LASER REBUILDING OF ENGINE EXHAUST VALVES

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Abstract

The study presents the results of tests concerning laser rebuilding of worn exhaust valve faces of combustion engines. Materials that are used for pad welding were reviewed and analyzed from the angle of their usability for pad welding of valve faces. The material that was selected was a powdered cobalt alloy (stellite). Subsequently, there was conducted a selection of the pad welding process parameters, taking into account, among other things, the heat capacity of valves being rebuilt. Rebuilding of worn out valves was realized and the properties of obtained layers were subject to evaluation.

It was found, among other things, that it was necessary to make machining undercuts at the point of the valve face in order to locate the pad welded stellite layer properly. In the case of valves made of H9S2 steel, it was found that it was necessary to preheat the valves so as to eliminate cracks in the layer being pad welded. Microscopic analyses of the structures of layers rebuilt with the use of stellite as well as microhardness tests confirmed the possibility of the application of laser pad welding in order to rebuild worn out valve faces.

Keywords: *exhaust valves, laser regenerative pad welding, service properties*

1. Introduction to component regeneration

Wear of vehicle components is a natural process, which cannot be avoided. Whereas damage formation is most often conditioned by mistakes made at a component's design, manufacturing, operating or regeneration stages. Component wear is understood as the effect of material defect on a component's surface, changes that are observed in the surface layer or both aforesaid phenomena taking place at the same time. They result from the operation of friction forces or simultaneous operation of friction and accompanying chemical and thermal phenomena throughout the whole service life of a component. Service wear increases gradually with an intensity that depends on the type of wear, factors that cause wear as well as the type and intensity of forcing. Wear degree depends on the operating time or mileage of vehicles. It should also be emphasized that wear intensity of components is not identical in individual operating periods [1, 2, 3]. There exist constructional and technological methods for counteracting wear with the use of traditional and modern technologies, which include laser technologies. Worn out vehicle components may be subject to regeneration processes.

It follows from the essence of the regeneration process that the regeneration technology only to a small degree constitutes the repetition of the process of the component manufacturing technology. The regeneration process denotes reconstructing the geometric features and properties of components or restoring the properties of materials and components of subassemblies. The regeneration process is oftentimes limited to spreading a material layer of a particular thickness and mechanical machining of only one or two surfaces and. In the case of using systems of repair dimensions, it is limited only to the machining of the said surfaces. Hence, regeneration costs are frequently much lower than the costs of manufacturing a particular component [4].

In some countries, including Poland, regenerated components are brought into the market. Nowadays, in authorized service centres of concerns that produce automotive vehicles, the client whose vehicle is being repaired is offered an installation of regenerated components. By way of example, in the trade offer of the Toyota automotive concern, there can be found the following vehicle subassemblies and components that were subject to regeneration:

- alternators;
- starters;
- automatic transmissions;
- clutches.

Volkswagen installs regenerated engines in certain models of new vehicles. Each of the regenerated components is designed particularly for a given model, in accordance with its specificity. In the case of the purchase of such a component, the automotive concern grants a full manufacturer's guarantee.

It should also be pointed out that components regeneration fosters environment protection. A lot of components are reused, which results in decreasing the amounts of materials and energy that are necessary to manufacture products as well as in decreasing the amount of waste.

The problem of the purposefulness of using regeneration is the determination of a reasonable range of its application. It is determined by numerous factors, the most crucial of which are three criteria, namely technical, operational and economical ones. In order to determine a reasonable and economically substantiated range of regeneration as well as adopt appropriate methods and proper organizational structure of units that would realize the regeneration, there were conducted many tests and analyses in the past. The aforementioned tests and analyses concerned traditional methods such as arc pad welding, electro-vibration pad welding, thermal, plasma and ultrasonic metal spraying, galvanic treatment methods as well as application of epoxide materials. On the basis of the said analyses, there were determined the most economically and qualitatively appropriate regeneration methods as well as essential technical equipment and there were performed analyses of the costs of individual methods, with indicating the most economically and technically substantiated method for a particular range of components. When evaluating the purposefulness of regeneration in technical and economical respects, it is vital to take into account the structural-technological properties of the component being regenerated as well as its operating conditions, wear degree and fatigue strength margin [4]. The aforesaid solutions have also been implemented in military overhaul plants.

The development of new technologies, laser technologies in particular [5-8], forces taking up studies that aim at the development of regeneration technologies for the components of military motor vehicles.

Summing up, it should be pointed out that in order to obtain favourable technical and economical results concerning component regeneration, it is crucial to:

- consider all criteria for the selection and purposefulness of the application of optimum, new regeneration technologies (technological, operational, economical and organizational ones);
- take into account making inventory of wearing out components which can be found in particular types of military motor vehicles;
- make use of all technological achievements, including laser technologies in particular, for regeneration processes, and thereby increase the process effectiveness;
- perform critical analyses of obtained economical results, taking into account current market conditions.

The present study discusses the possibilities of regenerating combustion engine valves with the use of laser technology.

