SCIENTIFIC
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Structural properties and comparative analysis of microhardness of an exhaust valve face strengthened with stellite and Fe_3Al intermetallic phase

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ABSTRACT:

In engines fuelled with concentrated natural gas, LPG, and other gaseous fuels, the necessity for more frequent replacement of exhaust valves is observed. These valves in combustion engines may be operated for a shorter period than their equivalents in engines fuelled with petrol and diesel oil. The exhaust valve face is most exposed to degradation. This stems from the combustion temperature of natural gas in the combustion chamber and the temperature of exhaust gas in contact with the valve. The paper presents a comparative distribution of microhardness in exhaust valves pad welded with Fe_3Al intermetallic phase and stellite.

Właściwości struktury oraz analiza porównawcza mikrotwardości przylgni zaworu wydechowego wzmacnianej stellitem oraz fazą międzymetaliczną Fe_3Al

Słowa kluczowe: mikrotwardość, zawór wydechowy, stellit, faza międzymetaliczna

Streszczenie:

W silnikach, w których stosuje się zasilanie sprężonym gazem ziemnym, LPG oraz innymi paliwami gazowymi, obserwuje się konieczność częstszej wymiany zaworów wydechowych. Zawory te w silnikach spalinowych mogą być eksploatowane przez krótszy czas niż ich odpowiedniki w silnikach zasilanych benzyną i olejem napędowym. Najbardziej narażona na degradację jest przylgnia zaworu wydechowego. Wynika to z temperatury spalania gazu ziemnego w komorze spalania oraz temperatury spalin mających kontakt z zaworem. W pracy przedstawiono porównawczy rozkład mikrotwardości w zaworach wydechowych napawanych fazą międzymetaliczną Fe_3Al oraz stellitem.

1. INTRODUCTION

According to a scenario published by the International Energy Agency, natural gas production in 2035 will show a 50% increase compared to production in 2010. [1] In the last decades, an increasingly significant number of natural gas vehicles can be observed in the transport industry [2, 3]. The path for finding new power sources for vehicles, ones capable of taking an important place in the fuel energy mix, is often the same as the one of efforts to reduce harmful emissions into the atmosphere. The development of new strategies aimed at freeing transport from conventional liquid fuels is leading to increased use of natural gas in this sector.

Use of both compressed natural gas (CNG) and liquefied natural gas (LNG) in internal combustion engines is common in passenger cars or trucks factory-fitted (OEM) with CNG systems. The growing demand for natural gas transported by sea is stimulating an increase in the production of LNG carriers. Implementing this fuel in maritime and inland shipping leads to measurable and economic benefits resulting from reduced fuel consumption and compliance with more stringent exhaust emission standards. The profitability of this investment has been particularly appreciated and studied in literature, for both land and sea transport. The economic feasibility of switching to natural gas for transport means increases in line with the distances travelled by the vessels; this is particularly important in terms of the amount of fuel consumed by the vessels and sulphur compound emissions.

When considering natural gas as a fuel, the following of its features need to be taken into account [4-6]:

- Methane has a higher octane number,
- Its flash point of 650°C is higher when compared to 350°C for petrol and 250°C for diesel),
- Its cetane number is lower,
- As a gas, it takes up more space in the engine's combustion chamber than its liquid fuel equivalent.

A comparison of the physicochemical properties of natural gas and other conventional fuels is presented in Table 1.

Natural gas demonstrates a very favourable ratio of energy produced by combustion of a given amount of natural gas versus the carbon content – the highest among all conventional liquid fuels. Comparative studies in literature on the subject, determining the emission of harmful compounds into the atmosphere by select trucks using natural gas-fuelled engines clearly demonstrate the benefits of using natural gas as a fuel in means of transport when compared to such vehicles with diesel engines. Vehicles with natural gas emit 76% less hydrocarbons, 90% less nitrogen oxides NO_x, 99% less PM dust and 23% less CO_2 compared to the same vehicles powered by diesel. [7]

However, burning natural gas in an engine engenders a risk of incomplete methane combustion and unburned natural gas entering the exhaust system (methane slip). The tightness of the combustion chamber throughout the vehicle's life cycle is important in this respect. The resilience of the exhaust valve face is a factor significantly influencing the combustion chamber's required tightness.

