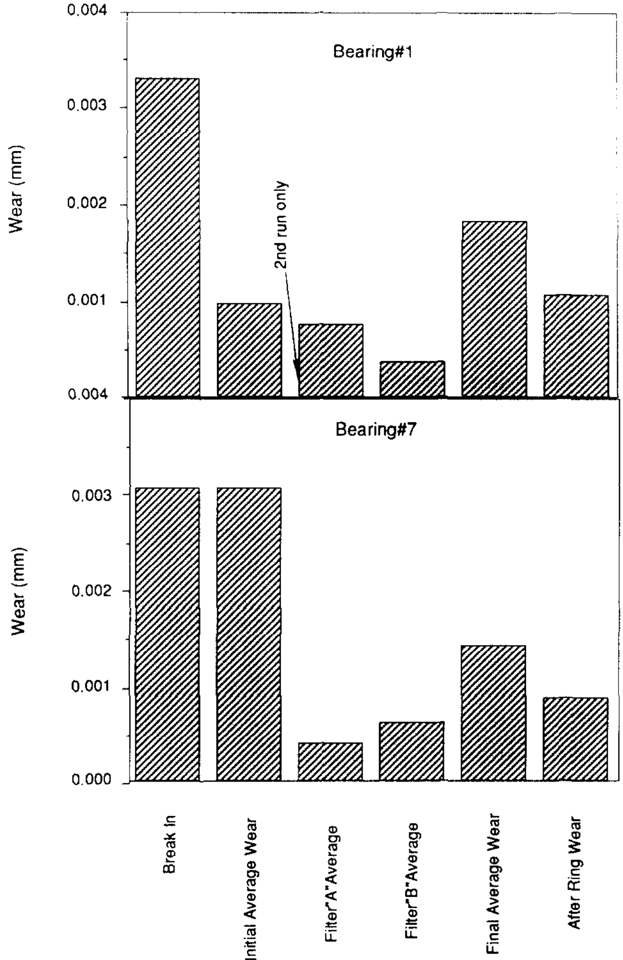


Fig. 11. Summary of different wear rates in the connecting rod bearings [8].

between the effects of 2.4 g dust added without an oil filter (6), 2.4 g dust added with an oil filter of type A (8) and the addition of 2.4 g dust with an oil filter of type B (9). The addition of an oil filter resulted in a reduction in wear of at least one order of magnitude. A comparison of the results presented by Jones *et al.* [8] for bearings (Fig. 10) and piston rings (Fig. 4) indicates that bearings wear less than rings. This observation is contrary to the results by Baczewski and Jaroszczyk [10] who showed that an engine bearing has a higher wear rate than a piston ring (Fig. 6) over the entire range of particle size.

From these results one can conclude that installing an oil filter will decrease the rate of wear in a bearing. Increasing the oil filter efficiency can also reduce the wear rate.

TABLE 1

The effect of the cleanliness of the oil on engine wear [18]

Serial number	Oil filtration quality and friction-decreasing additive	Dust load (g cycle^{-1})[c]	Oil contamination		Average friction pressure (kPa)	Wear of Fe (g cycle^{-1})
			wt.%	ISO code number[d]		
1	SF–SSF	–	0.003	26/24	170.5	0.0843
2	SF–SSF–CMOC[a]	–	0.003	27/22	167.5	0.0738
3	SF–SSF–CMOC	1.25	0.0025	26/22	167.3	0.0954
4	SF–SSF–CMOC	1.25	0.0025	25/22	166.8	0.1235
5	SF–CMOC	2.50	0.005	25/23	168.2	0.5307
6	normal–CMOC	5.0	0.016	27/25	171.8	1.7493
7	normal–CMOC	10.0	0.016	27/25	171.8	1.8097
8	SF–SSF–CMOC[b]	–	0.003	26/22	162.5	0.0683

[a]First addition of CMOC.

[b]Second addition of CMOC.

[c]The cycle refers to 2 h engine test duration; 1.25 g of ACFTD load was fed into the oil; repeat of the above after 2 h etc.

[d]ISO code refers to international standard (*e.g.* 26/24 refers to the ratio of the number of particles ml^{-1} over 5 μm in size to the number of particles ml^{-1} over 15 μm in size; category number 26 above refers to the count up to 640000 particles ml^{-1} and 24 refers to the count up to 160000 particles ml^{-1}).