2. Valve failures

Generally known operating conditions of a valve and resultant loads that act during the operating period of an engine cause wear of valves and mating components (valve seat, valve guide, valve rocker). Wear may be intensified by deviations from particular parameters of the engine operation or as a result of improper servicing of the engine. Examples of factors that affect a valve's fatigue life may be an improper air-fuel mixture ratio or improperly regulated valve clearance. As a result of improper or long-lasting valve operation, the valve wears out. The component that is the most exposed to wear and which, at the same time, guarantees proper engine operation is the head face of a valve. Even a small damage of the valve face causes the leakiness of the combustion chamber, which affects the engine operation and, at the same time, results in temperature accumulation in the said area. A temperature increase of almost one point causes the burning of a valve face, which, as a result, leads to a permanent damage of the valve (see Figure 1).

Another reason for valve face damage may be a cyclic action of mechanical loads, which leads to partial or complete deformation ('flatting') of the valve face. The aforesaid phenomenon causes a total collapse of the valve face into the valve seat and affects the engine operation (see Figure 2).

A valve face washed by combustion gases at a high speed undergoes erosive wear (see Figure 3). The aforesaid wear may be the reason for the leakiness of the combustion chamber and, in extreme cases, the burning of a part of the valve can take place, as illustrated in Figure 1.

Fig. 1. The burning of a valve face as a result of improper operation

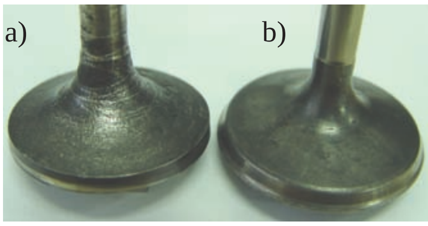


Fig. 2. Damage of a valve face as a result of plastic deformation: a) complete; b) partial

Fig. 3. Erosive wear of a valve face

As a result of the action of cyclic loads, fatigue failure of a valve can take place. The area that is the most exposed to failures of the said type is the transition zone between the valve head and the valve stem, where there is present notch-related stress concentration. Failures of the said type most often occur as a consequence of technological errors, which take place at the stage of valve production.

3. The process of laser pad welding of layers

In the laser pad welding process, there is used laser beam energy, which melts the additional material in the forms of flux-cored wires or powders and partially melts the matrix, which results in creating a permanent metallurgical joint [9-11]. In the laser pad welding process, there are used shielding gases in order to protect liquid metal from external factors and as a carrier of the additional material (powder). Frequently used shielding gases include Ar or CO_2 and their mixtures.

The advantages of laser pad welding include a limited effect of the thermal action of a laser beam on the object, as a result of which there are obtained insignificant stresses and deformations of the component after pad welding. Thanks to great possibilities of controlling the process, it is possible to reduce the fraction of the matrix material in the padding weld to approximately 4%, which facilitates obtaining a surface layer with desired properties as early as in the first padding weld layer [10].

4. Materials used for laser rebuilding

In order to perform the rebuilding of outlet valve faces with the use of a laser, it is necessary to determine the parameters of the said process, with taking into account, among other things, the form and type of the material being pad welded.

For the purpose of laser pad welding, it is most favourable to use the pad welding material in the form of powder, since it makes it easier to control the pad welding process and the properties obtained along the whole width of the padding weld bead are uniform. The powder should have particular properties that result from the specificity of the laser pad welding process (e.g. a particular powder granularity) so that the process can be realized properly.

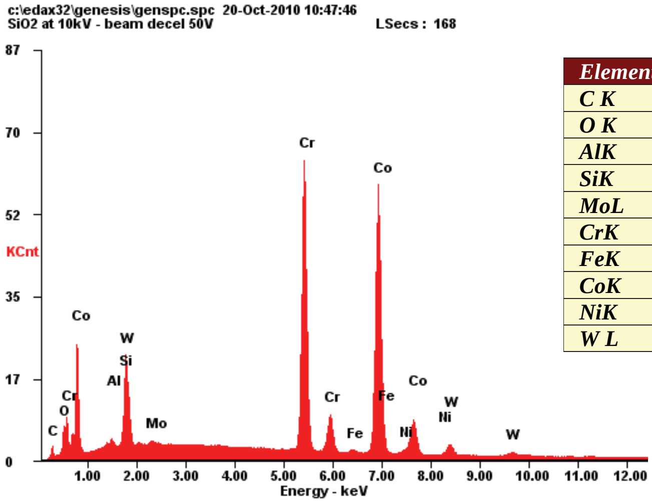
Tab. 1. The chemical composition, properties and sample applications of powders on a cobalt matrix produced by Castolin, which are used in plasma pad welding [11]

