CAVITATION EROSION OF WET-SLEEVE LINERS:

CASE STUDY

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ABSTRACT

Cavitation erosion is a major type of wear on wet-sleeve liners of the heavy-duty diesel engines. The cavitation phenomenon occurs on the outer surface of the liners during combustion. As the fuel inside ignites, the liner vibrates within the engine block causing the creation of air bubbles. The air bubbles implode repeatedly against the liner wall surface at a very high intensity. The collapse of these bubbles produces small holes in the liner. Widespread attention and intensive investigation has been given to optimise the design and operating parameters in order to avoid the perforation of wet-sleeve liners. During the last 10 years, we have investigated the cavitation phenomenon on cylinder liners into 2000 diesel engines from independent manufacturers. The aim of this paper is to present the cavitation erosion mechanism through three practical examples. The first one concerns heavily damaged by cavitation erosion on diesel engine in the cooling system of which, no cooling conditioners had been used. The second one presents several cases of cavitation damage on cylinder liners that had been protected by different anticorrosion inhibitors. The last example is a diesel engine the cooling system of which is not properly maintained. These cylinder liners were not damaged.

Key words: Cavitation, erosion, wet-sleeve liners, diesel engine.

1. INTRODUCTION

Corrosive wear is the progressive removal of material from a metal surface caused by a combination of chemical attack and mechanical action. The financial losses from corrosion wear are great at every year. The common chemical reactions between the metal and its environment are: (i) uniform attack, (ii) pitting, (iii) differential aeration cells, (iv) erosion and (v) cracking [1] [2]. Erosion is a type of attack connected with high velocity, and consists of two sub-categories, impingement and cavitation. Cavitation refers to the formation of vapour bubbles in flowing liquids due to the hydrodynamic generation of low pressure. The collapse of the vapour bubbles produce deformation, material failure and, finally, erosion of the metal surfaces [3].

Cavitation erosion can occur if the pressure of liquid is reduced sufficiently to cause formation of vapour bubbles (cavities). In the case of heavy-duty diesel engines, the following is happening: The fuel detonates in the combustion chamber. This causes the wet-sleeve liner wall to flex outward slightly, due to the pressure inside the liner. When the liner returns to its original shape, the water cannot follow

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quickly enough. As a result, microscopically small vapour bubbles are created on the wall of the liner. When the wet-sleeve liner stops moving, the vapour bubbles collapse violently. Frequently, the impact is so hard that it breaks off a microscopic flake of iron from the liner wall [4] [5]. If it is allowed to proceed, the wet-sleeve liner may be completely penetrated. The pitting can penetrate the liner wall until perforations go all the way through to the combustion chamber. Cavitation erosion of the outside of cylinder liners is more rapid than progressive wear of the inside surface by piston ring action. It is difficult to estimate the periods of time that can cavitation occur. In some cases, can be identified within the first several hours of use. Sometimes it takes 1000÷1200 hours or more. Thus cavitation erosion of liners often seriously reduces the reliability and life of many types of diesel engines [4] [5] [6] [7].

Water hammer was considered the cause for cavitational deterioration. According to some antifreeze experts [8] [9], the main task is to select additions that change the nature of the coolant. The term "coolant" describes a mixture of antifreeze and water. Coolant transfers heat out of the diesel engine and helps to protect all type of metals common to cooling system. The term "antifreeze" refers to a mixture of glycol and chemical inhibitors package. Antifreeze is usually glycol based with Ethylene Glycol (EG) (green colour). Also Propylene Glycol (PG) (red colour) is used. The main difference between them is that PG is less toxic. Metals protection is accomplished by adding the proper amount of Supplemental Coolant Additives (SCA) to an EG cooling system. The use of SCA is necessary to provide a continuous protective coating on the metal surfaces and this coating will help in controlling and limiting the damage done to the liners as a result of cavitation. In conclusion the proper use of SCA provide: (i) cavitation protection, (ii) pH control to prevent corrosion and (iii) deter the creation of mineral deposits. Moore [10] refers that SCA contains nitrite for protecting (wet-sleeves) iron and steel, tolyltriazole to protect copper and brass, borate or phosphate to buffer acids (formed as glycol breaks down), silicate to protect aluminium. But too much nitrite may cause solder corrosion and excess accumulation of other additives causes "Total Dissolved Solids" (TDS). Since the fully formulated conventional coolant may replacing at two year intervals to avoid TDS problems. To simplify maintenance, the antifreeze industry developed "Extended Life Coolants" (ELC). These formulations, replaced the additive package used in conventional antifreeze with "Organic Acid Inhibitors" designed to protect metal surfaces by forming a thin protective layer against destructive forces in the coolant.