The exhaust valve is responsible for removing combustion products from the combustion chamber. Especially in the case of prolonged use, the valve seat is exposed to accelerated wear due to the higher combustion temperature of

Table 1 A comparison of the physicochemical properties of natural gas and other conventional fuels [6]

Selected parameters	Fuel			
	Petrol	Diesel oil	Natural gas	CNG (20 MPa)
Self-ignition temperature [°C]	260	210	580	
Energy density [MJ/L]	34	39	0.039	9.54
Energy equivalent of 1 litre of petrol [l]	1l	0.87	0,8	3.56
Calorific value [MJ/kg]	45,7	47	53	53
Octane number	92-98	-	-	130
Cetane number	5-20	40-55	0	0

natural gas in the combustion chamber. This results in an increased risk of methane slip in the exhaust system. However, this issue arises from the design of internal combustion engines, not from the nature or properties of natural gas.
A diagram of the valve face – valve seat friction pair is shown in Figure 1.
The influence of the number of work cycles, combustion pressure, and temperature on valve wear was investigated by Y. Wang. In 1996, his team proved that the valve's abrasive wear grows as pressure in the combustion chamber increases. However, a reduction in valve wear along with increasing temperature was observed. This effect is attributed to the surface layer of metal oxides that forms when the exhaust valves comes into contact with the high-temperature exhaust gases. [9, 10]

2. OWN RESEARCH

Stellite alloys are currently the most common method of strengthening the exhaust valve's face. Stellites are alloys based on cobalt with chromium and contain approx. 30% Cr, 4-17% W and 1.0-3.2% C. They are primarily used as coatings that increase the wear resistance of non-lubricated tribological pairs, also at high temperatures. For this reason, they have found their application as hardfacing for valve faces of currently produced exhaust valves. Stellite 6 and Stellite 12 are typical uses for cobalt matrix coatings. Stellite 6 and 12 are cobalt-based hardened alloys with high corrosion and high temperature operation resistance. They are used in friction pairs, for example as a surface layer for valve faces in internal combustion engines, in gas turbines, aviation turbines, in the petrochemical industry and in the energy sector [11, 12].
It has been observed that exhaust valves in combustion engines fuelled with natural gas require replacement more often than petrol engine valves.
Microhardness measured parallel and perpendicular in relation to the valve has been compared for an Fe_3Al intermetallic phase and a stellite hardfaced valve face. For this, a cross-section of an exhaust valve head was prepared and mounted. Then the samples were tested on a Zwick/Roell ZHV-30S hardness tester in accordance with the PN-EN ISO 6507-01:2018-05 standard. Twenty-five measurements were taken perpendicular to the valve axis and 15 measurements parallel to the valve axis.
Figure 1 shows a sample prepared for testing with Fe_3Al intermetallic phase hardfacing.