Powder designation		Chemical composition	The padding weld properties and sample applications
Castolin	EuroMat		
EuTroLoy PG 5218	AMI 3903	Co+1.3%C+29%Cr+5%W+1.3% Si	47-50 HRC; metal-metal type abrasion resistance, high temperature oxidation resistance, acid corrosion resistance; components of pipes and tube couplings of the systems of steam, crude oil, sea water and chemicals, Diesel engine valves
EuTroLoy PG 4298	AMI 3905	Co+1.75%C+31%Cr+9%W	47-50 HRC; high temperature oxidation resistance, corrosion resistance and metal-metal type abrasion resistance; bolts for plastics extrusion machines, locks of steam valves and Diesel engines, articulated joints
EuTroLoy 16001	AMI 3900	Co+2.5%C+30%Cr+12.5%W	52-56 HRC; abrasive wear resistance, corrosion resistance and high temperature resistance; bolts for plastics extrusion machines, pump shafts, impellers and blades of rubber mixers, valves
EuTroLoy 16006	AMI 3901	Co+1.1%C+28%Cr_4.5%W	~40 HRC; corrosion resistance, high temperature oxidation resistance, metal-metal type abrasion resistance; valves in steam, crude oil and chemical systems, bolts for plastics extrusion machines, Diesel engine valves
EuTroLoy 16012	AMI 3902	Co+1.6%C+29%Cr+8.5%W	~46 HRC; high corrosion and oxidation resistance, metal-metal type abrasion resistance; bolts for plastics extrusion machines, valves in steam systems
EuTroLoy 16008	-	Co+0,3%C+26%Cr+5,5%Mo+3 %Ni	27-30 HRC; organic and mineral acid corrosion resistance, heat resistance; hot-work tools: dies, cutting edges, components of pumps and turbines, large steam valves

Alloys that are called stellites are most often used for the purpose of modifying the head face of a valve. Stellite coatings have been widely used for many years, while the coating creation process itself is still being modified and the latest materials engineering techniques are being applied.

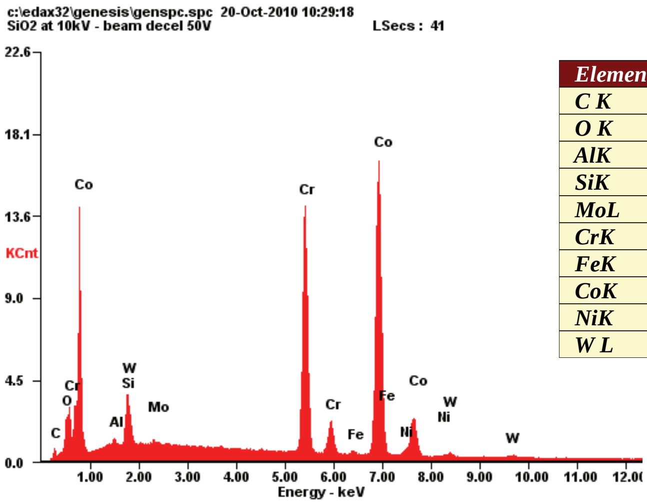
Stellites are metal alloys that are characterized by a high percentage of elements such as: chromium (up to 35%) and wolfram (up to 30%) and the main element of the said alloys is cobalt (up to 65%), which constitutes a matrix, whereas, as a rule, the percentage of carbon does not exceed 2%. Additional elements are manganese and silicon, however, with a low percentage. Sample compositions of stellite alloys can be found in Table 1. Stellites were first studied and compiled in 1900 by Elwood Haynes [12].

Using cobalt alloys to create coatings on the valve faces of combustion engines, among other things, is imposed by their specific properties. Chemical elements that are included in the composition of stellites have a decisive effect on the aforesaid properties.



Element	Wt %	At %
C K	01.11	05.24
O K	00.61	02.14
AlK	00.15	00.31
SiK	01.76	03.54
MoL	00.42	00.25
CrK	29.48	32.02
FeK	00.51	00.51
CoK	53.87	51.62
NiK	00.99	00.96
W L	11.10	03.41

Fig. 4. The chemical composition of the 16012 powder



Element	Wt %	At %
C K	01.00	04.52
O K	00.80	02.71
AlK	00.15	00.30
SiK	01.71	03.29
MoL	00.48	00.27
CrK	26.37	27.41
FeK	00.48	00.46
CoK	64.17	58.85
NiK	01.22	01.12
W L	03.61	01.06

Fig. 5. The chemical composition of the AMI 3901 powder

The basic composition of stellites is oftentimes modified by adding chemical elements such as molybdenum, nickel and iron, which increases impact strength and matrix stability, whereas adding boron and silicon to the chemical composition decreases the melting temperature of the alloy, which makes it easier to apply layers by spraying. The hardness of stellites is within the range of 20÷65 HRC and depends on the chemical composition, while the impact strength of stellites decreases if the percentage of carbon increases.

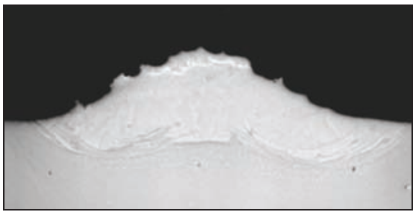
In tests concerning the possibility of valves rebuilding, there were used two powder types selected on the basis of separate analyses, namely 16012 produced by Castolin and AMI 3906 produced by EuroMat, the chemical compositions of which are presented in Figures 4 and 5.

