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Assessment of engine valve materials

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This paper presents an analysis of six sets of engine valves, each set consisting of one exhaust valve and one intake valve. Each pair of valves was used in an engine with different displacement and mileage. The valves were subjected to microscopic analysis, hardness measurement and chemical composition analysis using a glow discharge spectrometer and energy dispersive spectroscopy (EDS). The design and materials of the valves showed that both the intake and exhaust valves in their present form would be a strength of the engine.

Key words: *automotive, engine valves, valve steels*

1. Introduction

1.1. Types of engine valves

Intake and exhaust valves are very important engine components. The intake valve system allows clean air or the fuel-air mixture to enter the chamber and the exhaust valves force the exhaust gases out of the engine. Air enters the cylinder with the intake valves open. Combustion in the cylinder takes place when the intake valves are closed by means of a spring. Once combustion is complete, the camshaft opens the exhaust valves and the burnt gases flow out of the cylinder [2]. The spring keeps the valve connected to the camshaft as it moves. The valve system moves in the valve guide, which may be an integral part of the cylinder head or may be a separate unit pressed into the head [4].

The most commonly used type of valves are the globe valves shown in Fig. 1, they have the following variations [6, 10]:

1. Uniform valves, valves made entirely of a single grade of steel
2. Bimetallic valves, where the stem is made of a different grade of steel than the plug and the parts are friction-welded. Valves of this type are mainly intake valves
3. Hollow-tube valves, a type of valve made of a single grade of steel hollow in the middle and filled with nitrogen [11].

Fig. 1. Valve set No. 6

1.2. Steels for engine valves

Many factors can cause a valve to fail, such as thermal overload caused by operating temperatures of up to 775°C for exhaust valves and 450°C to 550°C [1, 8, 9] for intake valves, mechanical or longitudinal cyclic stresses, and exposure to chemically attacking metals [7, 8, 12], such as lead tetroxide, which can cause corrosion. Intake and exhaust valve materials differ due to the operating conditions under which they are subjected. Exhaust valves operate under much heavier conditions than inlet valves and are subjected to, among other things, high temperatures, complex chemical erosion of gasses and potential particles [5, 8]. In the production of uniform valves, the intake and exhaust valves are manufactured from different types of steel [8]. In the case of inlet valves, these are ferritic-martensitic steels, e.g. X45CrSi9-3 or X80CrNiSi20; in the case of outlet valves, austenitic steels, e.g. X53CrMnNiN21-9 or X50CrMnNiNbN21-9, are used. In the case of bimetal valves, the plug is made from X85CrMoV18-2 steel and the stem from a Cr-Si steel alloy such as X45CrSi9-3. In some situations, nickel alloys such as NiCr20TiAl designed for high-temperature service, thus providing high resistance to corrosion.

Table 1. Chemical composition of steel X45CrSi9-3

Object	Chemical composition [wt%]						
X45CrSi9-3	C	Mn	Si	P	S	Cr	Ni
	0.35–0.5	<0.7	2.0–3.0	<0.030	<0.030	8.0–10.0	<0.6

Table 2. Chemical composition of steel X53CrMnNiN21-9

Object	Chemical composition [wt%]						
X53CrMnNiN21-9	C	Mn	Si	P	S	Cr	Ni
	0.48–0.58	8–10	≤0.25	<0.045	<0.03	20–22	0.3–0.5

1.3. How engine valves are produced

The production of engine valves is a complex process starting with the selection of material, which is then cut to length in the form of steel rods supplied by the supplier and the ends are chamfered by grinding. The cut bars are then transferred to a hydraulic press, where they are swelled and forged to form the valve disc [3]. In the case of bimetallic valves, the disc section is first joined to the stem section and then swelled and forged. The next step is to machine the valve face and disc according to the customer's order and, in addition, to machine the stem in order to achieve the right transition between disc and stem. Finally, the stem end is machined to produce the corresponding grooves, which are the connecting element between the valve and the rocker arm. Once the valves have been manufactured, they are tested to check for any defects using ultrasonic inspection and, finally, the valves are cleaned in an alkaline bath [6].

2. Research objective and method

2.1. Subject of the study

The subject of the tests conducted in this study was six sets of engine valves, each consisting of one intake valve and one intake valve, in order to evaluate engine valve materials. All that is known about each pair of valves is that they operated in an engine with a different displacement and drove a different mileage or, as in the case of pair number 3, experienced engine failure. Half of the valves worked in a diesel engine and the rest in a gasoline engine. The valves were labeled as follows:

Table 3. Overview of valve sets

Set 1	Petrol 2.0 mileage 200,000 km
Set 2	Diesel 1.9 TDI, mileage 250,000 km
Set 3	Diesel 1.9 broken timing belt
Set 4	Petrol 1.4, mileage 110,000 km
Set 5	Petrol 1.8 mileage 230,000 km
Set 6	Diesel 2.0 TDI mileage 200,000 km

