Wear aspects of internal combustion engine valves

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Abstract. Because the surface engineering is becoming an increasingly viable alternative to the constructive changes made to improve the efficiency of internal combustion engines, have been proposed and tested various types of coatings of some organs of internal combustion engines. One vital organ is the engine valves, which is subjected during operation to combined thermal, mechanical, corrosion and wear solicitations, which are leading to severe corrosion and complete breakdown. In this paper were analyzed aspects of valves wear and the active surfaces were coated using the atmospheric plasma spraying method (APS) with two commercial powders: Ni-Al and YSZ. Microstructural analyzes were made on these layers and also observations regarding the possibility of using them as thermal barrier and anti-oxidant coatings.

1. Introduction

At the moment, in the automotive industry, in the internal combustion engine domain runs various researches intended to achieve technological innovations that will have as result both lowering the production and maintenance engine costs and lowering fuel consumption.

It is known that the engine is the most exposed system to severe working conditions, mechanical, thermal and chemical types. The character of service is variable, with successive and very sudden passes from high temperatures lower ones, in the operating conditions when starting, stopping, accelerating, stopping while functioning. For these reasons, the thermal shock is the most important wear factor from the whole range of wear factors acting simultaneously in operation [1].

Currently, surface engineering is becoming an increasingly viable alternative to constructive modifications developed in order to improve the efficiency of internal combustion engines. Thus, were proposed and already tested various types of coatings applied to some organs of internal combustion engines in order to increase life span in operation, to reduce maintenance costs, to recondition worn areas, to increase the fuel efficiency by increasing the temperatures inside the combustion chamber.

These goals are possible because the coatings obtained by thermal deposition provide a functional surface with protective role or even base material behavior modification.

In the literature [2,3] are presented many of the functions of layers produced by thermal deposition, among which are the following: improving the abrasive wear behavior, the corrosion protection, adhesive wear and seizure, contact fatigue, surfaces reconditioning, thermal insulation, electrical insulation, improving thermal conductivity, resistance to oxidation or hot corrosion.

In case of the coatings made on parts of internal combustion engines presented in the literature, they have mainly protective role to the thermal and mechanical solicitations in operation. In order to
achieve these coatings have been used various kinds of materials such as metals, metal oxides, alloys, carbides, cermets and composite materials. The most materials are currently the ceramic materials filled with role of thermal barrier.

When studying the operation behavior of the coatings, it must be taken into consideration that their life span is influenced in internal combustion engines from factors such as chemical stability at variable working temperatures, thermal conductivity, thermal expansion coefficient, high thermo-mechanical stability at maximum working temperatures.

Some of the machine elements with vital role in the operation of internal combustion engines are the engine valves. They serve for opening and closing the inlet port for fresh gases in the combustion chamber (intake valves) and output for the combustion gases (exhaust valves). Figure 1 shows a section through the distribution system, where is seen that an engine valve consists of two parts: valve disc (6) with the role of obstructing the hole in the cylinder head and valve stem or tail (4) as a guide movement and evacuation of part of the heat received from the disc.

![Figure 1. Distribution system section: 1 – tumbler shaft, 2 – valve plunger, 3 – valve spring, 4 – valve stem, 5 – gas flue, 6 – valve disc, 7 – combustion [4].](image1)

![Figure 2. Temperature fields inside a exhaust valve [5].](image2)

Because of the operating mode, the engine valves are subjected to combined solicitations: thermal, mechanical, corrosion and wear. Average temperatures for operation of the valves are between 300-400°C for intake valves and 500-900 °C for exhaust valves, as shown in figure 2. Also from mechanical point of view, the valves are strongly solicited because the operation at very high speeds, which can reach values of 600 m/s. The corrosion requirements are the most important ones, because the high thermal working conditions favor the acids formation, which act on the materials microstructure. At these solicitations adds the abrasive wear phenomena caused by hard particles dragged along in the working fluid and the adhesive wear caused by friction between stem and guide. Another request is the one caused by the very high operating pressures, which along with the other solicitation may cause deformation of the valve discs and thus removing them from use.

For these reasons, the valves are produced from special heat-resistant material with anticorrosive properties, such as medium alloyed steels with chromium, martensitic and austenitic stainless steels, titanium alloys, nickel-based super-alloys (Inconel, Nimonic, Nichrome, etc.). To increase the wear resistance of the valve disc and/or the stem, in some cases are applied at their surface some hard materials layers of alloys based on Co, W and Cr (stellite), of nichrome (an alloy based on Cr, Ni, Co, W etc.) or other materials, through established processes: hard chrome plating, nitridation, aluminizing or phosphating.