Other experimental studies were carried out as well to increase the wear resistance of materials, e.g. special steels and also protective coatings [11] [12] [13] [14]. The widespread use of electrodeposited coatings of cadmium, chromium, copper and also diffusion aluminising, chromizing, and impregnation of grey cast iron with carbide-forming elements, has been used in order to protect wet-sleeve liners from cavitation erosion [13] [14]. However milky chromium electrodeposits are a very difficult and expensive operation and it is necessary, therefore, to develop a cheaper and simpler method of liner coating. Liners of magnesium cast iron are not inferior to steel with regard to interval wear and their cavitational wear is intermediate between cast iron and steel. According to Okada et al. [7], the metal coating of cast iron with zinc, chromium, nickel, cadmium and vanadium appeared to have little effect due, as a rule, to insufficient adhesive strength. Thermally sprayed coatings have also been used in diesel engines [12]. The coatings have been applied to the cylinder head, the valves, the pistons and the liners. Thermally sprayed coatings have a lamellar microstructure. The layered structure forms due to the repeated deposition of molten and semi-molten particles. Porosity and microcracks can be distinguished within single splats. Every coating structure is highly oriented with the lamellae parallel to the surface of the substrate. But the coating microstructure and phase distribution of thermally sprayed coatings are dissimilar to those of the bulk constituents. Therefore material properties of the coating such as thermal diffusivity, mechanical strength in tension and shear, and wear characteristics will be different from the properties of the bulk material. Thus the microstructure of coatings determines their utility and this recognition enables the user to take full advantage of coating properties. In conclusion, DMI (UK) [15] asserts that hard chromium plating provides excellent wear resistance, low friction and anti-stick properties. Hard chromium offers much greater wear resistance than conventional base materials and surface treatments. The porosity in the chromium surface does not extend through the chromium to the base material, resulting in excellent corrosion resistance. Also, the wet-sleeve liners can be reconditioned by a combination of pre-machining, nickel electroplating and finish machining. The nickel plating provides excellent corrosion resistance, anti-cavitation and anti-fretting characteristics.

The aim of this paper is to present the cavitation erosion mechanism through three practical examples. The first one concerns heavily damaged by cavitation erosion on diesel engine in the cooling system of which, no cooling conditioners had been used. The second one presents several cases of cavitation damage on cylinder liners that had been protected by different anticorrosion inhibitors. The last example is a diesel engine the cooling system of which is not properly maintained.

2. MATERIALS AND METHODS

Most large industrial and commercial diesel engines use wet-sleeve liners. This type of engine block design allows for quick rebuilds, often in the field. If one cylinder fails, the old piston and wet liner are removed together and a new set is installed. Engines using a wet-sleeve liners design are prone to cavitation erosion around the cylinder liners. Cavitation is a localized low-pressure zone that forms to the outer wall of wet liners. Liner damage is usually well defined and occurs within a zone extending from the middle to the bottom of the liner on the thrust side. An investigation of the cavitation erosion resistance on wet-sleeve liners has been performed in total 2000 tractors of different makes at Greek territory from 1993 until 2003. The liners were collected from many coactive vehicle workshops. In most tractors cooling systems described in this paper were used commercially available heavy-duty engine coolants. After an engine failed due to cavitation erosion, the liners were removed from the engine and returned to laboratory for testing. Chemical and metallographical analysis was performed and results are recorded. All specimens for metallographical analysis were well polished before tests.

