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ANALYSIS OF DAMAGE OF THE COOLING AGGREGATE IN VEHICLE WITH COLD STORAGE CHAMBER

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Abstract

Vehicles with cold storage chambers realize the transport of fast spoil articles. The cooling system of such chamber is its critical subsystem, the essential component of which is a cooling aggregate driven by vehicle combustion engine via belt transmission. The main assembly of the analysed aggregate was the axial five-piston compressor. Small aluminum pistons were led in cylinders in fixed head made of aluminum alloy. Such pistons were driven through steel tappets, mating through their spherical surfaces with spherical seats made in small pistons. Through their front surfaces, placed opposite to the spherical surfaces, the spatial disc cam made of aluminum alloy drove small pistons. The cam was mounted on the steel shaft. The co-operation of described parts was in presence of refrigerant oil. The abrasive and fatigue wear of elements occurred. Because of long-term utilizing of the aggregate the damage of radial sealing ring occurred. Then, external impurities of high hardness got into the contact zone between the mating surfaces. The main aim of the study was to analyse consequences of such fact. The failure was noticed in the form of wear of disc cam, front surfaces of tappets, and the plastic deformation in the spherical surfaces of the seats. Then, due to deformation and the displacements of the rotating shaft, wear of the side surface of disc cam during contacts with small pistons surfaces took place. Moreover, we noticed wear of the side surfaces of the pistons and the cylinders mating with them in the fixed head. In the article, we present figures of damaged surfaces of elements and results of the SEM analysis of spherical surfaces of tappets. The material transfer occurred between the spherical surfaces of tappets and their seats.

Keywords: *cooling aggregate, combustion engine, sealing ring damage, failure, blurring*

1. Introduction

The transport of many fast spoil articles (example eatables) need to be realized under the steady lowered temperature of environment. In practice, the special vehicles with a cold storage realize it. The cooling system of the vehicle with a cold storage is its critical subsystem. The essential component of this system is the cooling aggregate driven by the vehicle combustion engine via the belt transmission. There are also other configurations, where cooling aggregate is driven by a separate electric, or combustion engine. Loading, rotatory speed, working cycle of a combustion engine driving the vehicle determines operational conditions of the cooling aggregate. Because of long-term utilization of the aggregate the damage of radial sealing rings can occur, as was in the case described in the article. Then, external impurities of high hardness got into the contact zone between the mating surfaces. The main aim of the study was to analyse consequences of such fact.

1.1. Aggregates used in air conditioning systems or vehicle refrigerator devices

Today, there are some manufacturers of modern high-quality air conditioning systems and cooling aggregates used, i.e. in cars and vehicles with cold storage chambers.

Drabpol, representing the Konvekta [1] brand in Poland, offers cooling 12 V electric aggregates FK 1120-E for vans. The refrigeration device is powered from the vehicle battery. The latest novelty is a two-chamber aggregate, with a narrow evaporator and a flat condenser. The parking cooling option has been integrated in the outdoor unit [2].

The Thermo King Company offers the platform of SLXi semi-trailer units [3]. These single- or multi-temperature devices are the result of long-term research, consultations with transport companies and analysis of data from aggregates tested under various conditions.

According to [4] Carrier Transicold released the smallest chiller on the market Basic 700, which is a very quiet thanks to the power supply from the car's electrical system. It works with the use of ecological refrigerant R134a and is normally equipped with hot gas defrosting. The next popular refrigeration unit is the Zephyr 540, driven from the vehicle's engine. It works with the use of ecological refrigerant R134a.

Carrier Transicold has also produced a modern Xarios series of refrigeration units powered by the vehicle engine. These automotive chillers are equipped with the mi-cochlear control and super flat evaporators. The aggregates use ecological refrigerant R404a. The aggregate option includes hot gas heating, power supply from the mains, installation on the roof of the vehicle, cooling installation-opening sensor. Carrier Transicold also produced the Supra series of self-propelled chillers. The aggregates use ecological refrigerant R404a. These chillers with drive from the CE engine are used in delivery vans.

Carrier Transicold has also released the Maxima series of trailer units driven by CE unit engines.