5. Selection of the parameters of laser rebuilding

A significant issue in the rebuilding (regenerative pad welding) process is the determination of proper parameters of the said process. The parameters should allow for the sizes of the valves being pad welded and valve materials, among other things. Valve size has a decisive effect on heat capacity, which, in correlation with the amount of supplied laser beam energy, affects thermal impact, which is connected with the possibility of structural changes in a larger valve volume or generation of additional internal stresses. The aforementioned changes may alter the service properties of the component being rebuilt.

The selection of pad welding parameters was conducted at variable parameters of the pad welding process, i.e., variation of beam power density P[W/mm^2], variation of pad welding velocity v[mm/min] and variation of the quantity of powder being fed q[g/min].

Evaluation of the pad welding process was conducted on the basis of qualitative and geometrical analyses of padding weld beads that had been made. The base material percentage (UMP) in the padding weld and the thickness of the pad welded layer were determined on the basis of pictures taken on metallographic micro-sections in specimen cross-sections. The manner of calculating the base material percentage, UMP, is presented in Figure 6.



$$UMP = \frac{F_w}{F_w + F_n} \cdot 100\%$$

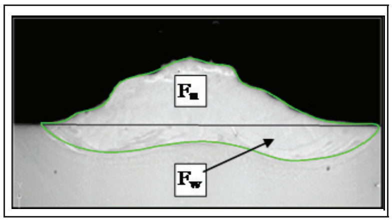


Fig. 6. The manner of calculating the base material percentage (UMP) in a padding weld: F_n - the surface area of the excess metal of the padding weld; F_w - the surface area of the padding weld fusion

The analysis of test results made it possible to determine the effects of particular parameters on the padding weld formation process. The parameter of the laser beam power has a decisive effect on the depth of fusion of the material layer and the melting of the powder being fed (see Figure 7). Together with an increase in the power density of a laser beam, UMP increases, which indicates that there takes place a better penetration of the powder being fed and the padding weld being created has a flatter face. In the pad welding process, a part of laser beam energy is absorbed by the powder being fed, which has an effect on the size of the padding weld pool being formed and, at the same time, affects weld penetration depth. Changing the parameter of the quantity of powder being fed leads to a situation where, along with an increase in powder quantity, beam energy absorption increases and the penetrated material pool becomes covered up. The aforesaid phenomenon results in a decrease in UMP and, at a maximum powder quantity, it is possible to obtain the lack of a permanent connection between the padding weld and the base along the whole length.

At properly selected beam power density and appropriate powder quantity, variations in velocity resulted in considerable changes in the padding weld height (together with a decrease in velocity), with keeping allowable values of UMP in the padding weld. Powder quantity and beam power affect the economics of the pad welding process, while the velocity parameter affects the process efficiency.

Microhardness measurements were performed linearly in the plane of the padding weld cross-section, from the face of the padding weld towards the parent material, with the use of a Shimadzu microhardness tester at the load of 100g. Measurement results are presented in the form of diagrams for selected laser beam power values and pad welding velocities (see Figure 8).

Obtained padding weld microhardness values for 50H21G9N4 steel were within the range of from 620 to 750 $HV_{0,1}$, whereas for H9S2 steel they were in the range of from 650 to 800$HV_{0,1}$. The aforementioned values varied depending on the types and values of pad welding parameters as well as on the parent material type. In the case of H9S2 steel, there was observed an increase in microhardness in the transition zone between the padding weld and the parent material, which was caused by material self-hardening in that area. The microhardness of the parent material of the austenitic steel (50H21G9N4) was approximately 400$HV_{0,1}$, whereas in the case of the martensitic steel (H9S2), it was approximately 300 HV. Therefore, a considerable growth of the surface layer after the process of laser pad welding can be observed.

