The laser welding of iridium-platinum tips to spark plug electrodes

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ABSTRACT

The paper presents selected results of model and technological experiments of welding iridium-platinum tips to spark plug electrodes. Variants of welding technology included different ways of preparing materials and the use of different Nd: YAG lasers (Rofin BLS 720 and Rofin Integral). The results of technological tests were verified by the metallographic evaluation of joints. Performance tests when powered by biogas were conducted for selected variants of welding.

Keywords: spark plugs, alloys of iridium and platinum, laser welding, microwelding, biogas

1. INTRODUCTION

Considerable progress in the miniaturization of cooperating components means that we are increasingly dealing with welding of small-sized components. Nowadays two methods of joining elements of spark plug electrodes are mainly being developed: resistance welding and laser welding gaining more and more importance. The use of laser micro welding is to eliminate or reduce the defects occurring in joints produced by resistance welding. The main disadvantages include a possible lack of metallurgical connection between the spark plug electrode and the tip. Due to significant differences in melting temperatures of materials to be joined, the connection of the tip to the central electrode is often of adhesive character and has higher thermal resistance. The use of a laser beam which is capable of melting both materials to be joined results in the material mixing, which provides a metallurgical connection [1-10].

Today spark plugs are more and more often used in generators and car engines powered by alternative, renewable energy sources. Biogas belongs to fuels of this type because it is used as a fuel to generate electrical energy in power stations with spark-ignition engines. Due to highly corrosive properties of the products of biogas combustion, the use of conventional spark plugs is unprofitable because of the very rapid wear of nickel electrodes. In order to extend the service life of spark plugs, electrodes are covered with tips made from special metals or metal alloys resistant to high-temperature corrosion such as iridium, yttrium, platinum, and platinum-iridium [1-5,11-14]. One of the conditions for the proper functioning of spark plugs in the environment of biogas is to achieve the smallest possible thermal resistance while producing a tip – central electrode connection. Increased thermal resistance hinders heat abstraction from the tip to the central electrode. This results in an increase in the operating temperature of the tip, which leads to its faster erosion wear.

The Center for Laser Technology of Metals has initiated research into the possibility of using platinum and iridium tips made of solid material for the production of spark plugs in order to extend their service life in engines powered by biogas. This paper presents selected results of the model, technological and operational experiments on spark plugs with laser welded tips. Variants of welding technology included different ways of preparing materials and the use of different Nd: YAG lasers (Rofin BLS 720 and Rofin Integral). The results of technological tests were verified by the metallographic evaluation of joints. Performance tests when powered by biogas were conducted for selected variants of welding.

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2. TECHNOLOGICAL EXPERIMENTS

In this case we are dealing with connecting dissimilar materials with significantly different melting points (T_{tNi} = 1455°C , T_{tPt} =1768°C , T_{tIr} = 2447°C) and dimensions. For this reason, , this type of welding is to be classified as difficult from a technological point of view. On the other hand, quality requirements of the joint are high because they determine heat abstraction from the combustion zone and the reliability of the joint of the tips to the electrodes. That is why the technological research began by modeling the welding process which took different ways of preparing weldments into account and sought the most favorable location of incidence of the laser beam [15]. Thanks to it, it was possible to reduce experimental technological investigations to a minimum.

2.1. MODELING OF THE LASER WELDING PROCESS

The purpose of modeling is to develop a model of fusing two surfaces (electrode – electrode tip) that are to be permanently joined and have adequate performance characteristics. As a result of modeling data are obtained for selecting the initial operating parameters of the laser device which guarantee the achievement of the fusion temperature of materials to be joined.

For calculations the Ansys - Fluent program was used for numerical modeling of processes related to fluid flow and heat transfer. Examples of the calculation results of the temperature distribution in the cross-section of a tip made of iridium is illustrated in Fig 1.The curves show the temperature distribution after the end of successive laser pulses and the time of 0.8019s. The pulse power was 1800 W. The fusion point of Ir was plotted (dashed line) in Fig. 1 for the sake of comparison. In turn, Fig. 2 makes it possible to evaluate the temperature distribution and the share of the liquid phase during the welding of the iridium tip to the nickel electrode.

