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Comparison of ignition engine valves of various construction

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The article juxtaposes monolithic and bimetallic valves – stratified and welded. Technology of production of the analysed valves and the comparison of the applied materials have been discussed in the article. Labour consumption and production costs have been compared. Heat transfer for particular valves and their impact on the engine work have been analysed.

1. Introduction

Valves applied in the combustion engines control supplying of the fresh load to the cylinder and exhaust of gases. They are subject to quickly-changing loadings arising from the pressure of gases in the combustion chamber, force resulting from the deflection of the valve springs, pressure force to the valve seat, and the valves produced as a result of heating. A valve is to fulfil its role in all possible conditions of the engine work. It is required also to be relatively light, have good heat abstraction characteristics, and be inexpensive in production. The presented demands are difficult to fulfil. Characteristics of valves manufactured with various technologies have been shown below.

2. Technologies of valves production

The process of manufacturing of valves is complex and multi-staged due to the demands made for valves, as well as for the materials they are made from, and the mass scale of their production. At present, there are two the most frequently applied methods of obtaining the forgings of the combustion engine valves. These are:

- induction heating and extrusion,
- electro-upsetting and forging.

The forging stock for the production of forgings with the induction heating and extrusion method are drawn or peeled bars of tolerance of h13, diameter of about 2/3 diameter of the valve forging head. The method is used for production of the small-size valves. Its characteristic feature is high efficiency and high repeatability of the dimensions. The extrusion method runs, as follows: a stem of a valve is formed in a matrix by extrusion from previously prepared segment of a bar, leaving on its end an unformed piece of the bar. Next, the semi-finished product is placed on another matrix, where the valve disk is pressed. Figure 1 presents a scheme and a picture of hot extrusion of valves.

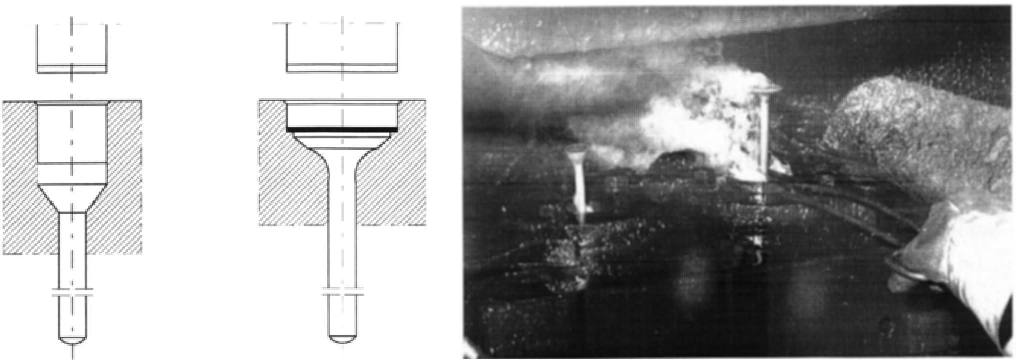

Fig. 1. Preliminary and final extrusion on the crank press „Maxi" Eumuco SP65
Rys. 1. Wyciskanie wstępne i na gotowo na prasie korbowej „Maxi" Eumuco SP65

The stock for production of valves using the electro-upsetting and forging method are polished bars of a diameter close to the diameter of the stem; the diameter is enlarged only for the indispensable allowance for the mechanical machining. Depending on the type, the volume of the allowance is 0,50÷1 mm. Upsetting and forging is a method of high efficiency of production of the semi-finished products for valves and is applied mainly for manufacturing of the valves of greater mass. The above mentioned method consists in: a semi-finished product is made from a bar of the diameter equal to the diameter of the valve stem. Afterwards, the arising fat edge is formed to a disk in the same matrix, as used in the extrusion method. A diagram and the photo of the course of the process has been shown on the figure 2 and 3.