6. Engine protection

In the previous sections the mechanisms of wear and the effects of various dust variables on wear are reviewed for different engine components. All methods of engine protection and extension of service life imply control of the dust intake in order to minimize the concentration, size and hardness of the dust particles reaching the sliding interfaces in critical components. To achieve this both air and oil filtration are used, and constitute the primary methods for engine protection. However, since the presence of dust in these areas cannot in practice be entirely eliminated, other measures which enhance the resistance of the materials to normal and abrasive wear, or ameliorate the interaction effects, are also desirable.

One of the measures which reduce the engine wear is the use of oil and fuel additives. Fodor and Ling [18] introduced new friction reduction additives. Their results, shown in Table 1, indicate that upon first adding the chelate–metal organic compound (CMOC) to the oil the average friction pressure decreased from 170.5 to 167.5 kPa, and upon a second addition, to 162.5 kPa. The friction pressure is the cylinder pressure equivalent to friction losses. In these experiments it was measured, in an engine operated without combustion, by means of a weight balance. Tarnok [2] also reported on a new type of friction-decreasing additive which was applied in his field experiments on buses; the fuel saving was 3%–4%. Astashkevich [15] detailed the properties required of additives for use in heavy diesel engines. He stated that the additives should be multifunctional for both fuel and oil and should reduce deposit formation, have low ash content, be effective antioxidants and increase the strength and the separation capacity of the lubricant films.

Filtration methods and their expected impact on engine life will now be discussed.

7. Air filtration

The most effective way to diminish the friction and wear losses caused by dust contaminants and wear particles is filtration. Filtration of air and fuel serves to reduce the quantity of contaminants entering the system from the environment. However, some dust particles will still enter the engine, since filtration will not provide complete protection under domestic climatic conditions, as stated by Kapuvary and Fodor [13].

Fodor [6], in his study of engine wear using γ-ray spectroscopy, discussed the effect of air filtration on engine life. In his study, three different types of engines were used, with different degrees of air filtration efficiency. These engines were of a truck, a bus and a farm tractor. The truck engine had an air filtration efficiency of 98% whereas the bus and the agricultural tractor filters each had an efficiency of 99.99%. His results are shown in Fig. 12 for the three different engines. The iron content in the wear debris, which represents the structural material, was about 30% of the total filter ash.