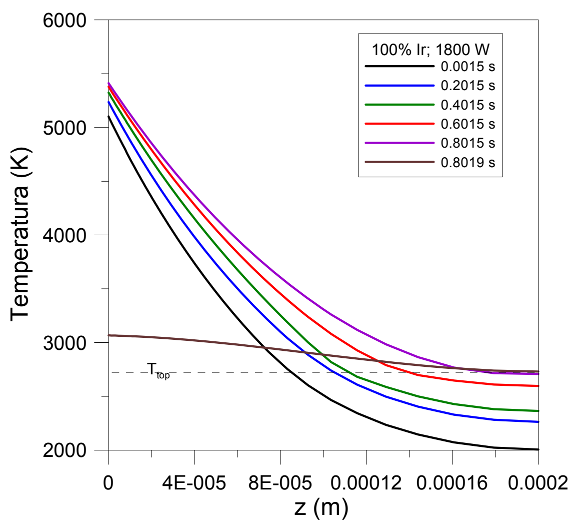


Fig. 1. Exemplary temperature distribution on the axis of the iridium tip after the end of successive laser pulses and the time of 0.8019 by means of the 1800 W pulse. The dashed line represents the fusion point of iridium.

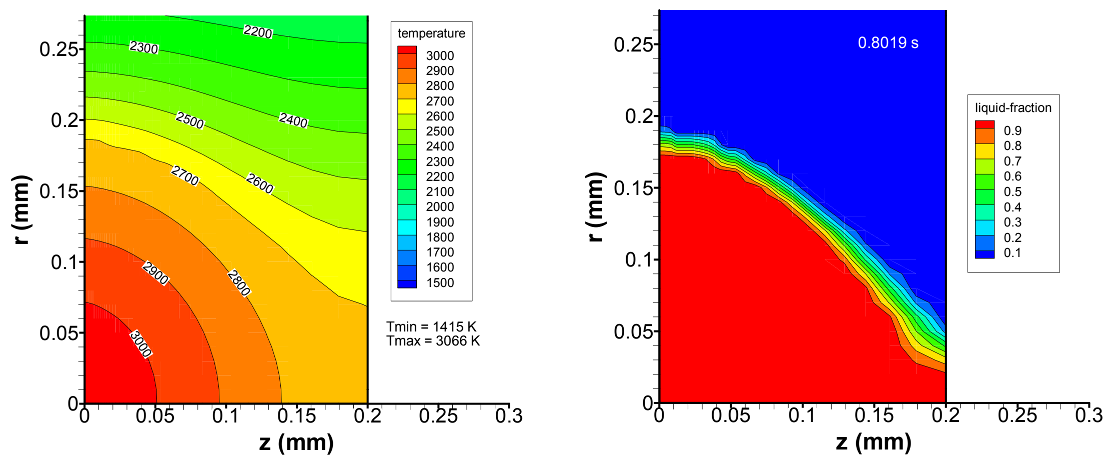


Fig. 2. Exemplary temperature distribution and a share of the liquid phase in the cross-section of the iridium tip after the end of the impact of 5 pulses of 1800 W.

Detailed modeling has been shown in studies [15].

2.2. LASER WELDING TESTS

Experimental technological investigations involved making a fillet weld on the joint, the tip (Ir or Pt) – spark plug nickel electrode. The tips placed at the central electrode were sections of solid iridium wire of 0.8 mm in diameter and 2 mm in length while those at the side electrode had the shape of platinum discs of 1.5 mm in diameter and 0.25 mm in thickness (Fig. 3). The precise positioning of the tips on the electrode surface as shown in Fig. 3 and fixing them in this position by resistance welding were a very important operation. Subsequently, the equally important problem of positioning the parts to be joined relative to the laser beam was solved. Therefore, the copyright set specially made was used for fixing electrodes on the work table of the device for laser welding.

Two different Rofin laser welding machines were used for micro welding the tips. The welding of the side electrodes was carried out using a Nd:YAG model BLS 720 laser generating a beam with a wavelength of 1064 nm and a focus diameter of 0.7 mm, and operating in pulse or quasi-continuous wave modes. The laser used had the following characteristics: average power: 150 W, peak power: 7 kW, pulse energy: 35 J, pulse duration from 0.3 to 20 ms, frequency up to 300 Hz. This laser is available at the Center for Laser Technology of Metals, (abbreviated to CLTM in Polish) of the Kielce University of Technology. To weld joints for central electrodes, a Rofin Integral welding machine available at the Warsaw-based Military University of Technology (abbreviated to WAT in Polish) was used. The machine is composed of a Nd: YAG laser generating a beam with a wavelength of 1064 nm and a focus diameter of 0.4 mm. The system with five degrees of freedom operates in pulsed or quasi-continuous wave modes. The maximum laser power is 12 kW while the pulse duration ranges from 0.3 to 50 ms. The choice of a Rofin Integral welding machine to weld tips to central electrodes arose from the need to achieve a more focused and precisely targeted radiation only on the iridium material. It could have been achieved more effectively if a laser with a smaller beam focus diameter had been used.