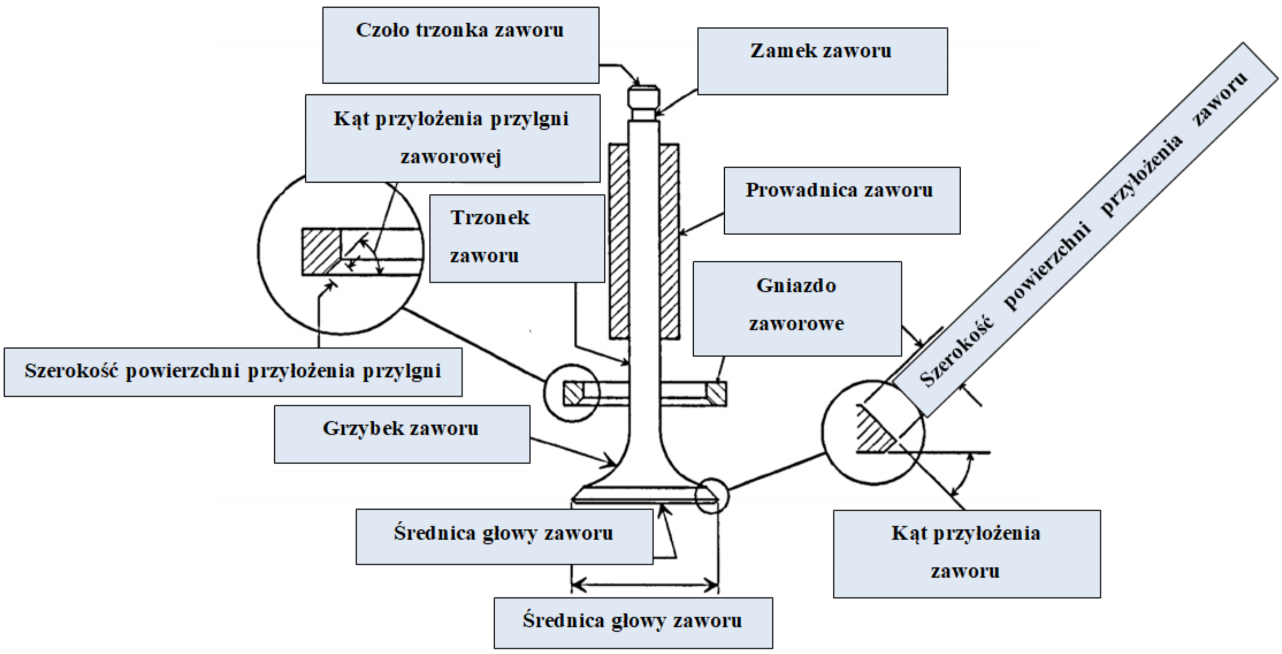

Figure 1 Diagram of a valve, including the valve face – valve seat friction pair [8]

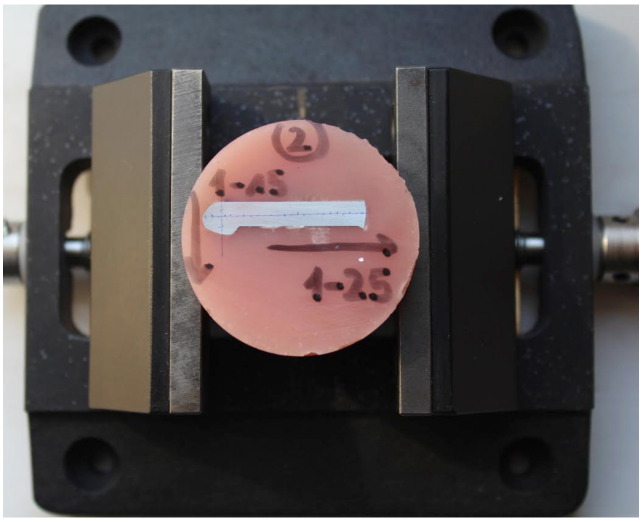

Figure 2 Sample of an Fe_3Al hardfaced valve prepared for microhardness tests

The microhardness value for the tested valves with a stellite valve face was between 310 $HV_{0.2}$ and 430 $HV_{0.2}$ for the test conducted perpendicular to the valve axis. In the parallel direction the measured microhardness was in the 225 $HV_{0.2}$ - 285 $HV_{0.2}$ range. The microhardness value for the tested valves with their face reinforced with the intermetallic phase Fe3Al ranged from 330 $HV_{0.2}$ to 453 $HV_{0.2}$ for the test conducted perpendicular to the valve axis. In the parallel direction the measured microhardness was in the 292 $HV_{0.2}$ – 424 $HV_{0.2}$ range. The highest $HV_{0.2}$ values were obtained at the valve face surface. The microhardness value decreased as the vale axis was approached. Measurement results for valves with stellite and Fe_3Al intermetallic phase hardfacing on the valve face are shown in Table 2.

Table 2 Measurement results for stellite valves in an engine powered with petrol and CNG

	Microhardness in the perpendicular direction		Microhardness in the parallel direction	
Measurement number	Valve with stellite hardfacing on the valve face	Valve with Fe_3Al intermetallic phase hardfacing on the valve face	Valve with stellite hardfacing on the valve face	Valve with Fe_3Al intermetallic phase hardfacing on the valve face
1.	401	453	225	293
2.	392	442	234	302
3.	388	428	252	314
4.	380	422	258	308
5.	374	418	264	292
6.	369	412	272	312
7.	366	415	285	318
8.	370	404	281	327
9.	334	372	272	336
10.	310	384	262	342
11.	347	372	267	356
12.	330	362	262	373
13.	362	372	254	382
14.	353	367	248	412
15.	342	334	249	424
16.	340	352		
17.	349	330		
18.	323	333		
19.	340	362		
20.	370	385		
21.	415	402		
22.	420	415		
23.	417	407		
24.	430	435		
25.	428	422		

The above results have been visualised. Figure 3 shows microhardness perpendicular to the valve axis with a stellite hardfaced valve face.