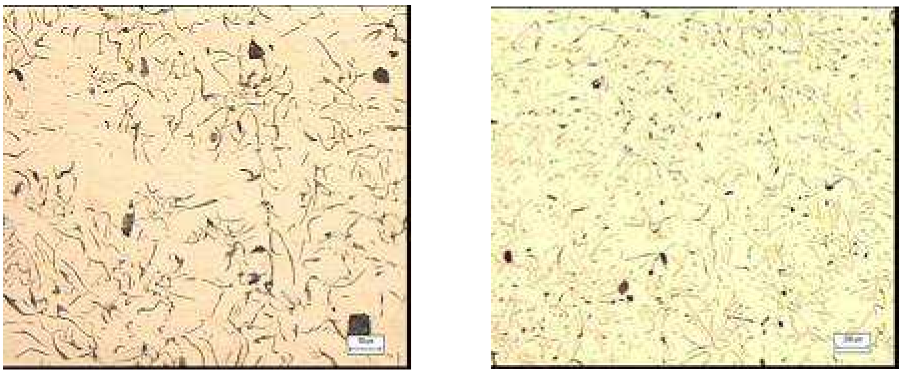
3. RESULTS AND DISCUSSION

The original goal of this project was to investigate a "ten-year field service performance of cavitation mechanisms". From 1993 until 2003, a field retrieval program was carried out to ascertain whether the cast iron wet-sleeve liners had demonstrated in actual service the superior cavitation erosion resistance. The investigation has been performed in 2000 old and new agricultural tractors. Five hundred and two (502) of these tractor engines were equipped with liners "type A", 455 were equipped with liners "type B", and 1043 were equipped with liners "type C".

Table 1 summarizes chemical compositions and mechanical properties of the wet-sleeve liners, which were used in the examinations reported here. By metallographical analysis, it is resulted that liners "type A" appear more quality microstructure. Figure 1 shows the metal microstructure of liners "type A" and "type B".

Table 1: Chemical compositions and mechanical properties of wet-sleeve liners.

		Wet-sleeve liners		
		Type A	**Type B**	**Type C**
Bore x Stroke [mm]		**105 x 115,5**	**110 x 120**	**102 x 110**
Hardness [HB]		**242,3**	**256,3**	**256,1**
Chemical composition [%]	**Carbon, (C)**	**3,47**	**3,52**	**3,25**
	Silicon, (Si)	**2,76**	**1,93**	**2,00**
	Manganese, (Mn)	**0,73**	**0,63**	**0,75**
	Phosphorus, (P)	**0,50**	**0,36**	**0,40**
	Sulfur, (S)	**0,024**	**0,023**	**0,080**
	Chromium, (Cr)	**0,47**	**0,37**	**0,37**
	Nickel, (Ni)	**0,11**	**0,28**	**0,30**



a) b)

Figure 1: a) Metal microstructure of liners "type A", and b) Metal microstructure of liners "type B".

The cavitation phenomenon was observed only into liners "type A". Particularly, in 502 diesel engines, with liners "type A", cavitation erosion was observed into 127 cases, that is 25,3%. Figure 2 presents the cavitation phenomenon evolution on 127 failed engines with or without turbocharged.

In most engine cooling systems proper maintainace was made. Distilled water solutions were used as comparison with: (i) ethylene glycol or propylene glycol with anticavitation/anticorrosion inhibitors and were used in appropriate dilution with distilled water, and (ii) long life/extended life cooling liquids, ready to use. The ambient pressure and the temperature in the cooling system of all tractor engines were maintained equivalent according to manufacturers' recommendations.