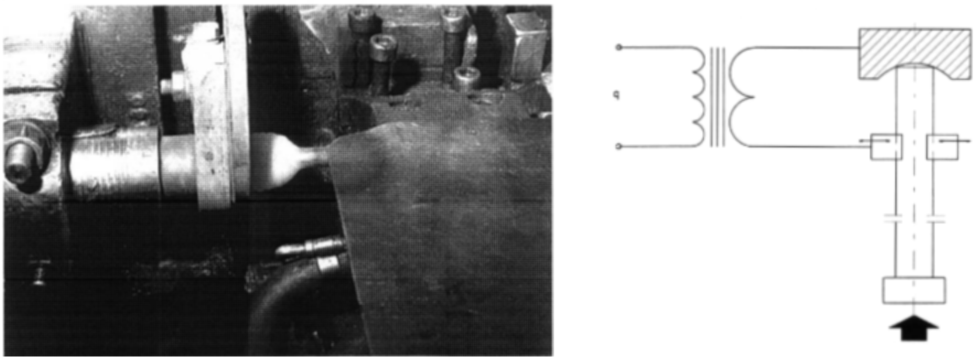

Fig. 2. Course of the upsetting process
Rys. 2. Przebieg procesu spęczania

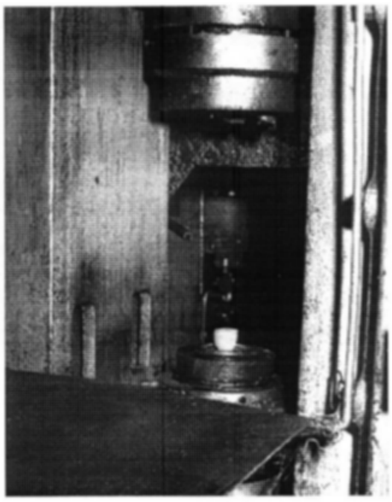

Fig. 3. Forging of the semi-finished product on the Hansenclever press
Rys. 3. Kucie półwyrobu na prasie Hansenclever

Another proposition is the production of the stratified bimetallic valves (fig.4).

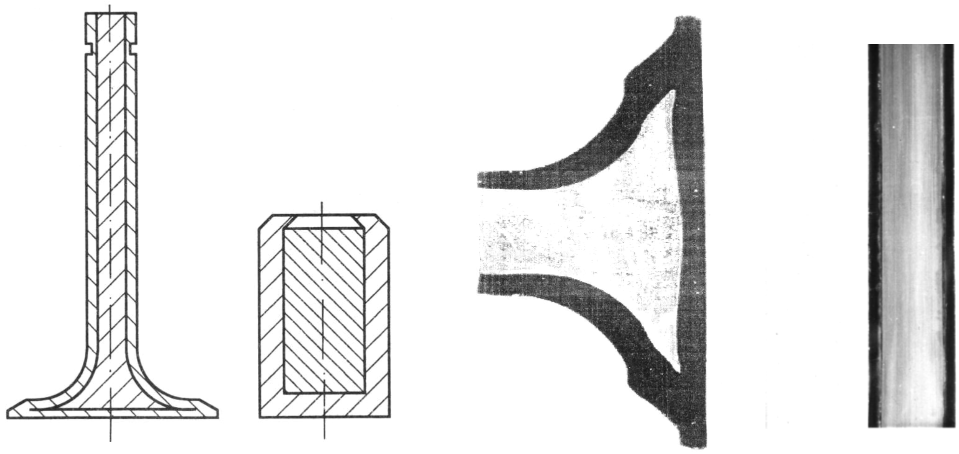

Fig. 4. Cross-section of a stratified bimetallic valve and a semi-finished product for its production
Rys. 4. Przekrój bimetalowego zaworu warstwowego i półwyrobu do jego produkcji

The stock here is the valve steel 50H21G9N4, which is for the external coating, whereas the core is made from the constructional steel, for example 45. Shaping of the valve is by hot extrusion, but there is an additional operation of preparing of the semi-finished product. To fulfil the demands of the mass production the manufacture of the semi-finished product must be highly efficient and can be realised by plastic working.

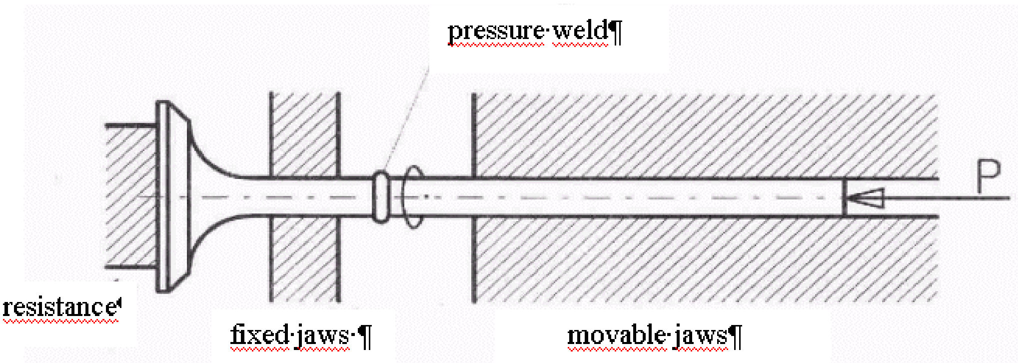

Fig. 5. Friction welding of a valve head with the stem
Rys. 5. Zgrzewanie tarciowe grzybka zaworu z trzonkiem

The demands made for the valve heads and stems are to a great extend contradictory, which is the result of different working conditions of the elements. The difficulties led to the development of methods of producing the bimetallic valves. Presently, there are valves, whose head is made from highly alloyed heat-resisting steel, whereas the stem is of the steel resistant to abrasion and seizing. Manufacturing of such a valve consists in forging of the head in a matrix, and afterwards, linking it with the stem by friction or electro-resistance welding. Welded valves can be made both in case of extruded and forged valves. Economic calculation decides of applying of welding in the mass production.