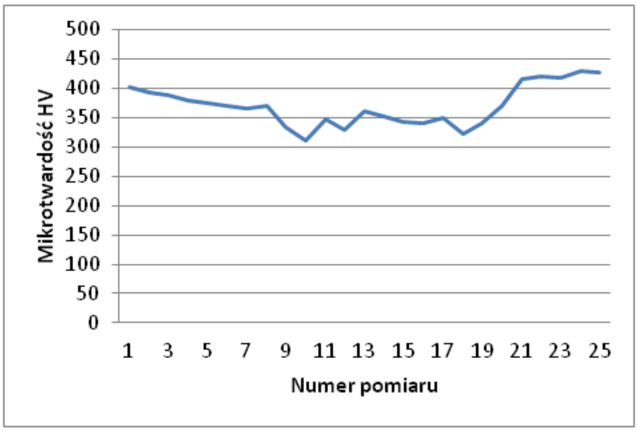

Figure 3 Shows microhardness perpendicular to the valve axis with a stellite hardfaced valve face

In a test carried out perpendicular to the axis of the valve, in which the seat was reinforced with stellite, the microhardness reaches the highest values in the area of the valve seat. This is due to the presence of a layer of stellite used in hardfacing the valve face. The microhardness reaches a maximum of approx. 400 $HV_{0.2}$ and decreases with distance from the stellite layer towards the valve stem. Increased hardness is observed in the area close to the valve stem.

Figure 4 shows the microhardness distribution in the direction perpendicular to the axis of a valve with stellite hardfacing on the valve face

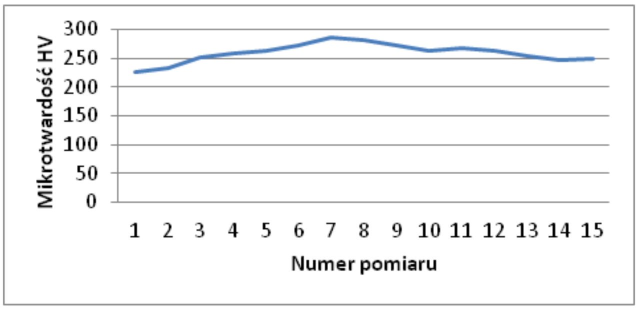

Figure 4 Microhardness distribution in the direction perpendicular to the axis of a valve with stellite hardfacing on the valve face

In a test performed perpendicular to the valve axis, in which the valve face was reinforced with stellite, the microhardness reaches the highest values in the conical contact surface between the valve face and the valve seat. This is due to the presence of a layer of stellite used as hardfacing for the valve face. Microhardness reaches the lowest value at the initial testing point in the lower part of the valve head, where the amount of stellite is the lowest, and amounts to approx. 230 $HV_{0.2}$. The maximum microhardness value has been observed at points near the valve face, approximately 280 $HV_{0.2}$. This is due to the presence of the greatest amount of stellite. Figure 5 shows the microhardness distribution perpendicular to the axis of a valve with Fe_3Al hardfacing on the valve face.

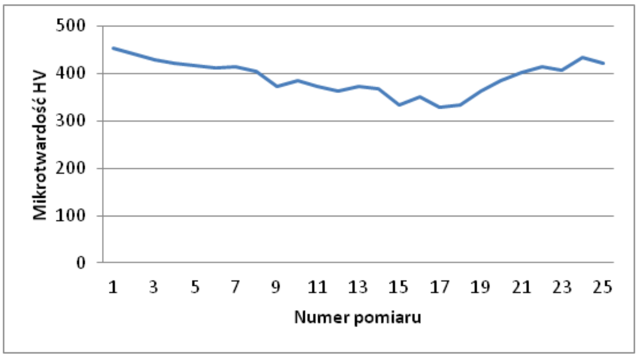

Figure 5 Microhardness distribution perpendicular to the axis of a valve with Fe_3Al intermetallic phase hardfacing on the valve face

In the microhardness test performed parallel to the axis of the valve with Fe_3Al intermetallic phase hardfacing, the highest microhardness values are observed in the coated area and are approximately 450 $HV_{0.2}$. Microhardness decreases along with the boundary between the padding and the base material. This is caused by a decrease in the proportion of the padding in the substrate and an increase of the base material. Figure 6 shows the microhardness distribution in the direction parallel to the axis of a valve with Fe_3Al intermetallic phase hardfacing on the valve face.

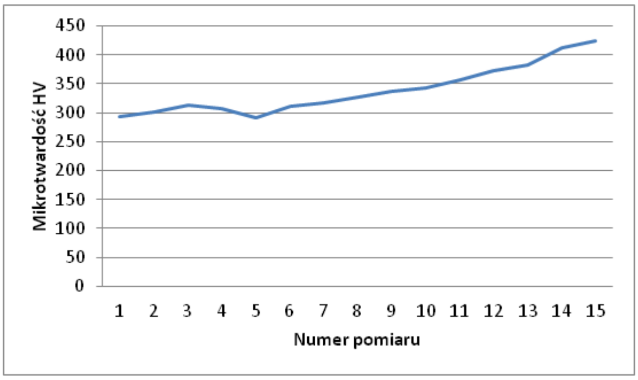

Figure 6 Distribution of microhardness in the direction parallel to the axis of a valve with intermetallic phase Fe_3Al hardcoating on the valve face

Microhardness reaches the lowest values in the lower part of the valve head, where there is no surface hardening, and amounts to approx. 298 $HV_{0.2}$. The microhardness increases along with the proportion of the padding in the valve face structure, reaching approx. 420 $HV_{0.2}$ where the padding has the largest share in the tested area. Figure 7 shows a comparison of the microhardness in the direction perpendicular to the axis of valves with stellite and Fe_3Al intermetallic phase hardfacing.