2.2. Methodology of research

All tests were conducted on samples cut from valve cross sections. Microscopic examinations were performed using a Nikon Eclipse MA 200 metallographic microscope coupled to a Nikon CCD MA digital camera. The studies were carried out at magnifications ranging from 100× to 500× in the undigested state and after etching. The samples were etched electrolytically after which the images were taken again. Hardness measurements were made using the Vickers method with a Zwick Roell Z2.5 hardness tester under a load of 2 kgf (19.61 N) at 15 s. Four measurements plus a control measurement were made for each sample. The chemical composition was analyzed in two ways. One method was analysis with a LECO GDS-500 A fluorescence spectroscope using fluorescence excited optical emission spectroscopy. The second method used to study the chemical composition was energy dispersive spectroscopy (EDS) performed with a JEOL JSM-6610A scanning microscope.

3. Results

3.1. Microscopic results

On microscopic examination in the unpreserved state, oxide inclusions in the form of bands of fine spherical black particles and larger, irregularly shaped silicate inclusions, which are ellipses of various sizes, can be observed in the inlet valves (Fig. 2a). In the case of outlet valves, groups of oxide inclusions and bright, irregular inclusions of titanium nitride compounds are similarly observed (Fig. 2b).

Each tests show for the inlet valves a tempering troostite structure with carbide precipitations, indicating that the steel has gone through a high tempering process (Fig. 3b). In the case of the exhaust valves, an alloyed austenite structure with carbide precipitations can be observed (Fig. 3a). The etching tests showed different grain sizes for the bottom valves and varying amounts of carbides, which influenced the values of the hardness measurements.

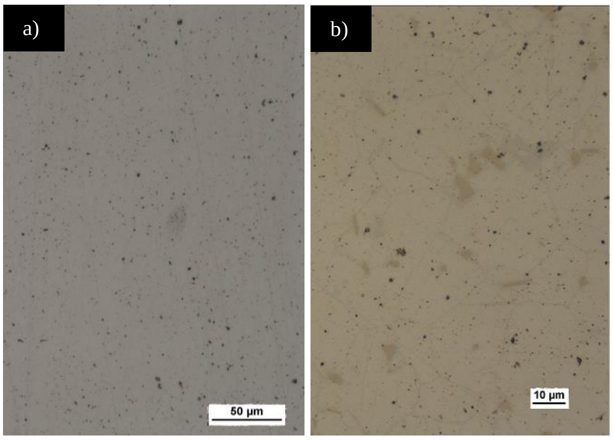

Fig. 2. (a) non-etched structure of the inlet valve from set 1 at (b) non-etched structure of the outlet valve from set 6

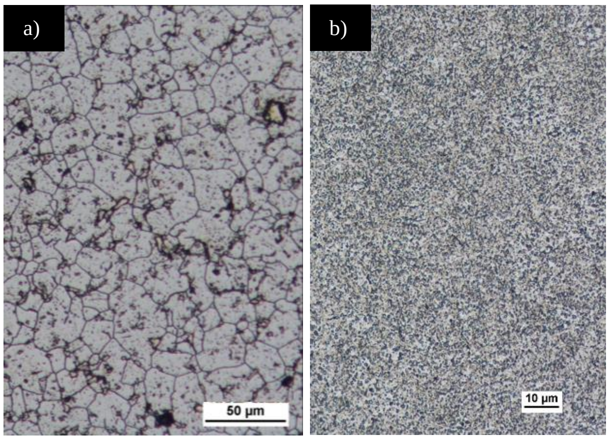

Fig. 3. a) alloyed austenite structure of the outlet valve from set 1 at b) troostite structure of the inlet valve from set 5

3.2. Chemical composition analysis

Investigations of the chemical composition with the fluorescence spectrometer were carried out in full for the sets 2,3,6; in addition, tests were made for the outlet valve of set 4 and for the inlet valve of set 5. The measurements showed that the outlet valves were made from a single steel grade, differing only minimally in the percent content of the elements. The steel from which the valves were made was 21-4NNbW, which is a medium-carbon heat-resistant alloy steel. In the case of the inlet valves, the valves were made from a single grade of steel, namely X45CrSi9-3, which is a medium-carbon heat-resistant chromium-silicon alloy steel and, as in the

Table 4. Chemical compositions of outlet valves

Object	Chemical composition [wt%]								
	C	Mn	Si	P	S	Cr	Ni	Nb	Ti
Set 2	0.535	9.33	0.264	0.007	0.003	21.29	3.62	1.82	0.028
Set 3	0.525	9.25	0.122	0.00	0.001	21.45	3.65	1.94	0.026
Set 4	0.572	9.12	0.332	0.01	0.005	21.21	3.66	1.77	0.03
Set 6	0.498	9.36	0.291	0.006	0.002	21.07	3.60	1.68	0.023