3. Analysis of the production costs of valves

It can be inferred from the analysis performed by the authors [11] that the costs are least during the production of valves by the induction heating and extrusion method. If we assume the cost of producing a valve by this method is equal to 1, the production costs of a valve by the electro-heating and extrusion + welding is 1,15, of a valve by electro-upsetting and forging is 1,20, whereas a valve made using electro-upsetting, forging and welding – 1,44. Special attention, in terms of the costs, should be paid to the stratified bimetallic valve. As simple computations show, introducing a core of constructional steel enables to diminish the wear by 40% of very expensive highly alloyed valve steels. The buying cost of 1 kg of the valve steel was about 22 zł/kg at the end of the year 2003, and of 1 kg of steel 45 – about 2,5 zł/kg.

4. Heat transfer in the combustion chamber of an engine

During the combustion reaction of the air-fuel mixture, great amount of heat is emitted. Thermal balance of an engine enables to determine the amount of heat provided to the effective work and to determine the heat carried away from the engine [7]. A part of the heat is released by the exhaust valve. Main equation of the thermal balance looks as follows:

$$Q = Q_e + Q_{ch} + Q_w + Q_n + Q_r,$$

where:

Q – heat provided to the engine, Q_e – effective heat,
Q_{ch} – cooling losses, Q_w – exhaust losses,
Q_n – losses of incomplete or deficient combustion,
Q_r – rest of balance,

It is assumed for the spark-combustion engines that efficient heat is about 24÷28 %, cooling loss 30÷32 %, exhaust losses of incomplete or deficient combustion 36÷40 %, and the rest of balance is about 8%.

Heat provided to the engine was defined on the basis of the dependence:

$$Q = G_e \cdot W = 240000 \text{ kJ/h} \quad (G_e \text{ – fuel consumption per hour, } W \text{ – heat value}) .$$

Efficient heat was defined from the equation:

$$Q_e = 3600 \cdot N_e = 57200 \text{ J/h.} \quad (N_e \text{ – power output}).$$

Cooling losses were determined from:

$$Q_{ch} = \sum G \cdot C \cdot (t_2 - t_1).$$

(G – expenditure of the cooling factor, C – specific heat, $(t_2 - t_1)$– difference of temperature on the inlet and outlet of the engine).

Heat, given away by the head walls, was determined basing on the Newton's equation

$$Q = A \cdot \alpha\ (t_o - t_s)$$

(A – surface area of the wall receiving heat, α – heat transfer coefficient, $(t_o - t_s)$ – difference of temperatures of walls and the surroundings).

For the purpose of determining the heat transfer coefficients, the dependencies worked out by Woschni [2,6] were used, and for the outlet channel by the authors Nishiwaki, Shimamoto, and Miyake [9]. The differences of temperatures were determined on the basis of the average value of temperature during one engine working cycle and the temperatures of the combustion chamber walls [10].

Amount of heat supplied to the engine head from the combustion chamber and the outlet channel was estimated for 780 W and 630 W. Amount of heat carried away from the combustion chamber and the outlet channel by the monolithic channel was defined on the basis of computations. Amount of heat carried away by monolithic, bimetallic-stratified, and welded valve received from the computations are: 41,8 W, 47,3 W i 41,9 W. For the monolithic and welded valve it is about 2,95% of the total amount of heat. In the bimetallic valves the share amounts to about 3,35 %.

5. Analysis of the heat transfer of the valves

The aim of the authors was to compare the impact of the design of the valves on the heat transfer in the cylinder. A monolithic valve was used for the comparison, made by extrusion, applied presently in the engine. Characteristics of valves: the bimetallic and the friction-welded made from different materials for the head and the stem, the same technology applied for manufacturing of both of them, have been compared to the results of the monolithic valve. The temperature distribution and the thermal balance have been subjected to comparison. A valve with the cooperating valve guide have been analysed.

A valve of a head diameter ϕ = 28 mm and length l = 116 mm, applied to the air-cooled engine, has been chosen for the comparison (due to the much higher work temperature).