The laser joint of the central electrode was conducted using a series of single partly overlapping pulses on both sides of the tip along the joint of the iridium wire and the electrode Similarly, discs of platinum tips were welded to side electrodes by a series of pulses at the periphery. The schematic layout of the tips and the electrodes is shown in Fig.3. In both cases, the welding was conducted in argon shielding gas.

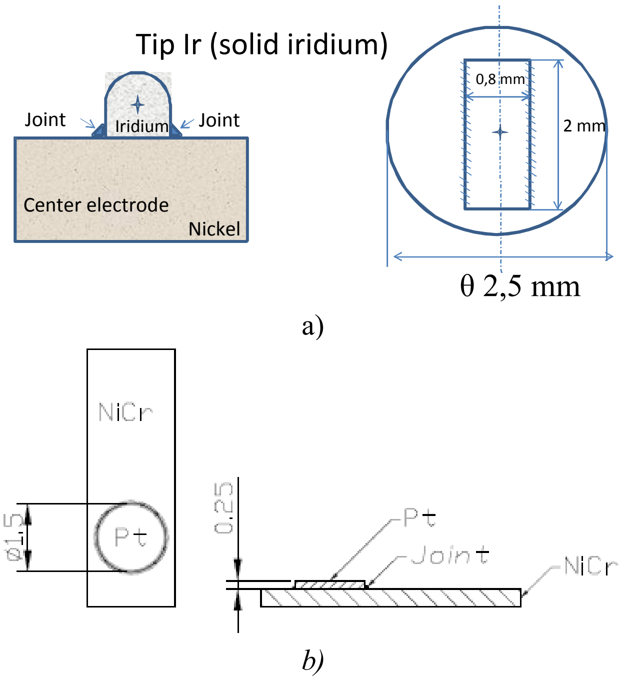


Fig. 3. Schematic diagram of laser micro welding (a) between iridium tips and central electrodes and (b) between platinum tips and side electrodes.

The tips were welded to the electrodes using different pulse durations and beam power levels, which made it possible to select the parameters ensuring the highest quality of the joint. To assess the quality of the joints, transverse metallographic specimens of the welded joints were prepared and observed under a metallographic microscope and a scanning electron microscope. In selected areas of the weld an additional analysis of linear distribution of elements was made. When assessing the quality of joints, the uniformity of weld face, the extent of the diffusion joint zone, and the presence of welding imperfections and micro cracks in particular were taken into account.