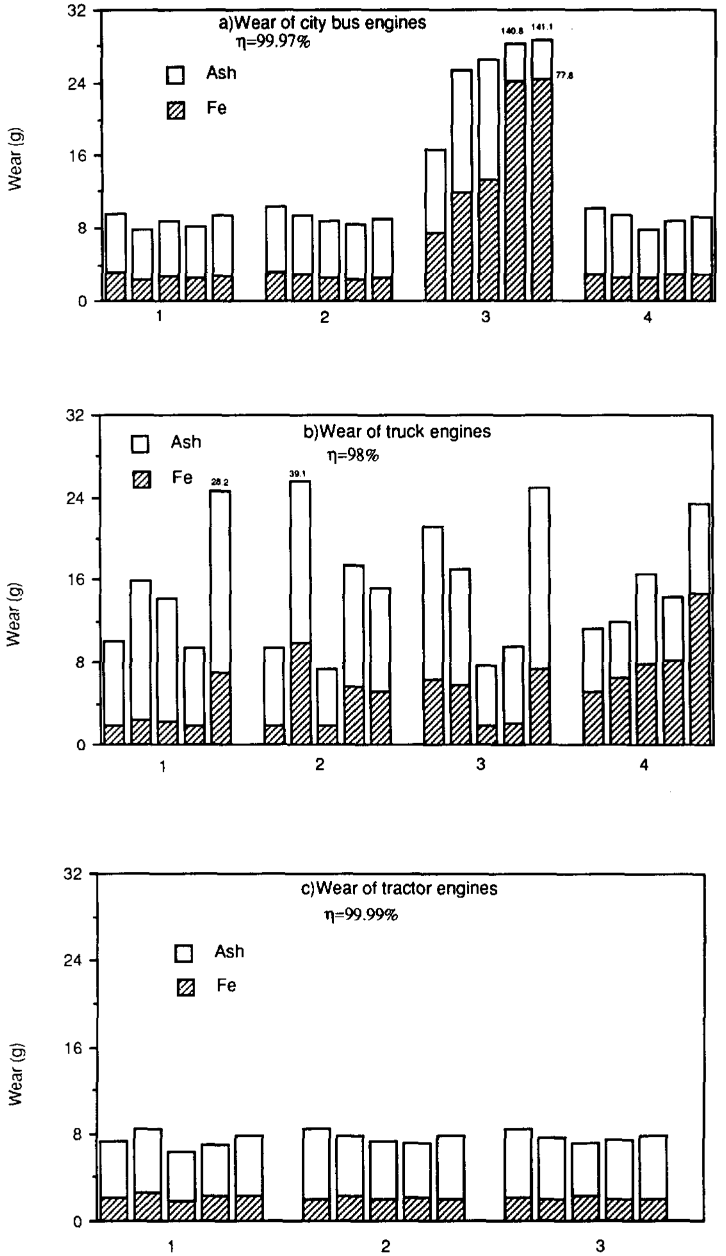


Fig. 12. Wear in three different types of engines [6].

Fodor concluded that the amount of wear is related to the concentration of the dust particles. It should be noted that truck engines with lower filtration efficiency exhibit greater wear than either bus or tractor engines with higher filtration efficiency. The considerable variability in the results may have been caused by unsatisfactory filtration.

Fodor later [1] considered that the air filter specification needed to provide a minimum quality of air entering the engine should reduce the dust concentration to below 10^{-5} g m^{-3}. He found that in agricultural operation the air filter efficiency must be 99.9% for a dust concentration* of 0.X g m^{-3}. For other types of use where the resulting concentration* is 0.0X g m^{-3} the air filter efficiency would have to be 99.99%. However, for a dust concentration of 1–2 g m^{-3} (as found in a desert), an air filtering efficiency of 99.999% is required. In view of these specifications, Fodor [1] decided to develop a new air filter, on the premise that the ability of an air filter to maintain the required air quality of 10^{-5} g m^{-3} depends not only on its quality but also on the dust concentration in the environment. He proved, using a test of sufficient sensitivity, that multiphased air filters where the last stage had a deep microporous structure operated well and the efficiency of the system could be improved by decreasing the air speed. The specified efficiency for the newly developed air filter was 99.99%, compared with 98.5% for the original one. This increased the potential actual lifetime of the engine from 60% to 95% of that of an engine subjected only to normal wear. Figure 13 illustrates the decrease and stabilization of wear brought about by this air filtration system. The bars show the quantity of impurities and wear particles collected in the oil filter in a 10 000 km running period. The upper part of each bar gives the quantity of impurities while the lower

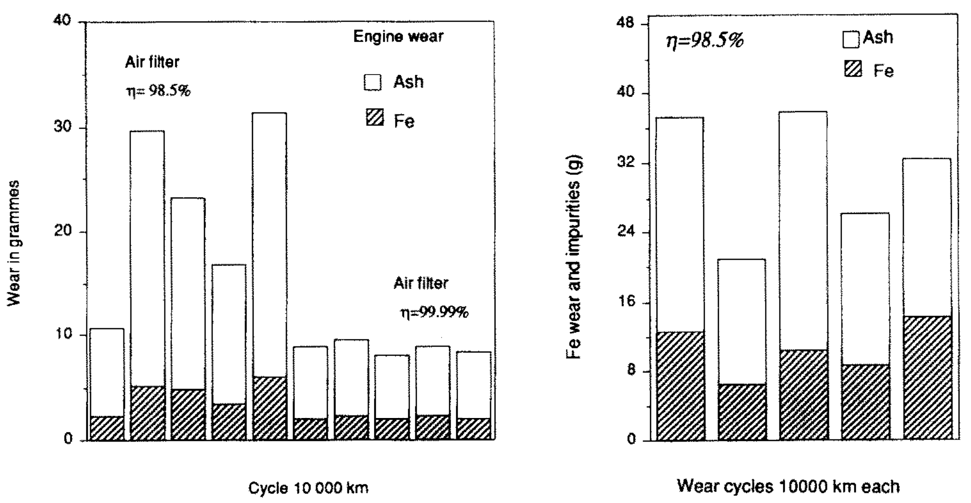


Fig. 13. Wear in the engine with the newly developed air inlet system [1].

Fig. 14. Wear in city bus engine with original air filtration [2].

*The dust concentration is measured here in tenths of a gram per cubic metre, which is expressed as 0. X g m^{-3}. A dust concentration of 0.0X g m^{-3} is an order of magnitude lower than that found in agricultural operation. In a desert environment, the concentration is higher and is measured in X g m^{-3}.

part shows the amount of wear. The figure also suggests that, when using an air filter of the original type, any change in dust concentration (climatic conditions) during the running period will influence the engine wear, whereas with the new air filter installed, *i.e.* with higher filtration efficiency, the engine can fully eliminate this climatic influence since the wear rates remain at about the same low value.