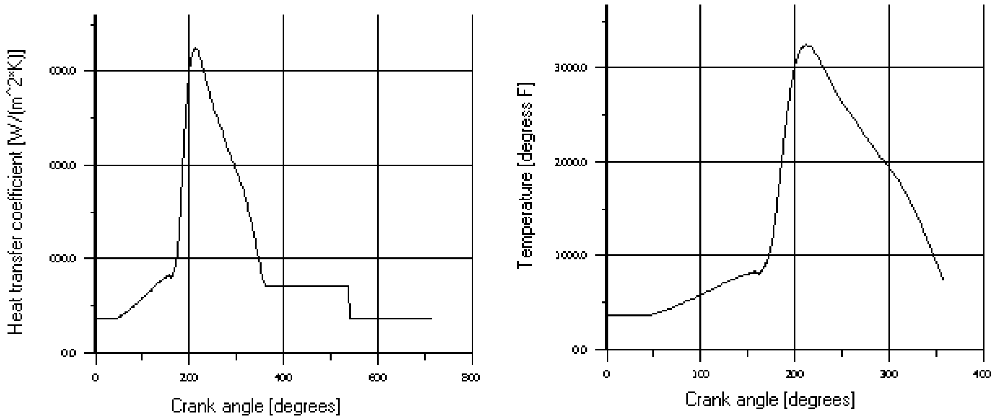

Fig . 6. Course of the temperature *T’* and the coefficient of heat transfer α' for one engine working cycle
Rys. 6. Przebieg temperatury *T’* i współczynnika przejmowania ciepła α' dla jednego cyklu pracy silnika

Working conditions corresponding to the rotational speed of 3500 rpm of the engine have been assumed. The average working conditions of a valve for the whole cycle have been determined for the analyses [12].

Average values for the working cycle of an engine may be defined from the analysis:

$$\overline{\alpha} = \frac{\Delta\varphi_o \cdot \alpha'}{2\pi} \quad \text{and} \quad \overline{T} = \frac{\Delta\varphi_o \cdot \alpha' \cdot T'}{2\pi \cdot \overline{\alpha}} .$$

($\Delta\varphi_o$– a increase of the crank angle on an engine).

Finite elements method has been used for the analyses of the heat transfer between a valve and a guide. Computations have been made in the ANSYS system. A 3D model of an exhaust valve with a guide, containing 45425 knots and 67868 elements, has been prepared for the purpose. For the description of the geometry of the valve the SOLID87 elements have been used. Simplifications have been assumed during the building of the model, presuming that the temperature of the factor in the cylinder is average for the whole cycle, as well as the temperature of the factor in the outlet channel and on the guide. Heat transfer conditions have been determined from the charts shown in figure 6. It has been also assumed that the sealing of the valve is appropriate and the clearance in the crevice between the valve and the guide is uniform. Amount of heat transferred with the surroundings through the walls of the model, and specifically by particular SOLID87 elements, has been analysed. Amount of heat has been summed according to the heat transfer conditions. On the basis, the amount of heat transferred with the surroundings has been defined for the analysed parts of the valve. For such determined object at the specified assumptions, computations of heat transfer by valves of various designs have been carried out.

As a result of analyses, the amount of heat transferred with the surroundings for the analysed fragments of a valve has been determined.

After comparison of valves of various design, relying on analyses of the assumed model of the valve work, it turned out that the double-layered – bimetallic valves enable to increase the amount of heat abstracted from the combustion chamber and the outlet channel from 41,8 W to 47,3 W; from the combustion chamber from 18,8 W to 21,5 W. Figure 7 presents the thermal balance for a valve with a guide. For comparison, the table 1 juxtaposes the share of the heat received and released by valves of various design.

Table 1. Share of particular fragments of a valve in heat transfer
Tabela 1. Udział poszczególnych elementów zaworów w przenoszeniu ciepła

No.	Fragment of a valve	Valve		
		monolithic	bimetallic	welded
heat provided				
1	Combustion chamber	44,9	45,3	45,7
2	Seat face of a valve	0,0	1,6	0,0
3	Arc part of a valve	0,1	0,5	0,1
4	Cylindrical part of a valve 1	3,8	6,0	3,1
5	Cylindrical part of a valve 2	16,4	17,0	17,3
6	Guide, frontal part	33,9	29,2	32,7
7	Guide, bottom part	0,5	0,05	0,5
8	Guide, upper part	0,3	0,3	0,4
heat abstracted				
1	Seat face of a valve	0,5	0,0	0,5
2	Arc part of a valve	23,0	16,9	23,4
3	Cylindrical part of a valve 1	1,4	0,5	1,0
4	Cylindrical part of a valve 2	0,0	0,0	0,0
5	Guide, frontal part	0,0	0,0	0,0
6	Guide, bottom part	56,3	63,9	55,7
7	Guide, upper part	13,0	13,4	13,3
8	Seat face of a valve	1,6	1,4	1,7
9	Upper part of a valve	3,4	3,6	3,4