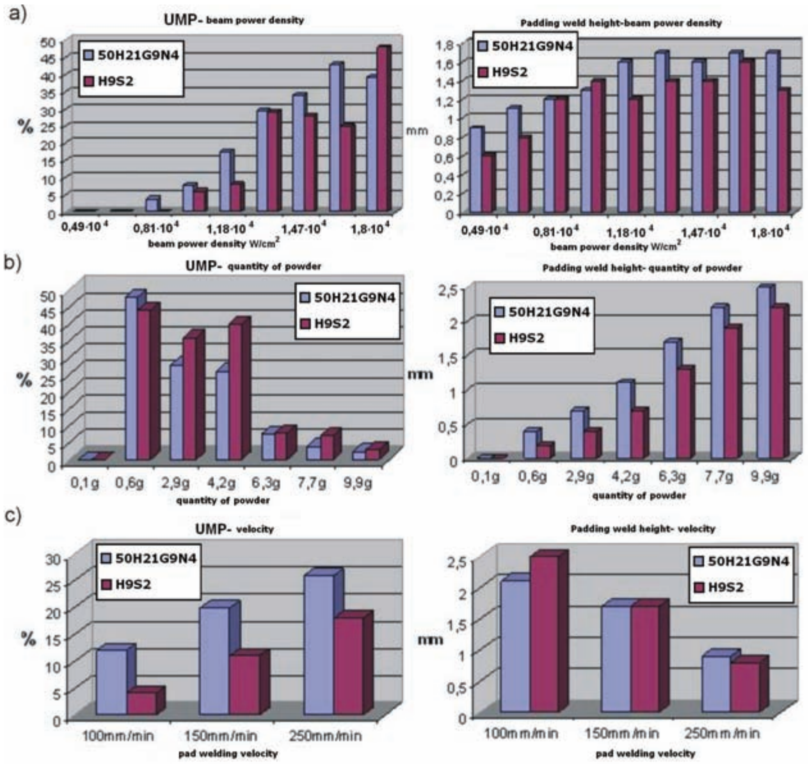


Fig. 7. UMP values and padding weld height depending on changes in: a) beam power density, b) the quantity of powder being fed, c) pad welding velocity

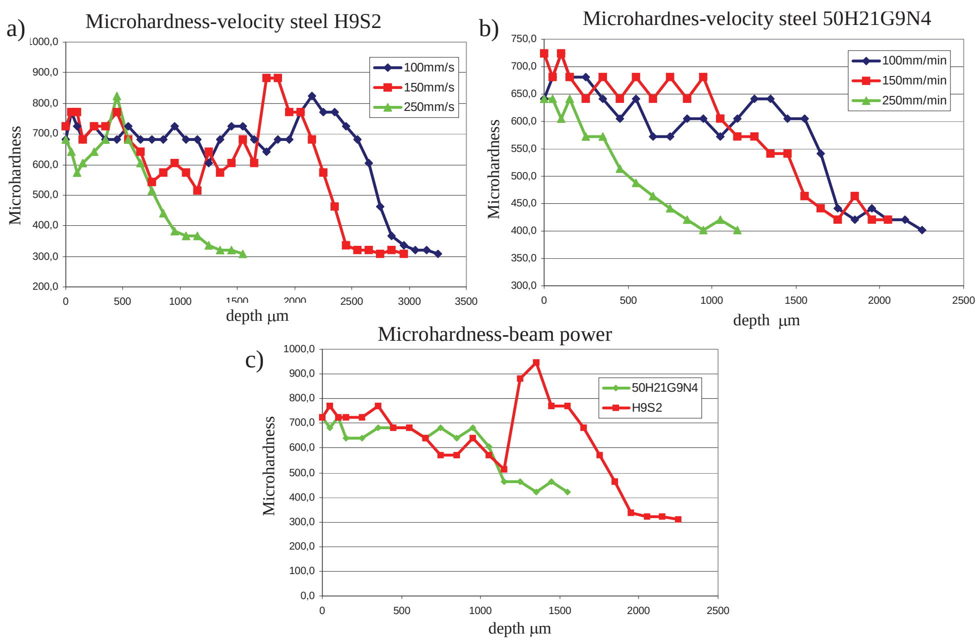


Fig. 8. Distribution of the microhardness of a padding weld made at various pad welding velocities: a) H9S2 steel; b) 50H21G9N4 steel; c) distribution of the microhardness of a padding weld for 50H21G9N4 and H9S2 steels - power: 1200[W]; q_{powd}=6.3[g/min]; V_{pw}=200[mm/min]

Depending on pad welding parameters, not only do the padding weld quality and shape change, but it also affects the transition zone between the parent material and the padding weld as well as the heat affected zone (HAZ). In the said zone, it is possible to observe grain growth. Depending on pad welding parameters, the growth zone width varies and so does grain size (see Figure 9).

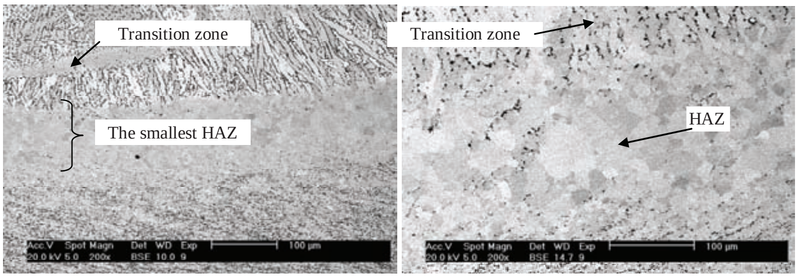


Fig. 9. Images of the transition zone structure for the following pad welding parameters: $v_{pw.}$=200mm/min; $q_{powd.}$=6,3g/min; power: a)1200[W]; b)2200[W]

6. Laser rebuilding of outlet valves

On the basis of determined pad welding parameters, there was performed laser pad welding of the valve faces of combustion engines such as: ASz-62 (50H21G9N4 steel), SW-680 (4H14N14W2M steel) and W-46 (H9S2 steel; see Fig 10.

For the purpose of guaranteeing proper realization of the pad welding process, the valve face surface was necked prior to pad welding in order to make a hollow for the padding weld (see Figure 11). The said hollow guaranteed obtaining a padding weld of a particular thickness and minimized the dressing of the valve face after the pad welding process.