Fodor and Ling [18] studied the effect of air contaminants on the wear of a 6-cylinder diesel engine. Their results are reproduced in Table 1 which shows the effect of different air contaminants on engine wear. In this table, run no. 9, with a dust load of 1.25 g cycle^{-1}, had a lower wear rate than that in run no.10, with 2.5 g cycle^{-1} under the same conditions.

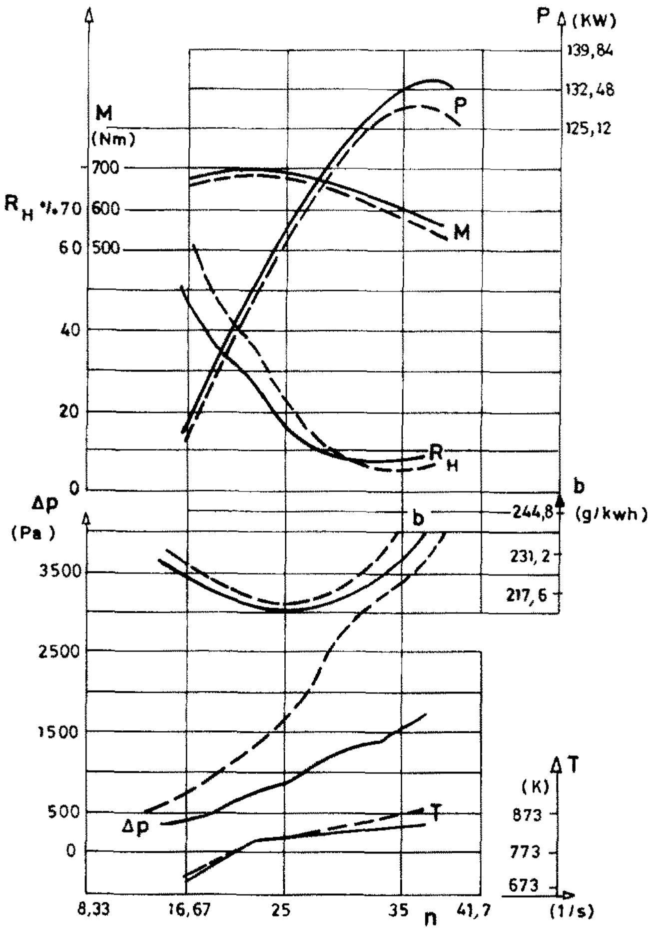
Tarnok's [2] results on ten bus engines, which were obtained under real-life conditions, are shown in Fig. 14. In these tests, the air filtration efficiency was 98%. His results suggest that this air filter efficiency is insufficient for the high dust concentration of the sites. The results shown in this figure also indicate that the quantities of contaminant material are variable. Moreover, the quantities of iron are increased in parallel with the increase in the quantity of ash. Thus he emphasized that a great improvement in air filtration efficiency is necessary in order fully to avoid the wear caused by the dust particles.

Tarnok [2] therefore designed a new multiphased air filter, with a paper filter cartridge. The new air filter had a mesh size of 10 μm in order to catch all particles over 10 μm in size. This value accounts for 90% of the dust particles entering the engine with the air, according to Baczewski and Jaroszczyk [10]. The results for the new air filter are shown in Fig. 15. The power output, the specific fuel consumption and the smoke properties of the engine were all improved by means of the newly developed air filter.

The field experiments were repeated using buses equipped with the air filters developed by Tarnok [2]. The field results are shown in Fig. 16 for one of the ten bus engines. From this figure, the quantity of iron wear is less than in the previous experiments and so is the quantity of the contaminant material (ash) which originates from the air, the fuel and the fresh oil. It was concluded that by better control of the air contaminants, using a very effective air filter, the contamination of the engine could be stabilized at lower levels.