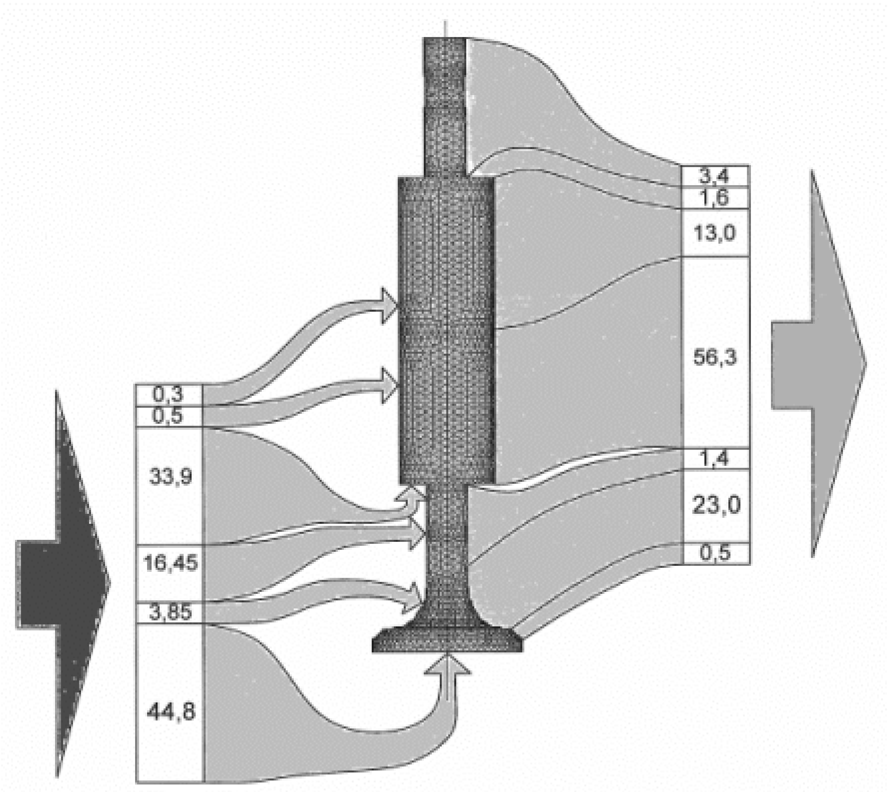

Fig. 7. The thermal balance of an outlet monolithic valve
Rys. 7. Bilans ciepła zaworu wylotowego o budowie monolitycznej

Relying on the results from the table 1 it can be stated that about 45% of hest is supplied to the valve head from the side of the combustion chamber, 22÷25 % to the part of the valve that is located in the outlet channel, and about 30÷34 % to the frontal part of the guide. Heat is to a lesser extent given away by the valve face, about 17÷23 % by the arc part of a valve, 70÷77 % by the valve guide and about 3,5% by the upper part of a valve. The remaining share of heat supplied and abstracted do not exceed 2 %. Heat transfer in the monolithic and the welded valve is very similar. Application of the double-layered bimetallic valves leads to the increase of the heat received by the valve in the "channel" part and decrease of the amount of heat received by the guide (by about 5%). The alteration results in the increase of the amount of heat given by the guide to the engine head (by about 7 %). The changes are caused by higher temperature of the bimetallic valve in the "channel" part and in the part cooperating with the guide.

6. Comparison of the mechanical characteristics of valves

6.1. Determination of the resistance characteristics of valves by the use of the shearing method

To define the resistance characteristics of valves with a core, as well as to compare them with the resistance of the traditional valves, a series of examination has been carried out, based on the Stefan Balicki method [3].

A few years of research on the adaptation of the shearing method to the evaluation of the resistance of the materials at the static loading enabled to determine dependencies between the resistance to uni-, bi-, and triple axial tension, and the proportion: $\frac{R'_{sp}}{R'_m}$.

Basic equations of the method have been put on figure 8. According to the figure, at the proportion $\frac{R'_{sp}}{R'_m} = 0{,}65$, there is the state of material that is characterised by identical resistance to uni-, bi-, and triple axial tension. It may be inferred from a number of research that the material of maximal R'_m is characterised by the maximal extension *A%*, the material of maximal resistance to biaxial tension R^+_m is characterised by maximal impact resistance, and the material of maximal resistance to triple axial tension R^*_m - by maximal narrowing $Z\,\%$.

State of the material $R'_m = R^+_m = R^*_m$ is confirmed by the literature data. A shearing test has been performed for a series of experimental bimetallic valves and, for a comparison, for traditional valves.