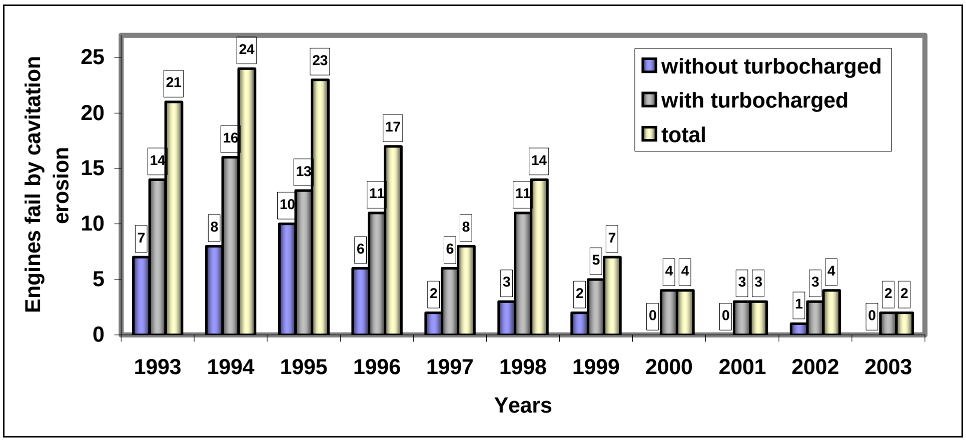


Figure 2: Evolution of the cavitation phenomenon on the 127 failed engines with or without turbocharged.

Therefore, the following questions were created: "Why cavitation phenomenon happens only in liners type A"? and "Why it does not happen in all liners of this type"? The answer in these queries was given by the analysis below.

3.1 WET-SLEEVE LINERS EXAMPLES OF CAVITATION FAILURE

This cavitation erosion study was based into 2000 tractor engines from three different manufactures, three types of wet-sleeve liners, distilled water and antifreeze cooling liquids were compared. The findings were consistent with the existing practice. Some particular findings are included in the following examples:

EXAMPLE 1

Corrosion and cavitation wear in wet-sleeve liners is shown in Figure 3. This approach was tested on four-cycle diesel engines, with 4 cylinders of bore x stroke = 105 x 115,5 mm, in the cooling system of which distilled water had been used. Figure 3 shows the liners after 1000 working hours subjected to the vibratory cavitation environment of diesel engine. The wear is evident and in advanced stage to all the cylinder liners. The corrosion erosion had little effect on forming the honeycombed structure of the eroded surface. Corrosion appears on the liner wall due to electrochemical action and causes damage but the rate normally decreases as an oxide layer is formed. When cavitation erosion also occurs, the protective oxide layer is removed by bubble collapse. The deeply pitted appearance of the eroded surface is characteristic of the cavitation erosion. The location of the pits is coming from the bottom to the middle of the liners on the thrust side. In the antithrust side of the liners cavitation eroded surface is not formed.

EXAMPLE 2

In order to reduce wet-sleeve liners erosion, different anticorrosion and anticavitation inhibitors were used in the coolant as an inexpensive and easy to use method. The inhibitors had been used according to the producers' advice. This approach was tested on four-cycle diesel engines with 4 and 6 cylinders of bore x stroke = 105 x 115,5 mm. However, after 800÷1500 h of operation, wear was still found on the liners. Figure 4 shows a liner, which was totally protected from corrosion erosion but on the liner wall uniform removal of further material layers was appeared due to cavitation erosion. The turbulence agitation caused by the cavitation in the liquid decreases the diffusion boundary near the metal surface and it probably incorporates dissolved oxygen into the cavities. These factors tend to increase the passivation of the metal. When the bubbles collapse, they create a very small, high velocity water jet, which, according to the photo below, is applied to a very small area of the liner surface and results to high stress. Cavitation exposure causes deformation of the grey cast iron and cracking of passive film due to mechanical impact forces of the cavity collapse exposing fresh surface at the liners wall. In this case cavitation erosion causes a pitted honeycombed surface and completely penetrates the liner wall, perforations go all the way through to the combustion chamber, resulting to the mixing of cooling liquid with lubricating oil.

Figure 3: Corrosion and cavitation erosion in wet-sleeve liners was observed after 1000 working hours. It is about a turbocharged engine with 4 cylinders of bore x stroke = 105 x 115,5 mm, in the cooling system of which anticorrosion and anticavitation inhibitors had not been used.