Table 5. Chemical compositions of inlet valves

Object	Chemical composition [wt%]								
	C	Mn	Si	P	S	Cr	Ni	Mo	Ti
Set 2	0.470	0.299	3.19	0.017	0.006	9.576	0.313	0.063	0.013
Set 3	0.455	0.268	3.34	0.009	0.006	9.754	0.172	0.033	0.012
Set 5	0.496	0.433	3.27	0.009	0.009	9.676	0.153	0.035	0.019
Set 6	0.471	0.314	3.53	0.005	0.008	8.955	0.087	0.032	0.026

case of the outlet valves, the same chemical composition contains the same elements with only minimal differences in elemental content. When tested by EDS, the valves tested were found to have similar significant element contents. In the case of the exhaust valves, the main elements with the highest content are Chromium at around 20%, Chromium at around 9% and Nickel at around 3%. As for the intake valves, similar values were found for the exhaust valves, with Chromium at around 9% and Silicon at around 3.5%. This allows us to conclude that the valves tested with EDS are made of the same steels as those tested with the glow spectrometer.

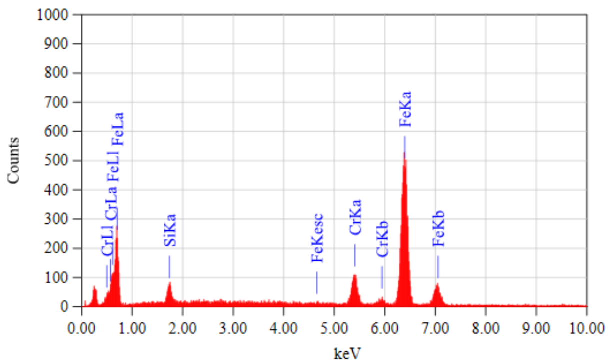

Fig. 4. EDS test spectrum for the inlet valve from kit no. 4

Table 6. Results of the chemical composition after EDS testing for the inlet valve from kit no. 4

Object	Chemical composition [wt%]		
Inlet valve	Fe	Cr	Si
no. 4	86.63	9.91	3.46

3.3. Results of hardness measurements

The results of the hardness measurements show a large discrepancy between the different valve samples, in the case of set No. 6 it can be seen that the inlet valve from this configuration obtained the highest average measurement result of 417.3 HV, while in the case of the outlet valves the second worst result was 321.6 HV and the best result was obtained by set No. 3, whose outlet valve obtained a value of 376.7 HV. The differences in hardness measurements are due to differences in microstructures and chemical compositions in the case of the inlet valve of set No. 6, it has the highest amount of silicon among the inlet valves, while the outlet valve of set No. 3 has the highest amount of chromium among the outlet valves.

Table 7. Averaged results of hardness measurements for sets 1-3

	Inlet valves	Outlet valves
Object	Average hardness [HV]	Average hardness [HV]
Set 1	353.2	323.3
Set 2	381.3	358.5
Set 3	394.0	376.7

Table 8. Averaged results of hardness measurements for sets 4-6

	Inlet valves	Outlet valves
Object	Average hardness [HV]	Average hardness [HV]
Set 4	378.9	303.4
Set 5	351.7	343.4
Set 6	417.3	321.6

4. Conclusions

On the basis of the tests carried out, it was found that in the case of the inlet valves, they were made from the X45CrSi9-3 steel grade, which is a medium-carbon alloy steel. These valves achieved quite varied hardness results, reaching higher hardness values compared to the valve steel in the exhaust valves. Testing in the undigested state showed the presence of oxides and silicates, which negatively affect the hardness and strength of the valves. In the pickled state, a tempering sorbite resulting from high tempering was identified. When analysing the chemical composition, we can note the presence of impurities in the form of sulphur and phosphorus, which negatively affect the hardness of the steel, but the high amount of chromium has a neutralising effect on the impurities. In addition, there are large amounts of silicon in the intake valve steels, plus the presence of elements such as titanium and manganese, which further affect the hardness and fineness of the steel. This allows us to conclude that the intake valve steel will perform well.

The steel grade of the exhaust valves is 21-4NNbW, which is a medium-carbon alloy steel. Similar to the inlet valves, the valves achieved quite different hardness measurements and these are due to the presence of an alloyed austenite structure. Tests in the undigested state showed a high presence of oxide inclusions and carbides affecting the hardness of the valves. In the case of the etched structure, the presence of a carbide structure in the alloy austenite matrix was identified. In the case of the chemical composition, we have the presence of impurities in the form of sulphur and phosphorus, negatively affecting the hardness and strength of the steel. However, the presence of a large amount of chromium and manganese reduces the influence of the presence of impurities; in addition, the large presence of elements such as manganese, nickel and cobalt are strongly austenitic elements, which only confirms the presence of an alloy austenite structure. In addition, manganese, chromium and titanium increase the hardness of the steel. In summary, the steel from which the outlet valves are made will perform well.

The design and materials of the valves allow us to conclude that both intake and exhaust valves, in their current form, will be a strong part of the engine. On the other hand, the fact that different grades of steel are used for exhaust and intake valves is due to the difference in operating conditions.

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