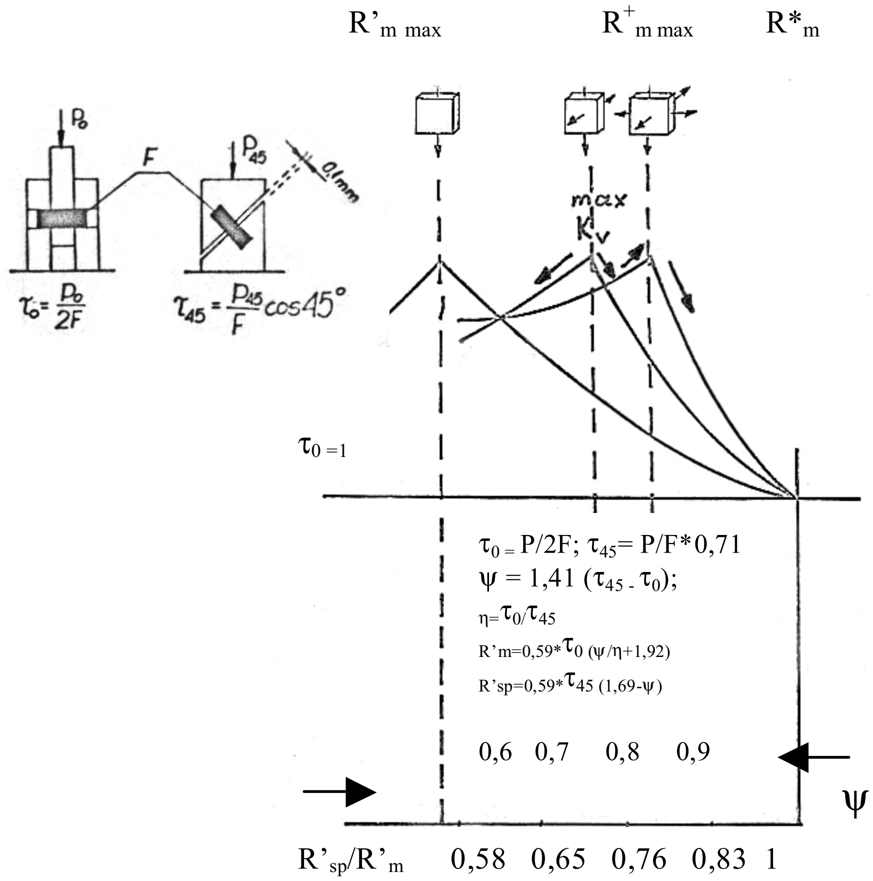

Fig. 8. Adaptation of the shearing test for the evaluation of the resistance of materials at the static loadings
Rys. 8. Przystosowanie próby ścinania do oceny wytrzymałości materiałów przy obciążeniach statycznych

The test has been performed on the testing machine, with the usage of a straight and angular (45°) matrix, anticipated by the theory of Balicki [3]. Parameters' values have been calculated according to the equations contained in the figure 8 and have been presented in table 2, together with the results of measurements. It can be noticed after the analysis of the proportion $\frac{R'_{sp}}{R'_m}$ that valves, in spite of applying of various materials of the core, do not exhibit significant differences. After dismissing of the extreme results, the average values of the quotient $\frac{R'_{sp}}{R'_m}$ are:

- for valves with the core 25 – 0,760
- for valves with the core 10 - 0,761
- for valves with the core 45 - 0,713
- for traditional valves - 0,721

Visible differences appear in the forces P_o i $P_{45.}$ Average values of forces P_o i P_{45} are, respectively:

- for valves with the core 25 P_o= 63,75 kN P_{45}= 56,6 kN
- for valves with the core 10 P_o= 54,0 kN P_{45}= 45,5 kN
- for valves with the core 45 P_o= 69,5 kN P_{45}= 60,4 kN
- for traditional valves P_o= 79,2 kN P_{45}= 67,7 kN

Taking into account the fact that in case of valves there is the possibility of shearing only around the valve key on the surface of the section of the jacket made of the valve steel, the above differences of forces Po i P45 are insignificant, which has been confirmed by the preliminary resistance tests, during which the valve has been extended by the testing machine with the forces applied through the key and the proper grip surrounding the valve head. The method did not lead to the breaking of the valve but there was a truncation of the key area around the valve steel jacket, both for the bimetallic and traditional valves.

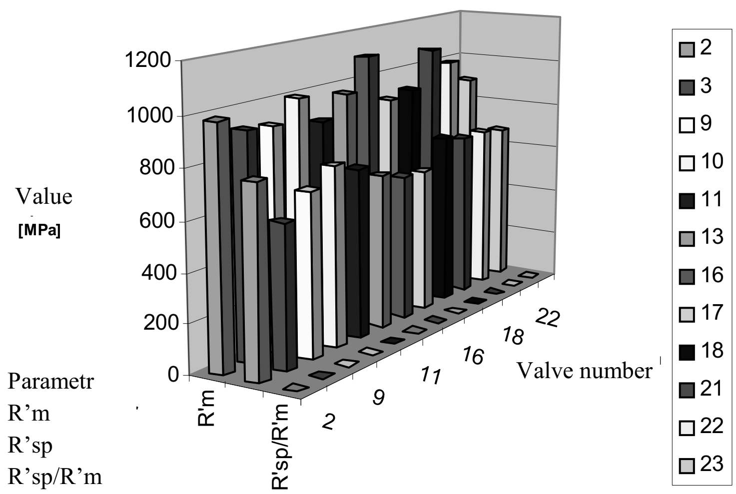

Fig. 9. The results of measurement of the resistance characteristics of bimetallic valves with the core of steel 45