According to [5] Zanotti offers a series Z of aggregates refrigeration equipment for vans with direct drive from the vehicle's engine. They can be retrofitted with the hot gas option. When the compressor cannot be mounted in the engine compartment, Zanotti offers aggregates called alternator. These compressors drive the compressor using an electric motor powered by 12 V from the car's electrical system (an alternator with a minimum power of 90 A is required for efficient operation). The above models can be equipped with 230 V power supply and heating with hot gas. Another Zanotti solution is aggregates with a condenser design allowing installation in the engine compartment or under the floor of the vehicle. Direct drive, no condenser on the roof, no interference with the roof structure, high cooling and ventilation capacity and the option of heating with hot gas are the characteristics of the aggregates used in panel vans.

Other aggregates of Cooljet series offered by the Kerstner can have a drive from a compressor installed in the vehicle's engine or from an alternator. They can be optionally equipped with 230 V stationary drive or heating option. An additional battery can temporarily power the electric aggregates, when the vehicle's engine is turned off.

The Eberspaecher Company offers two cooling solutions. The traditional refrigeration unit Frosty 700 with electric drive is available in two versions. Power supply is only from the 12 V car and with power from the car installation and at the standstill from the 230 V socket. A completely different solution proposed by this Company is refrigerators. The system under the name Coolbox is a replaceable refrigeration box with its own unit. They can be powered by 12, 24 and 230 V. This system does not require a car to be processed and can be used as a cold storage for temporary use.

1.2. The operation of a compressor refrigeration system

According to [6], the operation of a compressor refrigeration system is based on the compressor sucking in the refrigerant vapours that leave the evaporator. Compressing the vapours causes their pressure and temperature to increase. The obtained vapours are directed to the oil separator, where oil is separated from the refrigerant. The vapours then pass to the condenser in which condensation occurs at constant pressure and temperature due to cooling with air or water. The condensed medium flows to the throttling valve. This valve expands the refrigerant entering the evaporator. In the evaporator, because of the heat being removed from the cooled medium, evaporation occurs at constant pressure and temperature.

In many systems, hermetic compressors are used. The sucked gas enters the compressor through a suction port located in the lower part of the housing. The gas, flowing over the electric motor, additionally causes its cooling. Usually, the oil drops are separated from the sucked gas and flow into the oil sump. After passing through the engine, the refrigerant goes to the mechanical elements where it is compressed. The compressed refrigerant is forced through the discharge port.

The operation of the refrigeration system is based on the circulation of the refrigerant between the elements of the refrigeration cycle. Due to different pressures and temperatures, the refrigerant in the system occurs in various phases. In addition, the refrigerant travels at different speeds. In the refrigeration systems, the compressor oil is entrained by the refrigerant, and it circulates inside the refrigeration system.

The correct operation of the compressor needs proper lubrication of the motor components.

Sliding parts of refrigeration compressors are exposed to various wear processes depending on the oils and refrigerants used in the compressors [7, 8]. Currently there is no universal oil for refrigeration compressors. In a cooling system, the oil-refrigerant system is characterized by complex interactions. If the miscibility is exceeded, the oil absorbs some of the agent. Depending on the composition of the mixture and temperature, the mixture of oil with medium may be single-phase or two-phase. Complex interactions in oil-refrigerant mixture reduce lubricating and anti-wear properties in comparison to the pure oil. To improve such properties, anti-wear and anti-seizure additives are added to oils.

1.3. Causes of compressors damage

In the article [9] thermodynamic analysis of car air cooler was carried out. The influence of refrigerant charge and the inlet air temperature on the coefficient of performance, exergy efficiency, heat flux and temperature in the evaporator and the compressor net power were investigated. The impact of improper refrigerant charge on the performance of A/C systems was also checked.

Damages to refrigeration compressors were analysed in [10-12]. As presented in [6], over 70% of damaged compressor parts could be exposed to the oil-refrigerant mixture. The actual failure of chillers related to compressor damage is about 15% of failures.

According to [6], the mechanical causes of compressor damage are the lack of oil, incorrect lubrication (unsuitable oil, formation of a mixture of liquid medium with oil, inappropriate oil properties) and liquid hammers. The lack of oil leads to a quick seizure of the compressor. Loss of the oil in the compressor may result from the lack of return of oil from the system or from the return of oil in an insufficient quantity. The refrigerant is an oil carrier in the installation. Its loss may also result from the lack of return of oil to the compressor. By using a low-pressure sensor, the compressor will not start during standstill or shut down during the operation. However, this will occur at oil pressure above the critical value set on the low-pressure sensor.