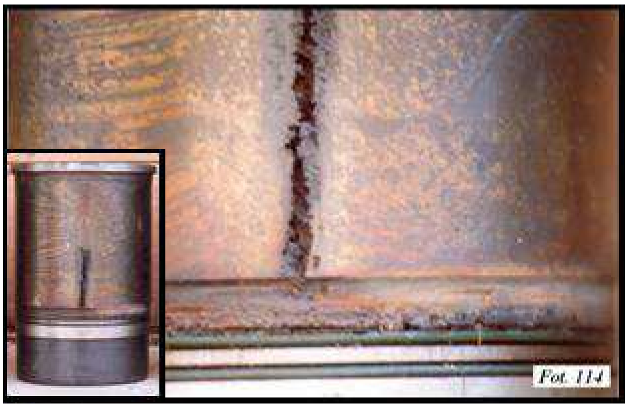


Figure 4: Cavitation erosion with removal of further material layers in wet-sleeve liners was observed after 1500 working hours. It is about a turbocharged engine with 6 cylinders of bore x stroke = 105 x 115,5 mm, in the cooling system of which anticorrosion and anticavitation inhibitors had been used.

EXAMPLE 3

Construction changes such as thickening the linear wall and coatings seem the only effective way in reducing cavitation erosion. Figure 5 shows wet-sleeve liners that were not damaged by cavitation erosion after 5600 h operation. This approach was tested on four-cycle diesel engines with 4 and 6 cylinders of bore x stroke = 110 x 120 mm. The thickness of the liner wall is 8,3 mm versus 5,3 mm of the above mentioned cases. The cooling system of this diesel engine was not properly maintained. Muddy deposit appears on the liners wall.

Figure 5: Wet-sleeve liners were not damaged by cavitation erosion after 5600 h operation. This approach was tested on a turbocharged engine with 6 cylinders of bore x stroke = 110 x 120 mm. The thickness of the liner wall was 8,3 mm, and the cooling system is not properly maintained.

A variety of strategies had been used to control cavitation erosion on wet-sleeve liners. Cooling additives that incorporate anticorrosion and anticavitation inhibitors were used to reduce the cavitation process to an acceptable rate. From the above, it appears that the proper cooling system maintenance using the right antifreeze and keeping up proper levels of recommended additives is essential to keep the surface corrosion under control, but it can't be a major force in preventing liners pitting. The aspects of "a good radiator pressure cap help keeping ambient pressures above the vapour pressure of the coolant, thereby, reducing the amount of cavitation" or "the thermostat keeps the temperature of the coolant at a level that reduces the energy level of the bubble collapse" they were not confirmed by our experiments in the field conditions.

It was observed also, that the expansion of the cylinder wall is clearer as the demand for power is increasing. The engines, which have a turbocharged unit, are increasing air charge and are pumping more fuel into the cylinder. This increase in fuel and air causes a more violent ignition, which increases further cylinder pressures and thus increases the flexing of the cylinder liner wall. The liners of these engines were completely damaged by cavitation erosion in short time. According to the above-mentioned results (Figure 2), 69,3% of the total failed engines by cavitation phenomenon, were equipped with turbocharged.

It is clear that the most significant variable in cavitation erosion is the vibration of the cylinder liners and thus this problem is addressed in the design of the engines. The liners with different hardening and mechanical properties exhibit varying degrees of cavitation erosion. The liners "type A" appeared high percentage of cavitation erosion in comparison with the others. In order to solve the cavitation phenomenon in liners "type A", it was decided to test a new type wet-sleeve liner. For this reason, a new liner "type A" with greater wall thickness was manufactured. According to the results in Figure 2, the cavitation erosion phenomenon after the year 1999 was limited. Today, the rebuilded engines operate up to 6000 working hours and all new liners "type A" were not attacked by cavitation erosion.

4. CONCLUSIONS

- Cavitation erosion is a major type of wear on wet-sleeve liners of the heavy-duty diesel engines.
- It is evident that, the cavitation erosion of wet-sleeve liners is different to conventional corrosion. Cavitation erosion is caused by vibration of the liners wall. Therefore, using the right antifreeze and keeping up proper levels of recommended additives, does not prevent the liners from cavitation erosion.
- Widespread attention and intensive investigation has been given to optimise the design and operating parameters in order to avoid the perforation of wet-sleeve liners. By manufacturing a new type of liners with greater wall thickness, the attack on wet-sleeve liners by cavitation erosion is limited.

5. LITERATURE

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