Rys. 9. Wyniki pomiarów właściwości wytrzymałościowych zaworów bimetalowych z rdzeniem ze stali 45

Table 2. The tabular juxtaposition of the results of the measurement of the resistance characteristics of valves with the core of steel 45
Tabela 2. Zestawienie wyników pomiarów właściwości wytrzymałościowych zaworów z rdzeniem ze stali 45

No. of a valve	R'_m	R'_{sp}	R'_{sp}/R'_m	No. of a valve	R'_m	R'_{sp}	R'_{sp}/R'_m
2	980,2	773,6	0,789	16	1100,8	605,1	0,560
3	921,2	584,2	0,634	17	893,9	600,8	0,672
9	911,0	673,4	0,739	18	916,0	715,5	0,781
10	995,8	743,6	0,746	21	1069,8	688,6	0,644
11	878,2	700,0	0,797	22	992,5	694,7	0,700
13	966,0	643,3	0,666	23	893,5	674,9	0,756

Table 2 and figure 9 present the results of measurement of the resistance characteristics of valves with core 45.

6.2. Analysis of the mechanical loadings of valves

The finite elements method is presently widely applied in the engineer design. It is treated as a universal verification of the modelling methods, analysis and evaluation of the technical objects. The presented in the paper analyses have been made with the finite elements method ANSYS.

The scheme of creating the model has been based on, successively, base points, lines, surfaces and the spatial areas. For a geometrical model prepared in such a way in the PROCESSING pack, the type of element has been defined during the creation of the grid of the finite elements for the spatial area of a valve. A SOLID92 element has been used for the static analyses. Afterwards, the division of the spatial area of a valve for the finite elements (MESH) has been made, and 17 908 elements have been obtained.

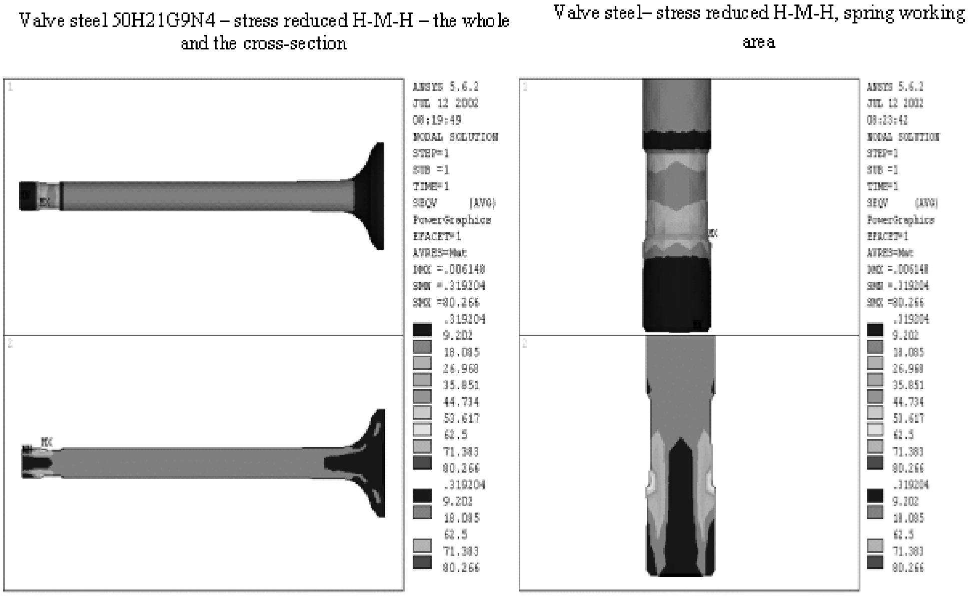

Fig. 10. The stress distribution in a traditional valve (valve steel)
Rys. 10. Rozkład naprężeń w zaworze klasycznym (stal zaworowa)

Material characteristics of the coating and the core have been defined.

For the purpose of the computations, the following computation conditions have been assumed:

- loading arising from the pressure of combustion chamber equal to 3,5 MPa, distributed uniformly on the whole frontal face of a valve head,
- loading with a force coming from the spring – 500 N, applied to the resistance surface of a valve key (direction X),
- fastening of the model by dismissing of the degree of freedom on the surface of a valve face (direction X, Y and Z),
- fastening on the resistance surface of a valve key (direction Y and Z).

The numerical model prepared in such a way has been solved, and the results in the form of the distributions of the stress areas have been presented in figures 10 and 11.