Increased discharge pressure due to an excess of the refrigerant can also damage the compressor. Damage due to the oil loss may be caused by an inappropriate oil defrosting, too little refrigerant or frequent starts. Lack of the oil can manifest with a high noise and vibrations.

One of the main causes of compressor damage is flooding with a liquid medium. During the stoppage, the refrigerant migrates to the oil because of the pressure difference between the oil vapour and refrigerant. When stationary, the oil in the crankcase is diluted with a large amount of liquid refrigerant. The oil with the refrigerant is heavier than pure oil, which is why it is located at the bottom of the crankcase. The refrigerant migrates to the clean oil at the top of the crankcase.

Uneven surface wear may result from oil loss or liquid flooding during standstill. Too low oil pressure may be caused by the wear of the sliding surfaces. The start-up of the flooded compressor is accompanied by the presence of agitated foam visible in the sight glass.

Incorrect operation of the refrigeration system causes the compressor to suck in a liquid medium together with the vapours.

This situation will occur if the quantity of superheated vapours in the evaporator is too small. A small amount of liquid medium due to the reduced flow rate can be separated in the suction channel and run to the bottom of the compressor causing a dilution of the oil. The oil pump pumps oil together with the carrying medium, where due to the friction the temperature increases, which leads to the evaporation of the refrigerant and leaving insufficient amount of oil.

When the compressor is switched off, there may be a sudden drop in pressure causing evaporation of the refrigerant which, when released from the oil, will form a mixture in the form of a foam. If foam gets into the moving elements, the oil is washed out.

Pouring the refrigerant takes place during the suction of the liquid through the suction line to the compressor during the operation. The sucked refrigerant vapour enters the suction valve through the suction channel. Due to the reduced speed and direction of the flow, a small amount of liquid refrigerant is separated in the suction chamber and drained to the crankcase of the compressor along with the returning oil. The liquid medium dilutes the oil in the cartridge deteriorating its lubricating properties. Most of the wet vapour can get into the cylinder, causing the oil to be washed out from its surface and from the pistons during the operation. An inadequate lubrication causes premature wear and even galling of the cooperating elements.

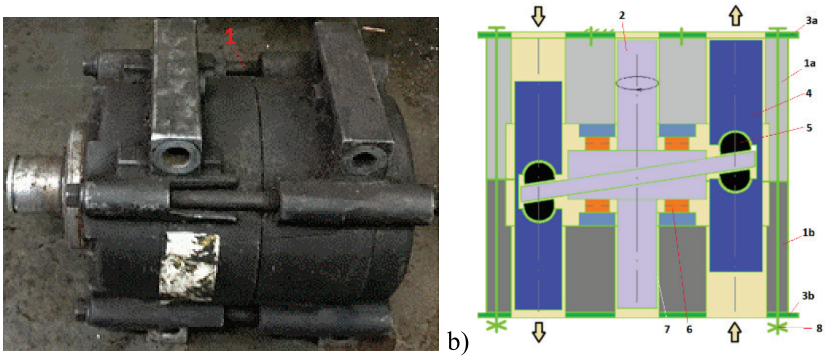
Due to the lack of possibility of evaporation of large amounts of the refrigerant, a liquid hammer on the compressor elements occurs. The effect of the liquid impact is loud operation and possible permanent deformation of the compressor elements [13].

The oil mixture with a large amount of refrigerant takes up the heat from the sliding surfaces. Because of an increase of heat, the agent evaporates, and therefore there is not enough quantity of the mixture capable of lubricating the moving elements. The result may be an uneven wear of the components of the friction nodes. Damages in refrigerator compressors can be detected using vibration and current signals [14].

2. Materials and methods

The studied aggregate was not of the new class. It was taken from the vehicle Ford Focus with 2L SI engine. The vehicle was manufactured in 2003 and its millage was of 215000 km.

The main assembly of the analysed aggregate was the axial five-piston compressor R57166 (Fig. 1a, b). Some components of the compressor are shown in Fig. 2a. Five small pistons (2) made of aluminium alloy were led, via lubricating rings (7) (surfaces E1), in cylinders (surfaces E2) arranged with the radial pattern in the fixed head (1) made of the other aluminium alloy. It consisted of two almost symmetrical parts. One of them was fixed relative to the compressor housing (Fig. 2b), made of aluminium alloy, through two steel pins. Both parts of the head were connected to the compressor housing by means of four common steel screws (1). Although there existed relatively high normal and friction forces between the front surfaces of head parts (1) (Fig. 2a), small radial displacements of such parts could occur in case of vibrations or loosening of screws.