8. Oil filtration

Fodor [19] in his experiments aimed at increasing engine life, found that particles of silica 10–20 μm in size (the main component of dust) cause the most severe wear. He also found that the oil filters used in IC engines are generally designed for particles 15–30 μm in size. To resolve this apparent conflict, Tarnok [2] designed a filter which he called a "superfine" – SF – oil filter, with a filtration fineness below 10 μm. With this it seemed possible to avoid the excess wear caused by particles larger than 10 μm. His results are shown in Fig. 17 which refers to the new oil filter, in comparison



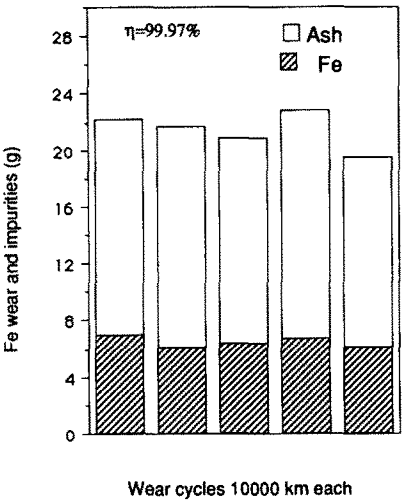
——— improved air filter
– – – – original air filter

P	output of the engine
M	moment
R_H	fume in Hardridge scale
b	fuel consumption
Δp	restriction of the air filter
T	temperature of the exhaust gases
n	revolutions of the engine

Fig. 15. Engine characteristics from test bench test showing the influence of improved air filtration [2].

with the results in Fig. 16 which reflect only air filtration improvement. The improvement achieved by better oil filtration is self-evident.

It should be noted that oil filtration also affects cylinder sleeve wear in a positive way. Pocock [20] showed that as the oil filter rating increased the cylinder wear decreased, thus increasing the engine life (Fig. 18). What



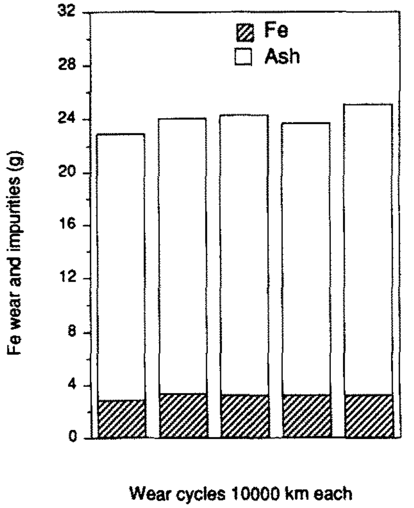


Fig. 16. Wear in city bus engine after air filtration improvement [2].

Fig. 17. Wear in city bus engine after air and oil filtration improvement [2].

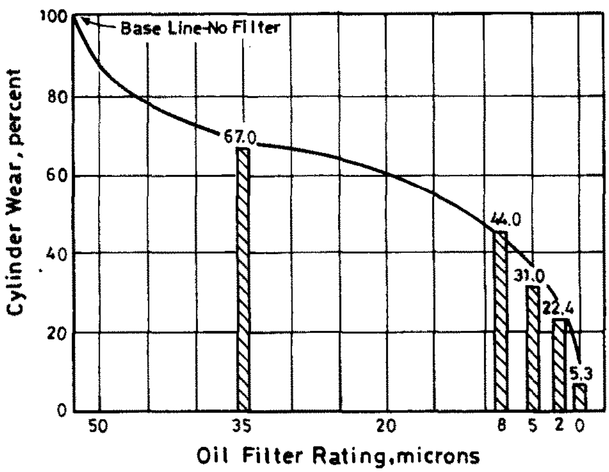


Fig. 18. Effect of lube oil filtering efficiency on the abrasive wear rate of the cylinder. [20].

is important in his study is that the abrasive particles below 10 μm in size cause about 44% of the wear on the cylinder. Therefore, in order to protect the engine from this type of wear, it is not only necessary to utilize an oil filter which filters out the 10 μm contaminants but perhaps a much finer filter should be sought, for further improvement. It is worth noting that, among all the critical components, the cylinder suffers the most severe wear.

Fodor [6] found that about 70% of the foreign material (not structural material) filtered from the lubricant oil is SiO_2. He stated that no further reduction in the quantity of foreign particles entering the oil is possible by

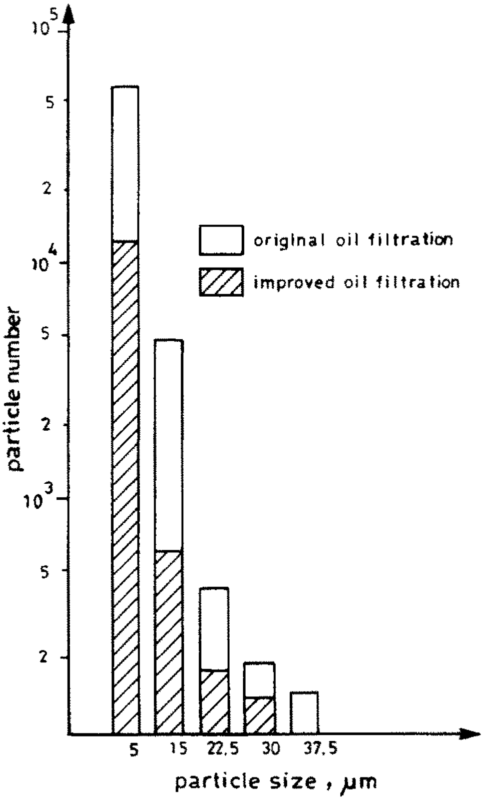


Fig. 19. Size distribution of solid particles in used oil [21].