In this paper are analyzed aspects of intake and exhaust valve discs wear and it is presented a possible solution to improve the effect of complex phenomena that lead them to complete breakdown, by using coatings deposited by thermal spraying.
2. Experimental setup
To accomplish the first objective proposed in this paper, were taken samples from different engine valve sets from two MAN LE8180 (7.5 to) vehicles, with a swept capacity of 4580 cm³, 180 hp power, functioning with diesel fuel. The macrostructure of these samples was analyzed using a stereo-microscope system, as seen in figure 3.

To achieve microstructural analysis, samples of the two types of engine valves were collected and metallographic prepared accordingly to standards by: cutting with cooling fluid, grinding, polishing and metallographic etching with chemical reagent. The cross-section of the samples were analyzed using optical DMI500 Leica microscope and scanning electron microscope (SEM) Quanta 200 3D (FEI, Holland, 2008). In figure 4 a, b are presented images of secondary electrons obtained on the two samples, together with spectra emitted during elemental chemical analysis performed with analysis module type EDS (AMETEK, Holland, 2008) integrated in the analysis system of SEM. Based on this analysis it was established with certainty the type of material used to produce the two types of analyzed valves: martensitic stainless steel for exhaust valve and medium alloyed steel with chromium for the intake valve.

In order to accomplish the second goal, four samples were prepared from the two types of valve steel above mentioned, which were coated by atmospheric plasma spraying (APS). There were obtained A1 and A2 samples on specific material for intake valves and E1 and E2 samples on specific material for exhaust valves. The samples preparation for coating was made by degreasing, surfaces activation by sandblasting and subsequent final cleaning in an ultrasonic bath with isopropyl alcohol.

The coating was made using the Spraywizard 9MCE (Sulzer Metco-2008) system, equipped with a spray gun 9MBM type. In order to obtain a coating resistant at the specific requests for internal combustion engine valves, was projected a double layer composed of an intermediate layer obtained from Ni2OAl (410NS) and an outer layer of ZrO2-8% Y2O3 (204B -NS). The intermediate layer was applied in order to increase the adherence of outer layer (with the role of thermal barrier), having also the role of stopping the oxidation and corrosion substrate phenomena. The working parameters are shown in Table 1.

| Sr.no. | Parameters                                      | 410NS | 204B-NS |
|--------|------------------------------------------------|-------|---------|
| 1      | Cleaning of substrate using isopropyl alcohol   | yes   | Yes     |
| 2      | Grit blasting with sand for surface activation  | yes   | Yes     |
| 3      | Nitrogen pressure (psig)                        | 50    | 50      |
| 4      | Hydrogen pressure (psig)                        | 50    | 50      |
| 5      | Spray distance (mm)                             | 100   | 64      |
| 6      | Electric parameters (A / V)                     | 500 / 75 | 500/75 |
| 7      | Carrier gas flow - Argon (S.C.F.H.)             | 12    | 12      |
| 8      | Feed rate (g / min)                             | 60    | 90      |

3. Results and discussions
Figure 3 presents the wear surfaces aspects of the intake valve (a) and exhaust valve (b) analyzed in this paper, which is specific to the conditions of operation in complex solicitations of mechanical wear, corrosion, variable thermal condition with high temperatures.

It is observed the corrosion apparition on the surface of the valve disc, which in case of the exhaust valve is a continuous corrosion, characterized by the formation of a dark layer without reflection, with severe wear and loss of material on great depths. The image detail presents the existence on the worn surface of a layer made of particles caused by wear, which are mainly oxides of chemical elements present in the valve disc material.

In the case of the intake valves, which are subject to reduced thermal stress, corrosion is almost continuous, with the same dark areas of material loss as the exhaust valves. There are though some areas with metallic reflecting aspect along the wear areas with severe loss of material.
The microstructures of the two materials were analyzed by scanning electron microscopy, on the cross-section surfaces prepared by standard metallographic techniques, as shown in figure 4. Note the specific aspects of the two types of material: fine pearlitic structure with chromium carbides, as evidenced in figure 4 and uniform martensitic structure with fine blades in figure 4 b.