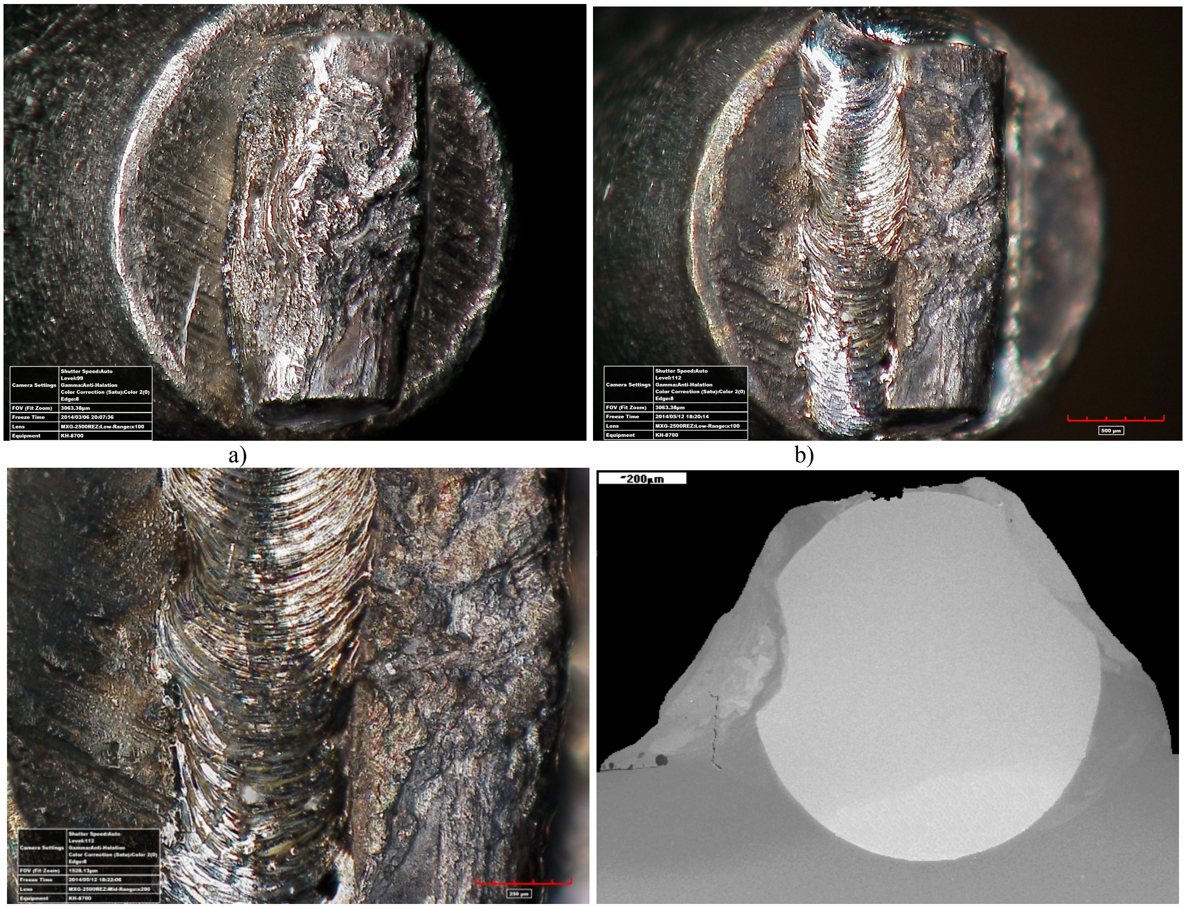
According to the adopted procedure, the selection of the parameters of micro welding the tips to the spark plug electrodes was made. And so, the best effects of the laser micro welding of tips to side electrodes were achieved with the following operating parameters of the BLS 720 laser: 50 W laser power, which corresponds to 600 V lamp voltage, 5 Hz frequency, and 120 mm/min feed rate.

Table 1 presents the parameters of the laser micro welding of side electrodes using a Rofin Integral laser such as laser power P, pulse duration t, laser energy density at the surface D, and beam energy per pulse E. Parameters assigned to the sample 3 were chosen as the best ones.

Table 1. Selected parameters of laser micro welding of tips to spark plug central electrodes using a Rofin Integral laser.

Sample number	Laser power (P) [kW]	Pulse duration (t) [ms]	Energy density (D) [J/cm^2]	Energy (E) [J]
1	2.02	3.0	3860	4.85
2	**2.50**	**3.0**	**4777**	**6.00**
3	2.02	3.5	3503	5.66