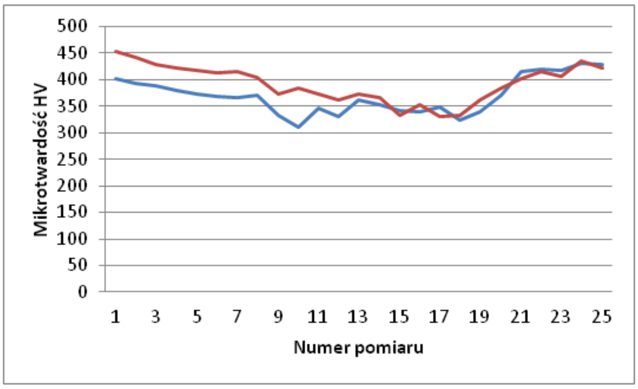

Figure 7 Comparison of microhardness distribution perpendicular to the axis of a valve with intermetallic phase Fe_3Al and stellite hardfacing of the valve face

The microhardness distribution points to increased microhardness within the valve face area with Fe_3Al intermetallic phase hardfacing when compared to stellite hardfacing. The distribution of microhardness in subsequent test points is similar due to the lack of valve surface reinforcements in these locations. Figure 8 shows a comparison of microhardness distribution in the direction parallel to the axis of a valve with stellite and Fe_3Al intermetallic phase hardfacing on the valve face.

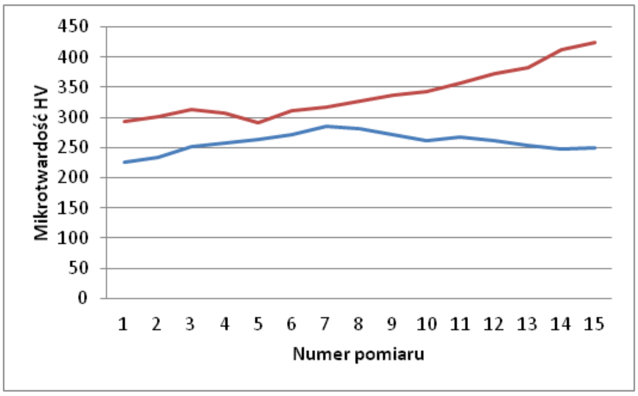

Figure 8 Microhardness distribution perpendicular to the axis of a valve with intermetallic phase Fe_3Al and stellite hardfacing of the valve face

Conducting a measurement in the direction parallel to the valve axis, there is a noticeable difference in the microhardness distribution at all test points. This is probably related to the visible presence of the intermetallic phase in the valve face area. A significant difference was observed in the microhardness at the end points during the test due to the presence of a greater proportion of intermetallic phase Fe_3Al in the examined area

3. CONCLUSIONS

Accelerated engine valve wear has for many years been a problem for internal combustion engine designers and manufacturers. Ongoing research in valve wear results in the development of newer materials for producing valves and improved manufacturing technologies. However, these advances are offset by demands related to increased engine performance. In a test carried out perpendicular to the axis of the valve, in which the seat was reinforced with stellite, the microhardness reaches the highest values in the area of the valve seat. This is due to the presence of a layer of stellite used as hardfacing for the valve face. For the same reason, in a test performed perpendicular to the axis of a valve with stellite hardfacing, the microhardness reaches the highest values in the conical contact surface between the valve face and the valve seat. In the microhardness test carried out parallel to the axis of the valve with Fe_3Al intermetallic phase hardfacing, the highest microhardness values are observed in the coated area and are approximately 450 $HV_{0.2}$. In a similar test of a stellite hardfaced valve, the single-point microhardness was, at its highest point, lower by approx. 50%. The microhardness distribution points to an increase in microhardness within the valve face area with Fe_3Al intermetallic phase hardfacing when compared to stellite hardfacing. The intermetallic phase part entails a local increase in the hardness of the hardfaced areas, which may translate into a reduction of wear during drive unit operations.

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