a) b)

Fig. 1. a) The axial five piston pump of cooling aggregate compressor R57166, 1 – screw, b) scheme of compressor, 1a, 1b – head components, 2 – shaft with the spatial disc cam, 3a, 3b – compressor body components, 4 – piston, 5 – tappet, 6- needle roller bearing, 7- journal sliding bearing

Fig. 2. a) Components of the axial compressor of cooling aggregate, b) compressor housing part, c) damaged seal ring, 1 – head component, 2 – piston, 3 – tappet, 4 - the spatial disc cam, 5 - needle roller bearing, 6 –rotating shaft, needle roller bearing, 7-lubricating rings

Pistons could make small radial and circumferential motions and swings within a clearance between surface E1 and E2 and between surfaces F1 and F2. Such pistons were driven through tappets (3) made of steel, mating through their spherical surfaces B1 with spherical seats B2 made in small pistons. Through their front surfaces A1, placed opposite to the spherical surfaces B1, the spatial disc cam (4) drove, small pistons (surface A2) made of aluminium alloy. The cam was mounted on the rotating steel shaft (6) via splined connection. The shaft (surface C1) was bearing in two head parts via two journal bearings (surfaces C2). The shaft could also make small radial motions and swings within a clearance in the journal bearings. The spatial disc cam (surface DO) was beared relative to the head parts using two axial needle roller bearings (5) (surface D1). It allowed small motions of the shaft within an axial clearance. As mentioned, the damage of radial sealing ring (Fig. 2b, c) was observed, which could initiate consequences that are more important.

The images of worn zones were made by hand camera with resolution of 20 Mpix.

Clearances in sliding bearings and in piston-cylinder contacts were determined with micrometre.

The surface structure and morphology of the worn tappets were studied using scanning electron microscope JSM-6610LV (JEOL) integrated with X-Max 80 EDS analyser (Oxford Instruments).

3. Results

The measured values of clearances in journal bearing were lower than 0.05 mm. In addition, the registered values of clearance between pistons and cylinders were in the range between 0.02 - 0.06 mm. The existence of such clearance values could not explain possible collisions between the cylindrical surface F1 of the spatial disc cam (Fig. 3a) and surfaces of pistons F2 (Fig. 3b). Nevertheless, such conditions resulted in visible wear of the cooperating surfaces. Probably, displacements of the head parts occurred − due to vibrations and loosening of screws. This together with noticed increase of clearances in journal bearing and between the pistons and cylinders allowed contacts between piston surfaces and cylindrical surface of the spatial disc cam. These contacts can become more dangerous when pistons are locked in the cylinders. This can result from the occurrence of foreign bodies, e.g. hard dusts, debris, recorded during the visual inspection of the interior of the disassembled compressor. The situation may be even worse, if dilution or lack of oil occurs. Dilution can result from a temporarily too high amounts of refrigerant in the refrigerant-oil mixture arising during disturbances of the refrigeration cycle performed by the aggregate with worn components. The registered damage of radial sealing rings in the compressor head could cause leakage of oil and refrigerant.