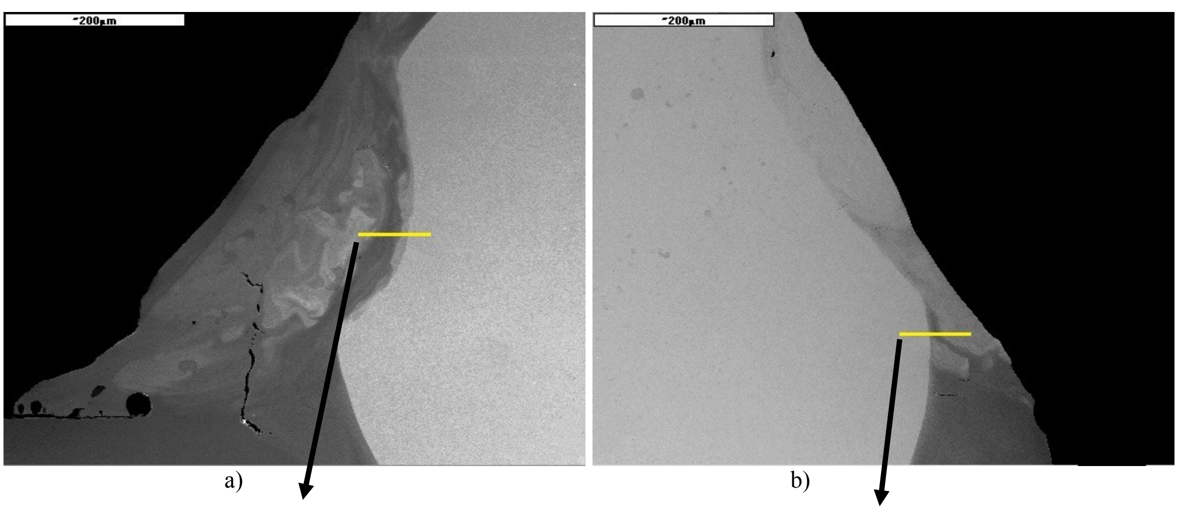
To analyse metallographic specimens under a microscope, a JEOL JSM 5400 scanning electron microscope with the option of analyzing the distribution of elements was used, while the macroscopic analysis was made using a HIROX KH-8700 digital microscope.



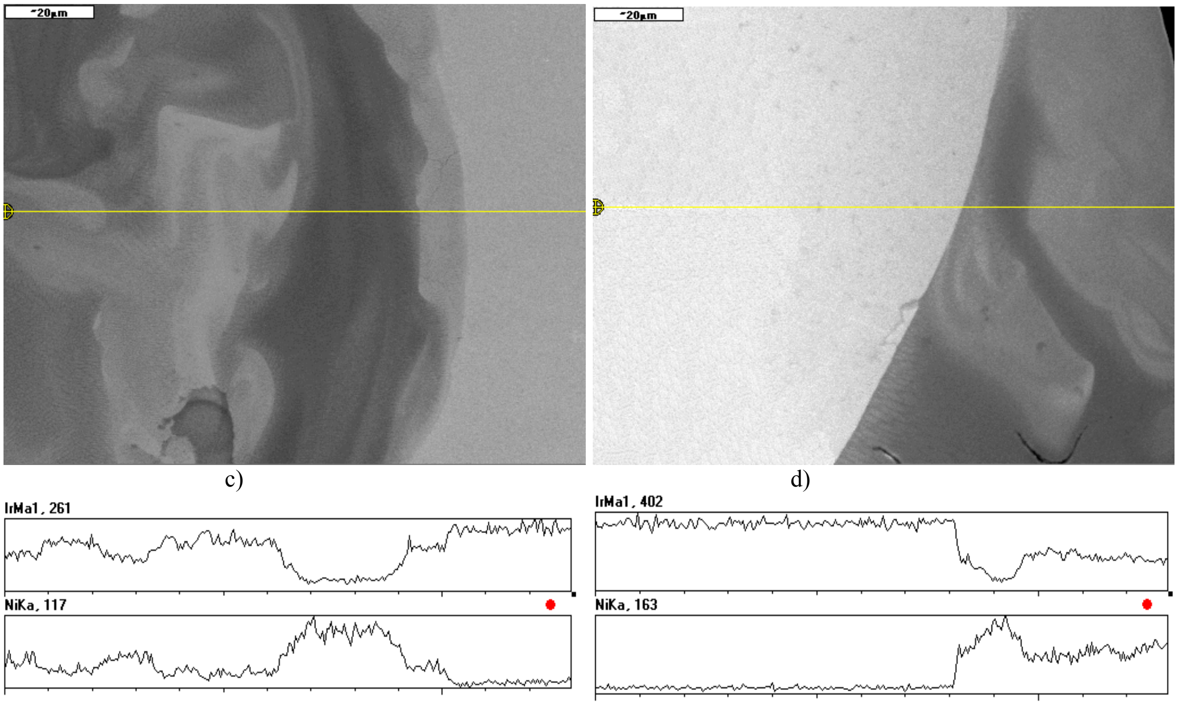
a) b)

c) d)

Fig. 4. A general view of electrode with iridium tip (a) – electric welded before laser welding (magnified 100x), (b, c) – laser welded (magnified 100x and 200x) sample no. 2 made using a HIROX KH-8700 digital microscope *and (d) – a general view of transverse metallographic specimen magnified 100x made using a JSM JEOL 5400 microscope.*



a) b)



c) d)

e) f)

Fig. 5. A general view (photo (a)) – from the left side and (b) – from the right side of the tip of central electrode with photo 4d magnified 200x along with the place of analyzing the distribution of elements. A view of the analysis (c) – from the left side and (d) – from the right side along with the linear distribution of elements, (e) – from the left side and (f) – from the right side. These photographs and the analysis of the distribution of elements were performed using a JEOL JSM 5400 microscope.