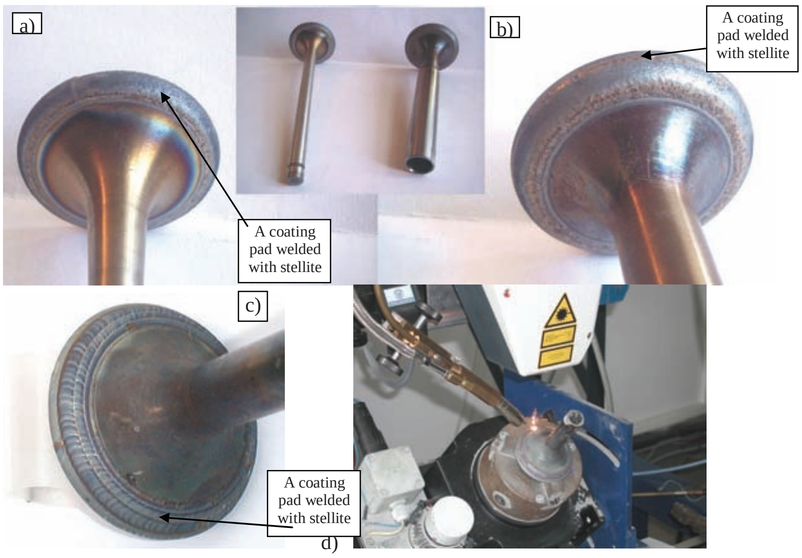


Fig. 10. A combustion engine valve with a valve face that was laser pad welded with stellite: a) - SW-680; b) - W46; c) – ASz 62, d) - the pad welding process

Fig. 11. Valve images before and after pad welding

During pad welding realization, it turned out to be necessary to heat up the W-46 engine valve head made of H9S2 steel to the temperature of approximately 200°C for the reason of the presence of cracks in the padding weld (see Figure 12). The said cracks were related to stresses generated by the self-hardening of the material under the padding weld layer, which was confirmed by preliminary tests.

Fig. 12. A crack in a padding weld made on a W-46 engine valve

7. Service properties of valves after rebuilding

7a. The microhardness of a pad welded coating

Microhardness measurements were conducted in order to determine the characteristics of hardness distribution into the padding weld. Linear microhardness distribution on the cross-sections of stellite coatings illustrates changes in hardness in transition zones between the padding weld and the parent material.

The abovementioned measurements were performed on specimens made from W-46 and ASz-62 combustion engine valves. Each valve had a multi-bead padding weld that was laser pad welded with stellite at the point of the valve face.

The measurements were performed in accordance with measurement planes marked in Figures 13 and 14.

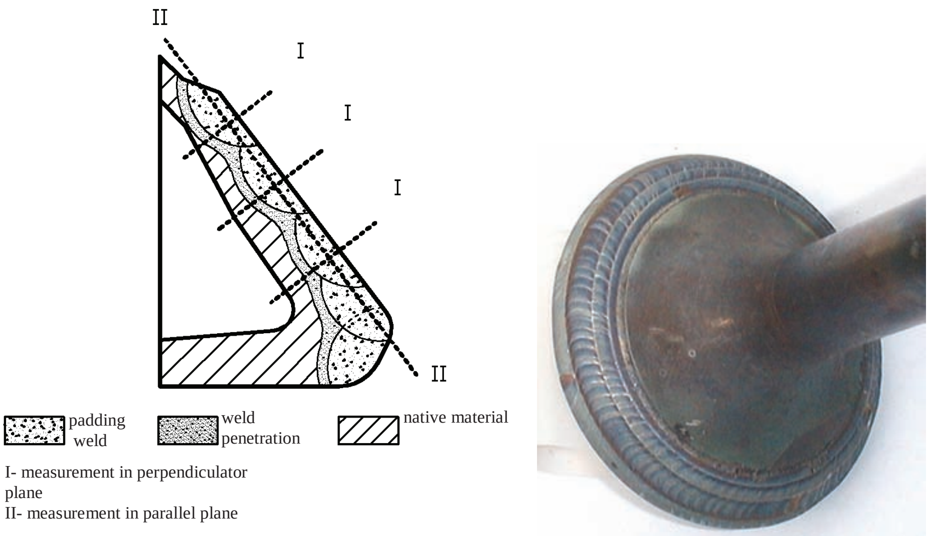


Fig. 13. An ASz62 engine valve that was laser pad welded with stellite: a) - a cross-section of the valve fragment with microhardness measurement planes marked; b) - an image of the valve after pad welding

When examining microhardness distributions of layers pad welded on ASz62 and W46 engine valves (see Figure 15), it can be observed that they have a similar character as in the case of microhardness measured in specimens. Microhardness value at the padding weld surface was approximately 680 $HV_{0,1}$. In the case of the W-46 engine valve, there was observed microhardness increase in the heat affected zone, just like in the case of laser pad welded specimens made of H9S2 steel, which was connected with self-hardening of material in the said zone.