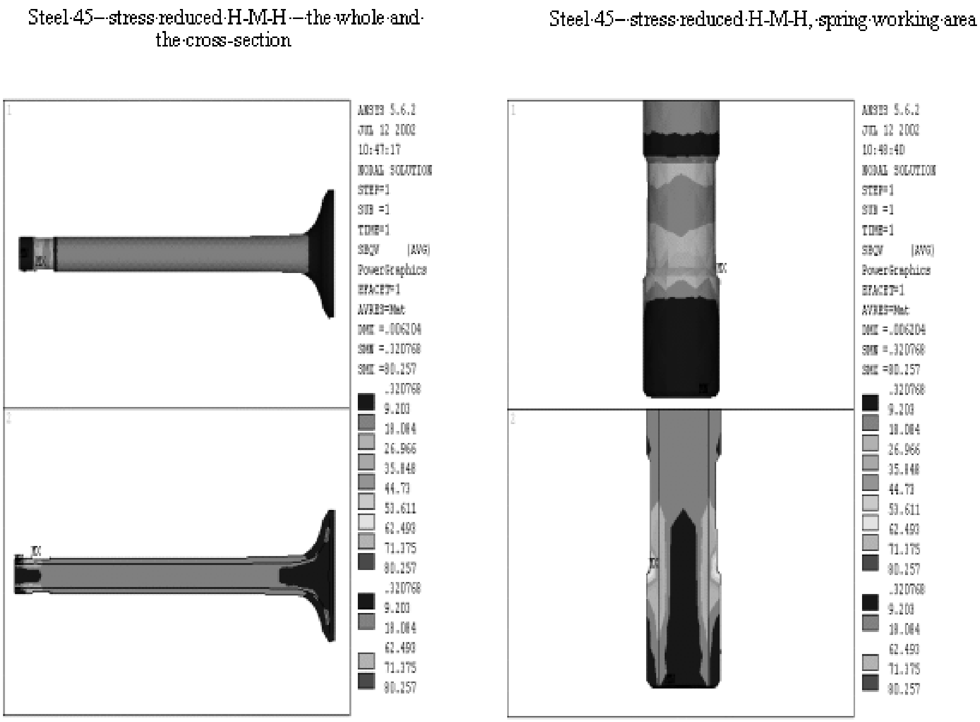

Fig. 11. Stress distribution in a bimetallic valve with core of steel 45
Rys. 11. Rozkład naprężeń w zaworze bimetalowym z rdzeniem ze stali 45

7. Summary and conclusions

It may be inferred from the performed analyses that:

1. Application of various technologies does not influence to a significant extent on the valves' resistance. Resistance of a bimetallic stratified valve is about 750 MPa and is only by about 100 MPa lower than the resistance of valve steel.
2. Technology of valves' production influences the "ability" of a valve to abstract heat. Bimetallic valves enable to increase the amount of abstracted heat by about 20 %, maintaining at the same time the same heat transfer conditions, which is about 0,5% of the total amount of heat abstracted by the walls of the combustion chamber.
3. Application of double-layered bimetallic valves produces changes in the distribution of the amount of heat transferred in the outlet channel and increase of heat transfer between a valve guide and a head. The changes are caused by higher temperature of a bimetallic valve in the "channel" part and in the part cooperating with the guide.
4. The production cost of valves is different and arises from the material cost and production cost. For a comparison of the valves, the lowest is the cost of manufacturing a bimetallic stratified valve.

5. The highest mechanical stresses in a valve appear around the valve key and are equal to 80 MPa.

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Porównanie zaworów o różnych konstrukcjach

S t r e s z c z e n i e

W pracy przedstawiono wyniki badań oraz analizę termiczną zaworów wykonanych z różnych materiałów. Porównywano zawory monolityczne (ze stali zaworowej) i bimetalowe wykonywane tą samą technologią, przy czym w zaworach bimetalowych zewnętrzna warstwa była zrobiona ze stali zaworowej, a wewnętrzna ze stali 45. Przedstawiono wyniki pomiarów nagrzewania zaworów i zmierzone temperatury na powierzchni zaworu, a także w prowadnicy. Przeprowadzono obliczenia modelowe z wykorzystaniem metody elementów skończonych, rozkładu temperatur w zaworze umieszczonym na stanowisku badawczym oraz podczas pracy silnika. Przeanalizowano również wpływ szczeliny między prowadnicą a zaworem na odprowadzanie ciepła (szerokość szczeliny i jej smarowanie). Do analiz zbudowano model zaworu wraz z prowadnicą. Na podstawie analizy ciepła wydzielanego w komorze spalania i kanale wylotowym, wyznaczono warunki wymiany ciepła. Przedstawiono wyniki analiz i porównano je z wynikami badań. Stwierdzono, że w przypadku stosowania zaworów bimetalowych, ilość ciepła odbierana od ścianek komory spalania i z kanału wylotowego jest większa, co pozwala na stosowanie ich w silnikach bardziej obciążonych cieplnie. Zastosowanie tego typu zaworów pozwala również na obniżenie kosztów ich wytworzenia.