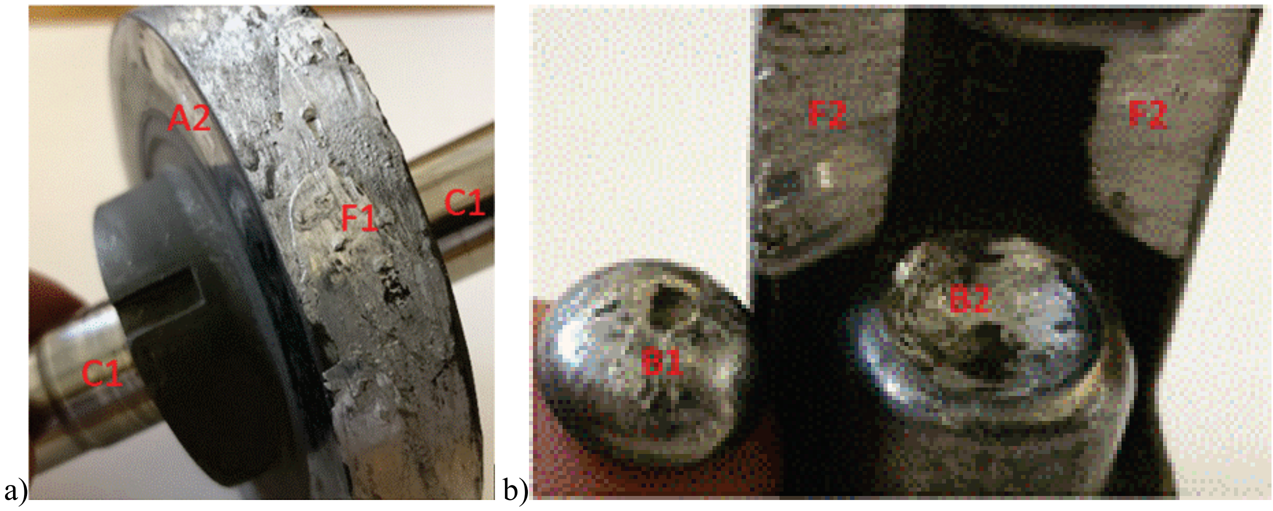


Fig. 3. The damaged surfaces of: a) the spatial disc cam and its shaft, b) the piston and the tappet

The failure was noticed in the form of wear of the disc cam (Fig. 3a), front and spherical surfaces of tappets (Fig. 4) and the plastic deformation of the spherical surfaces B2 of seats (Fig. 3b). Then, due to the deformation and displacements of the rotating shaft, collisions and wear of the side surface of the disc cam occurred during contacts with small pistons surfaces. Moreover, noticeable wear of the side surfaces of pistons, their lubricating rings (Fig. 4a) and the cylinders in fixed head was registered. On the surface of tappets are visible traces of the material transfer. In order to analyse the character of wear the surface of tappet was analysed with use of SEM.

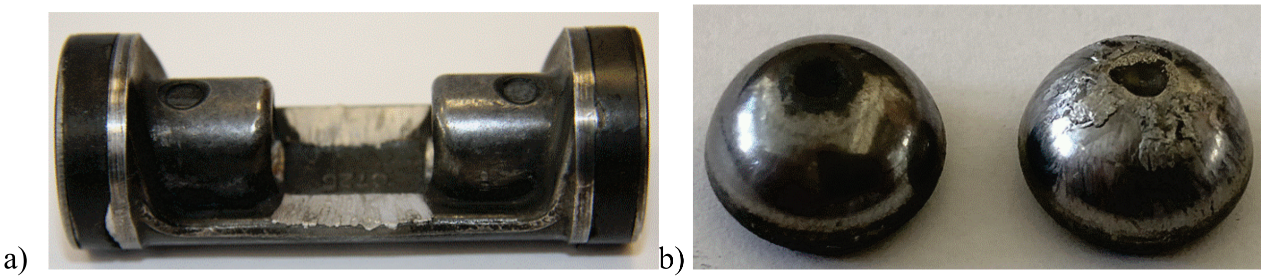
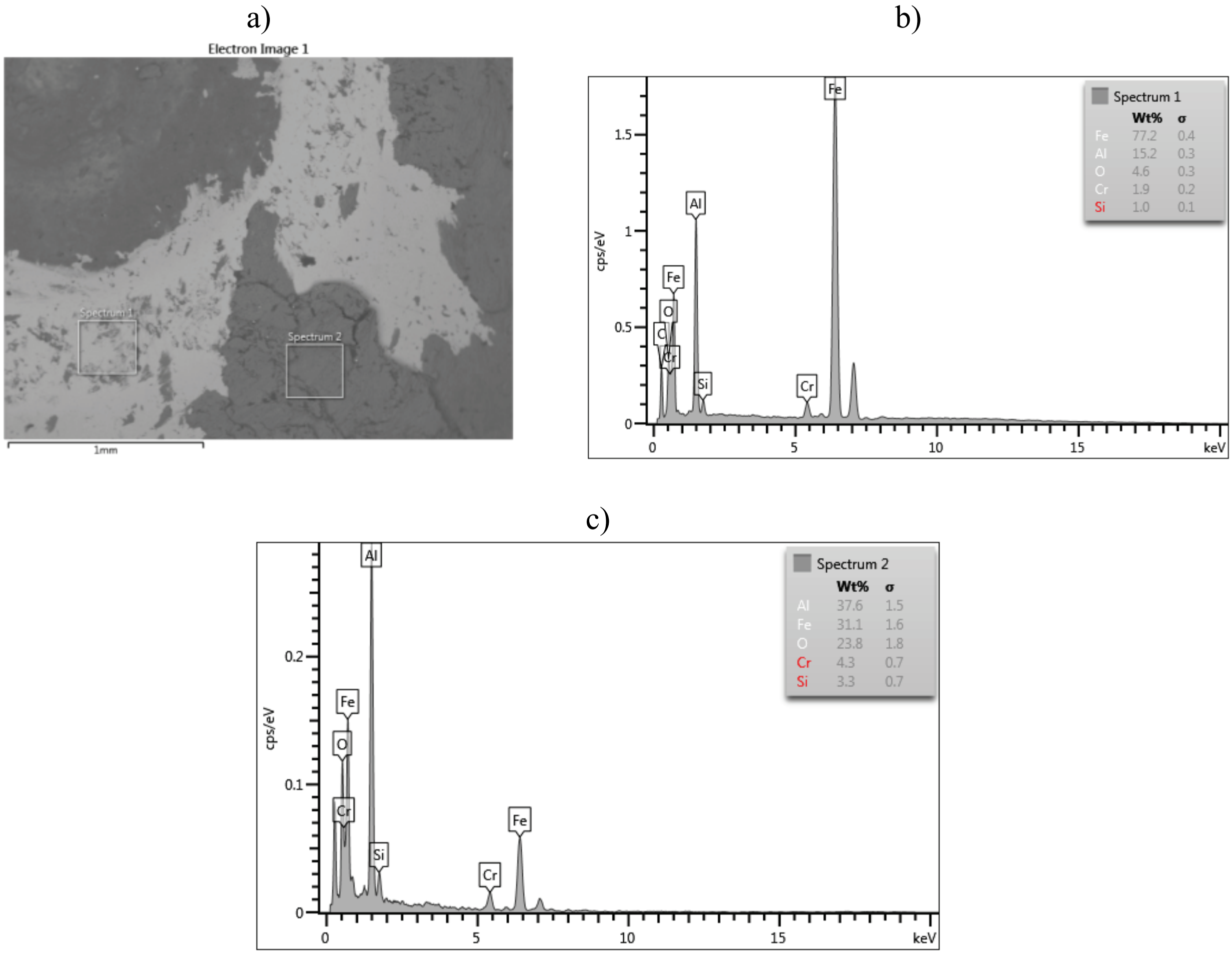