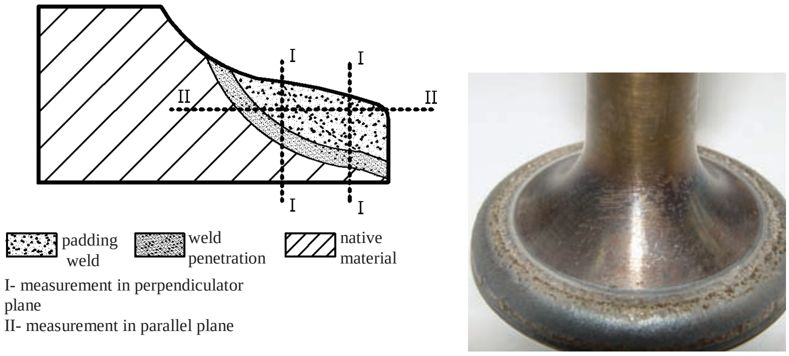


Fig. 14. An W-46 engine valve that was laser pad welded with stellite: a) - a cross-section of the valve fragment with microhardness measurement planes marked; b) - an image of the valve after pad welding

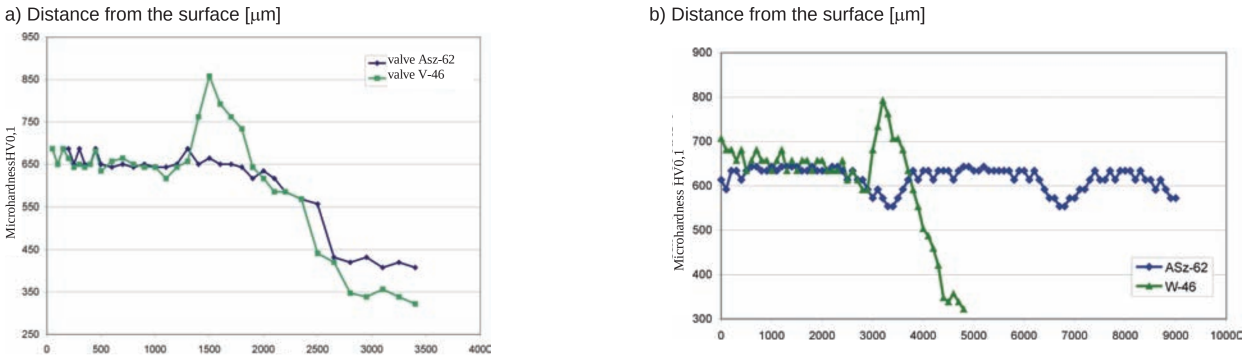


Fig. 15. Microhardness distribution of a stellite coating pad welded on ASz-62 and W-46 valves: a) - in a perpendicular measurement plane (plane I, Figure 13); b) - in a parallel measurement plane (plane II, Figure 14)

Microhardness distribution of the ASz-62 engine valve measured in plane II (see Figure 13) had characteristic microhardness value drops, which was related to overlapping of the beads of the multi-bead padding weld and partial material tempering as a result of heat action in successive laser beam passes.

7b. The structure of a pad welded coating

The microstructure of the pad welded layer is a fine-grained one (see Figure 17) and therefore favourable in terms of service properties.

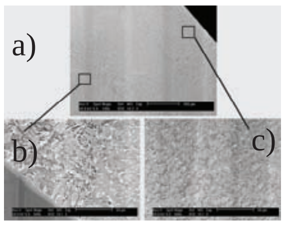


Fig. 16. The structure of a stellite layer after rebuilding: a) the view of the layer; b) the structure in the transition zone; c) the structure in the near-to-surface zone

The padding weld structure consists of lamellar carbides in dendritic units surrounded by white zones with prevailing wolfram and cobalt content. A local analysis of the chemical composition of distinctive areas of the structure (see Figure 18), dendrites (1), white zones (3) and a phase located in inter-dendritic spaces (2) showed a significant percentage of cobalt in area 1, chromium in area 2 as well as chromium and wolfram in area 3. Additionally, specimens were etched in *Murakami* solution in order to reveal chromium carbides in the padding weld structure. On the basis of the colours of etched areas and a description of the structure of Stellite 6 alloy by J. Kusiński [9], there was identified the presence of M_7C_3 type carbides in the inter-dendritic spaces of the padding weld structure.