The photos included in Fig.4 present a view of the central electrode with a heated tip made of solid iridium wire (Fig.4a) and after the laser welding (Fig.4b and Fig.4c) according to the parameters of the sample 3 given in Table 1. The tip is welded to the central electrode with a continuous movement of the material in relation to the incidence of the laser beam resulting in a substantial overlapping of pulses. Solidifying traces of welding are arranged in a uniform sequence of arcs, as shown in Fig. 4c Fig. 4d shows a view of the metallographic specimen taken for the discussed sample. As can be seen on the left side there is a higher fusion of the materials to be welded than in the case of the fusion on the right side of the tip. . This is due to the incorrect setting of the material in relation to the incident beam. This problem is particularly complicated and requires a precise setting of the sample in relation to the incident laser beam to be avoided. On both sides of the tip the same operating parameters of the laser device were used, but an incorrect setting of the sample on the right side resulted in poor fusion and a narrow diffusion zone which does not guarantee an adequate joint strength.

Fig. 5 shows metallographic specimens and a linear analysis of the distribution of elements in the central electrode weld. For the sample under discussion an analysis of both sides of the joint was made, but the joint on the left side shown in Figs 5a, 5c, 5e is more desirable in the further technological process due to a better mixing of the base material of the electrode (nickel) with the material of the tip (iridium). This joint also shows more noticeable effects of convective movements (Fig.5c) providing extensive diffusion zones of different content of iridium in the joint (Fig. 5e). Brighter areas are zones richer in iridium, darker zones are richer in nickel. In the lower part of the joint (Fig. 4d and 5a) the micro crack extending from the joint zone into the zone of the substrate is visible. This may be due to significant differences in fusion temperatures of welded materials and sometimes in temperatures of their cooling. Single micro cracks are not likely to make the tip detach but they can weaken the heat transfer. The authors analyzed this problem more broadly and described in the article [16,17] and presented solutions to minimize it. In the central zone of the presented joint a lack of fusion and joints which are joints with an extremely thin diffusion zone can be observed (Fig. 4d) The upper part of the elements to be joined is partly fused by the action of the laser beam. Fusion zones differ according to the site of administering a laser beam. In each case, if the laser beam evenly covers the area of the electrode and the tip, the fusion zone is noticeably more extensive than the fusion of the tip itself. Comparing the size of fusion zones with the values of the parameters of the laser microwelding listed in Table 1 it can be seen that the size of the fusion zone is mainly dependent on the pulse duration τ .. With the highest pulse duration τ = 3.5 μs and laser power P=2.02 kW , a marked increase in the fusion zone was achieved. For these values of the parameters P and τ, the beam energy in a pulse is set to E = 5.66 J.

3. DURABILITY TESTING OF SPARK PLUGS

Durability studies were made in two ways. The first way involves laboratory tests on a specially prepared copyright laboratory stand (Fig. 6) simulating operating conditions of spark plugs to which they are subjected during the actual operation. The second way involves operational tests carried out in real conditions on the CATERPILLAR type G3412 generators (12 cylinders) powered by biogas, which can be found in the municipal sewage treatment plant at Sitkówka - Nowiny.

The aim of these studies was to evaluate the impact of the polluted environment of spark plugs and, in particular, laser-made joints on their durability and corrosion resistance.

3.1. LABORATORY TESTS

The laboratory stand made it possible to control the temperature of the operational environment of the spark plug as well as the concentration of its pollution, namely SO_2 which is metered into the fuel (methane - the main component of biogas) in specified amounts using a Tecfluid rotameter with a flow of up to 12 l/h. It is also possible to control the frequency of spark-over on the laboratory stand (Fig.6).