Fig. 4. a) Surface damaging for the piston and lubricating rings, b) Different rate of surface damaging for the tappets

Results of SEM analysis of the tappet surface are presented in Fig. 5. The backscattered electrons image shows a strong phase contrast on surface of the tappet. Moreover, a build-up layer with visible cracks is visible. This indicates strong material transfer between the tappet and cooperating seat in the piston. Different materials of the piston (aluminium alloy) and the tappet (steel) indicate wear of the seat in the piston and transfer of the seat material on the surface of the tappet. The EDS spectra collected from the surface without the build-up layer shows noticeable amounts of iron, whereas the chemical composition of the build-up layer indicates large amounts of aluminium, which proves the material transfer between the seat and the tappet.



Spectrum 1

	Wt%	σ
Fe	77.2	0.4
Al	15.2	0.3
O	4.6	0.3
Cr	1.9	0.2
Si	1.0	0.1

Spectrum 2

	Wt%	σ
Al	37.6	1.5
Fe	31.1	1.6
O	23.8	1.8
Cr	4.3	0.7
Si	3.3	0.7

Fig. 5. Results of SEM analysis of tappet surface: a) SEM image, b) EDS spectra of the surface without the build-up layer, c) EDS spectra of the build-up layer

7. Summary

The analysis of the damage of the cooling aggregate in vehicle was carried out. The failure was initiated by, at first appearing harmless, damage of the radial sealing ring. However, it caused the following, much more serious and complex, consequences. When external impurities of high hardness together with generated wear debris got inside the contact zone between the mating surfaces, it resulted in wear, collisions, and in consequence plastic deformation of many elements. These phenomena resulted from a possible locking of pistons in cylinders under diluted oil and occurrence of hard micrograins in contact zones. Finally, the failure of the whole aggregate happened. It is necessary to improve the relative positioning of head components, i.e. through additional pins. The material transfer between tappets and their seats was also identified. The mating of pistons with tappets and cylinders was complex and difficult to describe, as the wear debris from piston material could get into contact zones and oil diluted by the refrigerant aggravated the lubrication.

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