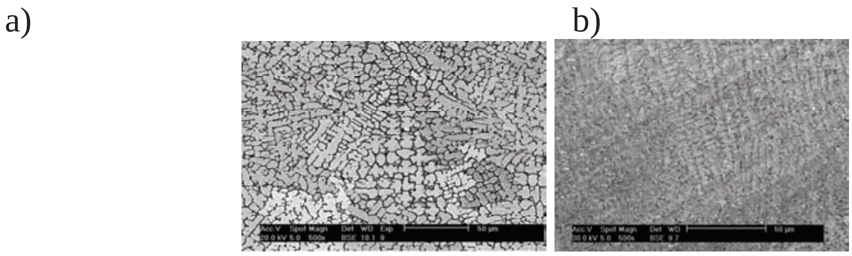


Fig. 17. The structure of a laser-made padding weld: a) on 50H21G9N4 steel; b) on H9S2 steel

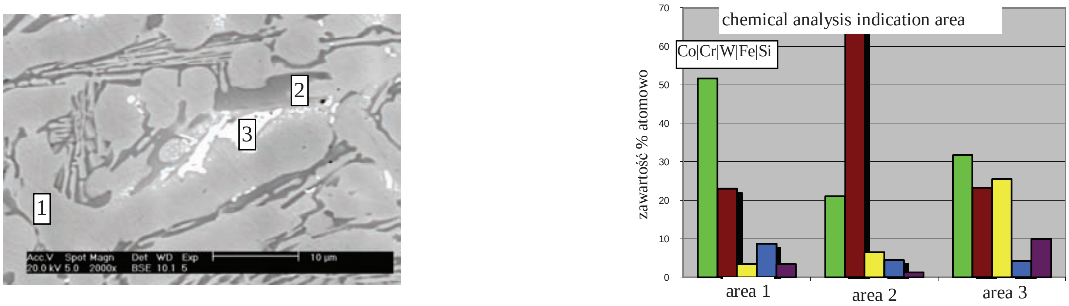


Fig. 18. The percentage of particular chemical elements in marked padding weld zones

7c. Valve face tests conducted on an engine test bench

Outlet valves of the ASz-62 aircraft engine (a set of 9 units) with laser pad welded stellite coatings at the points of valve faces were also subject to tests under actual operating conditions. The said valves were installed in an engine that was tested on an engine test bench in PZL Kalisz over a period of 200 hours. Engine tests were conducted in order to determine the effects of fuel type used on obtained engine parameters. During tests, the engine was subject to loads that constituted 75% of maximum engine loads.

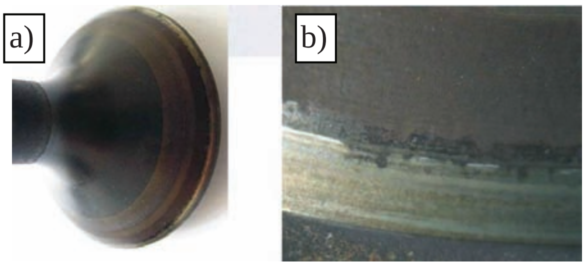


Fig. 19. An ASz-62 engine valve after a bench test: a) - a valve head; b) - a valve face

After the bench test, there was conducted a visual inspection of the valves and the stellite coating at the point of the valve face (see Figure 19). There was confirmed a high resistance of the stellite coating to operation under conditions that result from the engine operation. The coating did not exhibit any macroscopic changes, nor were there found any cracks, burnings, defects or deformations of the layer after intensive tests on the engine test bench. The above-described issue was discussed during the realization of a specific targeted research project with the Warsaw University of Technology and PZL Kalisz.

8. Conclusions

1. The research has indicated a significant influence of the selection of pad welding parameters, the power density of the laser beam in particular, on effects obtained in the pad welding process. At the initial stage of tests, there was observed a considerable effect of the aforesaid parameter on the quality and shape of the padding weld as well as on the metallurgical joint of

the layer being made. The said parameter is strongly dependent on the parameter of the quantity of powder being fed as well as the heat capacity of components being pad welded. Whereas the scanning speed of a laser beam has a significant effect on the geometric dimensions of a padding weld, which may be used in the technology of regeneration by means of the said method and affect the efficiency of the process. There were determined the most appropriate pad welding parameters, namely the power density of a laser beam: $1{,}02 \cdot 10^4$[W/cm^2], pad welding velocity: 200[mm/min], quantity of powder being fed: 6,3[g/min].

2. An analysis of laser pad welded structures displayed their fine-grained character, which is very favourable considering the service properties. The obtained layer had comminuted structure with no porosity and the chemical composition of the layer was uniformly distributed.
3. Microhardness tests of laser pad welded layers confirmed a significant increase in microhardness in relation to the parent material microhardness. Microhardness increased from 400 to 720HV for 50H21G9N4 steel and from 300 to 800$HV_{0,1}$ for H9S2 steel.
4. Valves made of martensitic steel (H9S2) before the laser pad welding process should be heated up to the temperature of at least 200°C considering the possibility of the formation of surface cracks as a result of the material self-hardening process in the heat affected zone.
5. Prior to the laser pad welding of a valve face, the valve needs to be prepared by making a neck of a shape and dimensions that depend on the overall dimensions of the valve face and the whole valve in order to lay the padding weld.
6. Tests on the ASz-62 engine with laser pad welded valves made of 50H21G9N4 steel conducted on an engine test bench confirmed high service properties of the layer that had been made. After tests under actual conditions, the layer that had been pad welded at the point of the valve face did not show any signs of wear in the forms of cracks, burnings or material defects on the surface.

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