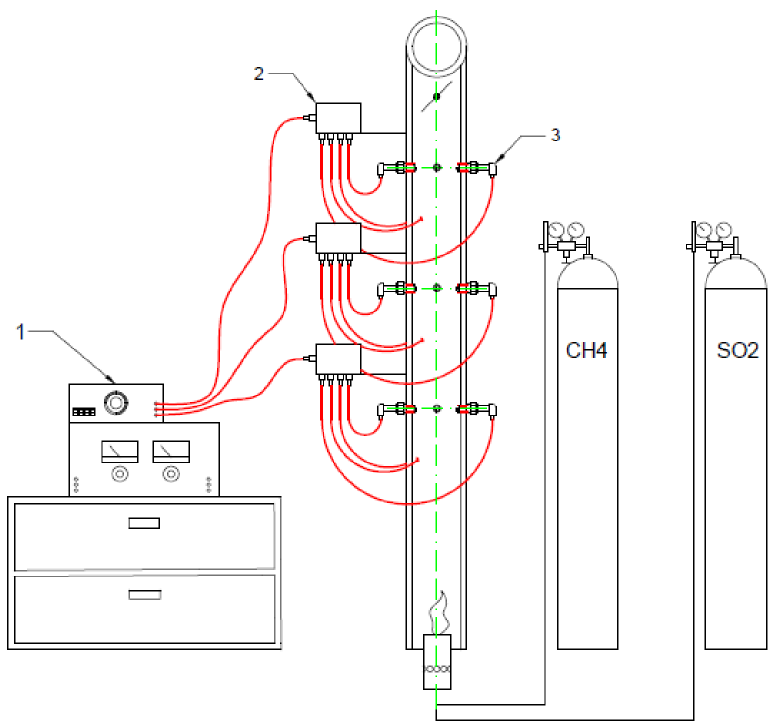
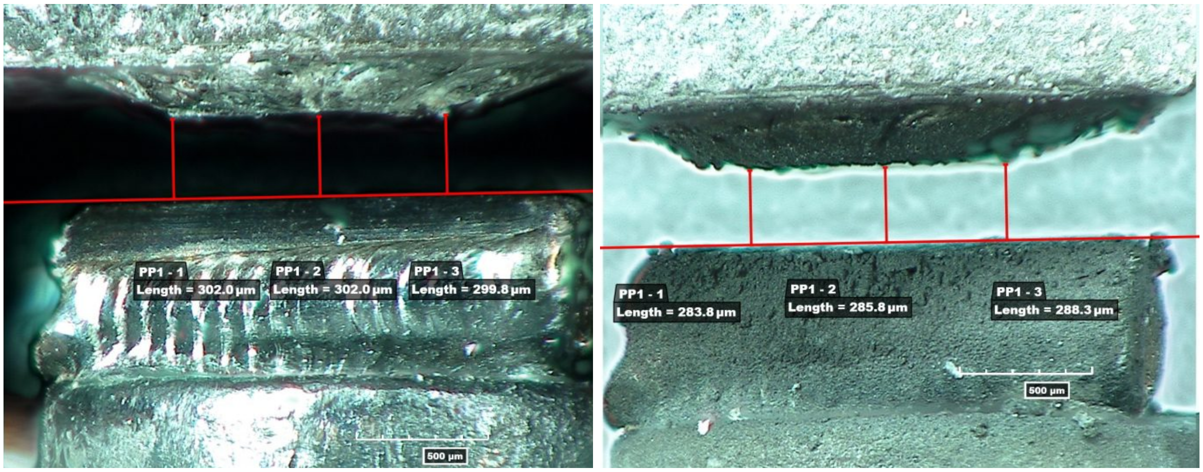


Fig.6. The scheme of the laboratory stand of spark plugs. 1 – electric power system, 2 – ignition coil, 3 – spark plug.

The photographs below showing the gap between the electrodes of a spark plug were taken by means of a HIROX KH 8700 microscope before the test (Fig. 7a) and after the laboratory test which simulated the operation of the actual internal combustion engine generating approx. 72 000 000 ignitions within 40 hours of the experiment.