Also using the scanning electron microscopy was analyzed the surface layer formed after corrosion processes on the cross section of a sample taken from an intake valve (see figure 5). It is observed the thickness of this layer of about 30 microns and the specific elemental chemical composition of oxide films: Fe, O, Cr, Si. The distribution of chemical elements presented in detail b clearly show that wear is caused by oxidation of Fe and Cr on the surface of the valve disc and the thermal and mechanical conditions only amplify this phenomenon and produce a continuous exposure of atoms by peeling off the corrosion residues.

For valve discs surface protection and in order to increase their wear resistance, in this paper we realized multilayer coatings using the APS method, from an intermediate layer of NiAl and an external layer with thermal barrier role of ZrO₂-8% Y₂O₃ (YSZ). Zirconia-based coatings are commonly used.
as TBC (Thermal Barrier Coatings) due to their low thermal conductivity and high thermal expansion coefficient. We chose the YSZ powder for the external layer because the lowering of the temperature at which the material is subjected will decrease the probability of valve disc deformation. Another positive effect of this type of coating is shown in the literature [6, 7, 8], where is presented the compaction ability of YSZ layers with the exposure to thermal shock, which means a decreased probability of chemical compounds from combustion gases in coating structure and thus a corrosion reduction.

Figure 5. Cross-section aspects of a worn intake valve sample:
(a) secondary electron image, (b) chemical elements cross-section distribution.

After completing the deposition process, the coatings were analyzed by scanning electron microscopy, both after deposition of the intermediate layer and after the deposition of YSZ. Figure 6 presents the appearance in cross-section of Ni-Al layer together with the distribution map of chemical elements sprayed on the sample A1.

In Figure 7 a, b are shown polished cross-sectional microstructure of the sample A1 in final state, with the Ni-Al/ YSZ multilayer at different magnifications.

Figure 6. Chemical elements distribution map of the cross-section of sample A1.

In both cases it is observed that the plasma sprayed coatings are generally composed of splats, some micro-cracks and pores, having the classical plate-like aspect. In the case of the intermediate layer made of Ni-Al it is observed a compact lamellar appearance with evenly distributed component
elements, which can successfully fulfill the role of protective layer, stable and slow-growing oxide (TGO) so as to prevent and to restrain the oxidative attack of substrate.

Typical SEM images of the multilayer deposited by APS (figure 7 a, b) presents an almost irregular texture of the layer with areas of semi-molten material in the vicinity of completely melted areas, looking slightly porous. On the surface could be observed splat boundaries, micro-cracks, pores and a rough aspect caused by the fragmented splats deposited with different flattening parameters. It is also observed that the interfaces between the two different layers are smooth and very difficult to distinguish. Additionally, there are no delaminations to be observed at the interface between the substrate material and the coating.

![SEM images of the multilayer](image)

**Figure 7.** SEM images of the polished cross-sectional microstructure of the as-sprayed multilayer a) 1200x, b) 2400x, c) line-distribution of chemical elements.

In figure 7c is presented the linear distribution map of chemical elements in the cross-section of the multilayer. It is visible the well-defined layers structure, according to the proposed objective, with transition areas that could be distinguished only by this method. The compactness of the coatings produced via APS is highlighted, together with its adhesion to the substrate and the lack of clear delineation between the two thermally sprayed layers. For these reasons we believe that this coating can be successfully used for surface protection of the valve discs of internal combustion engines. In support of this objective come the experiments presented in literature, which showed that the sprayed YSZ layers, after sintering in air at high temperatures (around 1000 °C) or by subjecting to successive thermal shock (by heating with open flame), have low porosity and lack of cracks. This is very important because, in operating conditions, corrosive agents enter the structure through cracks and pores and affect the integrity of the substrate, resulting in peeling and exfoliation.
4. Conclusions
The wear of the valve discs of the intake respectively exhaust valves of internal combustion engines is caused by complex combined solicitations: thermal (thermal condition with temperatures between 300 and 900°C), mechanical solicitations caused by the high-speed operation and very high operating pressures in the combustion chamber, high temperature corrosion and abrasive wear caused by hard particles dragged along in the working fluid. For these reasons there is an intense wear of working surfaces with the formation of oxides of discs material chemical elements and material losses which produce in the final step the valve geometry modification and its disuse. The coatings sprayed of Ni-Al/YSZ using APS method in this study have a classic lamellar appearance with few areas of pores and micro-cracks, but compact and adherent to the substrate and with an obvious lack of clear demarcation between the two layers. These observations, along with data collected from the literature, justified the proposal to use this type of multi-layer as thermal barrier and corrosion protection materials for the valve discs of internal combustion engines.

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