means of air filtration. Thus the only way of removing the abrasive particles from the lubricating oil as fast as possible is by improving the oil filtering system. In another study, Fodor [1] analysed several thousand samples taken from vehicles belonging to transport companies, and the impurity level in the used oil was generally found to be 0.00*X* g ash per 100 ml of oil* when centrifugal filtering or paper cartridge filters with 96%–98% efficiency were used.

A new oil filter was produced by Fodor and Kolimar [21] in order to provide the engine with better protection from abrasive wear. Their results are shown in Fig. 19 for two types of oil filters. The first one is an original paper filter and the other is an improved oil filter with a centrifugal filtering system. Comparing the two types, it is evident that by improving the oil filtering efficiency the contaminant level in the lubricating oil could be reduced by 30%–60%.

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*The quantity of foreign material in used oil may be measured in milligrams per decilitre (100 ml), and this is expressed as 0.00*X* g per 100 ml or alternatively as *X* mg per 100 ml, the 100 ml being a standard sample volume.

TABLE 2

The effect of air-borne contaminants on engine wear [18]

Serial number	Oil filtration quality and friction-decreasing additive	Dust load (air filtration quality) (g cycle^{-1})	Average friction pressure (kPa)	Wear of Fe (g cycle^{-1})
9	SF–SSF–CMOC	1.25	162.8	0.0832
10	SF–SSF–CMOC	2.5	164	0.5213
11	SF–CMOC	5.0	165	1.0097
12	normal–CMOC	10.0[a]	166	3.0474
13	normal–CMOC	20.0[a]	170	5.9537
14	normal–CMOC	40.0[a]	179.6	10.1387
15	SF–CMOC	–	164.5	1.1354

[a]Air filtration efficiency $\eta = 98.5\%$ (oil bath air filtration).

Fodor and Ling [18] studied three types of oil filtration and their effect on engine wear. All the oil used in their experiments was of API-CB quality. They compared normal filters with superfine oil filtration (SF) and with superfine bypass oil filtration (SSF). The results are reproduced in Table 2 for 8 different runs and with different dust concentrations. In this table, it is shown that the contamination level of the oil decreased, because of the improved quality of the oil filtration, from 0.016% to 0.005% when SF oil filtration was used, and to 0.0025% with SSF filtration.

9. Conclusions

The following conclusions may be drawn from the foregoing review and analysis.

(1) Dust concentration, particle size and type (hardness of particles) affect the wear rate of all critical engine components. Dust concentration appears to have a greater effect on cylinder sleeves and piston rings than on lubricated bearings.

(2) The critical dust particle size for piston rings appears to be different from that for cylinder sleeves and bearings. However, no conclusive argument can be made concerning this effect owing to the wide variability in the findings of the various investigators.

(3) The data available on the effect of the type of dust (hardness of particles) are few, inconclusive and limited to piston ring wear.

(4) Air filtration can be used to good effect in controlling the dust infiltration into the engine. The efficiency of the filter has a significant effect on the wear rate and it is recommended that filters with the highest available efficiency be used. Better-designed air filters can further reduce wear and failure incidents, and hence improve the economics of IC engines operating in dusty environments.

(5) The quality of oil filtration not only affects the wear of bearings but also of the cylinder sleeve. Since the sleeve wear is of the order of three times that of the bearings and piston rings, it is critical to any improvement in the wear resistance of an engine.

(6) Fine dust (less than 10 μm in size) contributes a little less than 50% to the cylinder sleeve wear. Thus a lower pass rate for the oil filter may prove effective in improving wear resistance. New filter designs for both air and oil have been developed with a pass size of 10 μm.

(7) The distribution of dust particle size is area specific and affects the amount of dust reaching the combustion chamber of an engine. The amount of dust remaining in the system (not discharged with exhaust gases) is somewhat uncertain, but is perhaps of the order of one tenth of the infiltrating dust.

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