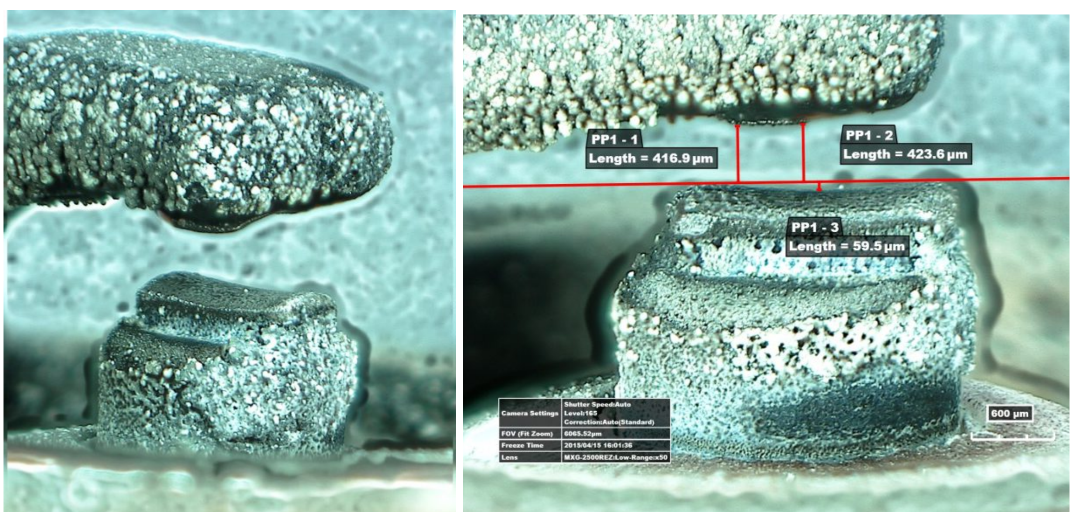


a) b)

Fig. 7. A view of the gap between electrodes before (a) and after the test (b) within 40 working hours on the laboratory stand, magnified 100x.

Fig. 7 shows a view of the gap between electrodes for a spark plug before the test in both laboratory and actual conditions. The value of the gap is usually given as about 300 µm. Fig. 7b presents a view of the gap between electrodes after 40 working hours in the environment similar in terms of chemical composition to that of natural biogas and after generating about 72 000 000 ignitions. In the present case, the combustion temperature amounted to approx. 450° C which had a significant influence on the deposition of biogas combustion products - mainly soot and other pollutants, including SO_2. This type of combustion results in reducing the gap between the electrodes which may ultimately lead to the fusion of the electrodes, to the cession of generating sparks, and to the damage of spark plugs. At higher temperatures of combustion this effect is much smaller.

3.2. EXPLOITATION TEST



a) b)

Fig. 8. A general view of electrodes of a spark plug magnified. 50x (a) and magnified 100x (b) and with dimensions of the gap. The photos taken by a Hirox KH 8700 digital microscope.

Fig. 8a presents a general view of the gap between the electrodes of a spark plug operating in a CATERPILLAR generator for about 1500 hours and after generating about 67 500 000 ignitions. Fig. 8b shows the same gap with values of the distance between the electrodes. The temperature in the combustion chamber of the generator greatly facilitates the self-cleaning process of the spark plug and thereby the values of the distance presented here are higher than those in Fig.

7b. Unfortunately, an increase in the distance between the electrodes also leads to the damage of the spark plug via a smaller energy of the spark-over and to generating the so-called "empty ignitions".

4. SUMMARY

Considering the technological experimental investigations of the laser pulse micro welding of tips to electrodes of spark plugs, the following conclusions can be drawn:

- the fusing of tips with electrodes was achieved at different parameters of pulse laser welding,
- the fusion zone makes a heterogenous mixture of the tip material with the base material of the electrode,
- the size of the fusion zone mainly depends on the duration of a single pulse forming a laser weld, and on the precise placement of the sample in relation to the laser beam,
- welds formed by individual laser pulses are characterized by the presence of single micro-cracks, regardless of the parameters of the laser treatment used.

The following conclusions have been drawn from the durability tests of spark plugs with iridium-platinum tips operating in the environment of polluted biogas or methane:

- investigations made on a copyright laboratory stand and in the real conditions on the generator confirm the strength of the laser joint produced (no detachment of the tip from the base material),
- investigations made confirm the satisfactory resistance of the iridium tip to the corrosive action of the operating environment of a spark plug,
- spark plugs with iridium and platinum tips generate approx. 72 000 000 ignitions, which is twice as much as in the case of spark plugs without tips (approx. 800 working hours and the generation of approx. 36 000 000 ignitions).

5. ACKNOWLEDGEMENTS

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