EXPERIMENTAL INVESTIGATIONS UPON SURFACE DAMAGES OF SPARK PLUG CENTRAL ELECTRODES

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Abstract: *The present paper describes an experimental study conducted in order to investigate the surfaces of the central electrodes for several types of spark plugs commonly used in the ignition systems of gasoline engines. Both new and worn spark plugs were investigated by aid of laser profilometry, in order to highlight particularities of the central electrode wear pattern after a certain period of usage. Spark plugs with single, double, triple and quadruple negative electrode configurations were considered. Both new and worn out surface shapes and dimensions were found to differ substantially for the four considered cases. Surface roughness parameters and their evolution were also determined.*

Keywords: *spark plugs, automotive, surface wear, laser profilometry,*

1. Introduction

The ignition system represents one of the auxiliary engine installations which assist in the formation of sparks between two electrodes and which make it possible to ignite the fuel mixture and thus make possible the operation of spark ignition engines. However varied and evolved nowadays ignition control systems may be, they basically all generate a spark between the electrodes of a spark plug.

There are several types of ignition systems developed and used in spark ignition engines, such as the magneto system, the battery and coil system, electronic ignition and electrostatic ignition.

Although the magneto system is the simplest type of spark ignition, it is no longer used in cars. The system, still used in small engines such as those from mopeds, lawnmowers, chainsaws or snowblowers, [Wik16], consists of a magnet spinned by the engine inside a coil and a contact breaker, which has the role of interrupting the current, thus allowing the voltage to increase enough to jump a small gap and create a spark.

Another ignition system is the battery and coil-operated ignition system, which usually consist of a battery, used as current source, an induction coil, a low voltage conductor (which connects the elements of the primary circuit), a breaker, a distributor comprising: contacts, camshaft, capacitor and distributor with the rotor, supplied by the central plug (high voltage conductor) and spark plugs, [Eau14].

For higher speed engines the classic ignition system is not suitable because the contact closing time is very short and the primary current doesn’t have enough build time so that it can reach high enough values to ensure a large the magnetic flux needed for the secondary coil to produce enough voltage to create a powerful spark between the electrodes of the spark plug, [Eau14]..

In modern engines this phenomenon is prevented by aid of electronic ignition systems. Depending on the mode of interruption of the current that controls the ignition, these systems can use transistors, can have mechanical or pulse breakers (electromagnetic or photoelectric switch), or can be built with semiconductor and capacitor elements.

The advantages of electronic ignition systems are many. The primary circuit in the induction coil is suddenly interrupted, which leads to a high voltage value in the secondary, which no longer depends on the motor speed. Especially in cold weather, due to the high voltage in the secondary, the wear of the contacts is attenuated, due to the very low value current in the primary circuit (0.25-0.5A compared to 3.5-4 A at classical ignition) and therefore not still requires repeated adjustments, [GOT08].

The use of such systems leads to a reduced fuel consumption and the engine runs better due to complete combustion of the fuel mixture.

Another modern electronic ignition variant is the individual induction coil installation for each spark plug. This removes the plug between the coil and the spark plug. The advantage of this ignition system is that it has a simple construction, which eliminates a series of subassemblies (switch-distributor and separate coil). Induction coil also incorporates the distributor in a compact assembly with stationary distribution without moving elements. The connection plugs between the distributor cover and the spark plugs are of special construction, having the core made of carbon fiber impregnated with carbon, and the protective mantle made of plastic with silicone content, [GOT08].

Regardless the type of ignition system their purpose is to ensure the needed voltage for the spark plug to generate a good enough sparks to ensure as good as possible a combustion of the fuel mixture.

2. Main characteristics of spark plugs

The spark plug consists of two electrodes, namely the central electrode (positive) and the side electrode (negative/ground). The electrodes are well insulated from each other, the central electrode being fixed in an insulating body, made of porcelain. The insulating body is fitted in a threaded metal body which is screwed into the cylinder head.

The main elements that differentiate various types of spark plugs are: the length and diameter of the threaded region, the thermal value, the shape, number and distance between the electrodes, insulator quality and electrical noise insulation.

The electric spark occurs between the spark plug electrodes and the phenomenon is explained as follows: although the air is an electrical insulator, between two electrodes supplied with electric current, however, from time to time a few free electrons appear, due to the ionization of air molecules produced by various natural phenomena; if an increasing potential difference is applied between the two electrodes, the free electrons move towards the positive electrode with increasing speed, as the potential difference increases; at the same time, the positive ions are attracted towards the negative electrode. When a spark is produced, the following aspects apply: the greater the distance between the electrodes, the greater the voltage required to form the spark. This is explained by the fact that the further away the electrodes are, the longer the distance electrons pass is and they collide with many molecules. The collisions mean losing speed and slower electrons can combine with positive ions to restore the neutral gas molecule. In order to travel from one electrode to the other, electrons must have a high speed, which is achieved by increasing the voltage. For that reason, the distance between the spark plug electrodes must not exceed 1.7 mm, or else the induction coil may not provide a sufficient voltage to produce a good spark.

Spark plug electrodes are normally consumed over time due to the electric spark, through the transport of material, as well as due to the corrosion of the burnt gases and especially those with sulfur traces.

The thermal value of the spark plug is an important feature for the smooth operation of the spark plug.

The inside of the spark plug is subjected to strong heating, the gas temperature varying during a cycle between 100-2300º C as well as very variable pressures of 0.95-40 at.

In spark plug operation, the temperature of the central electrode can vary between 200 and 1000ºC. The behavior of the spark plugs that work between these temperatures is as follows:

– up to a temperature of 250ºC, the spark plug is quickly removed from operation by fouling; on the inside, the spark plug is dirty, watered by a mixture of calamine and oil, [POS72]
– between 250-500ºC the spark plug is also taken out of service although after a longer time than in the first case and is dry but smoked with a coal dust deposited on the electrodes and on the tip of the insulator or dark brown around the central electrode, and the rest smoked, [POS72].
– between 500-800ºC the spark plug works in the best conditions; its appearance is clean the central electrode is light gray and brown towards the base of the insulator tip; the coal dust resulting from the combustion of the fuel mixture, as well as drops of oil that would reach the electrodes are burned at this temperature, the electrodes being kept clean. The temperature between these limits is called the spark plug self-cleaning temperature, [POS72];
– above 800ºC, the engine operation once again worsens: the appearance of the spark plug looks clean with the central electrode and insulator being light gray or white. Malfunction of the engine is due to the fact that at this high temperature of the central electrode self-ignition occurs, the fuel mixture igniting from the incandescent electrode before the spark appears.

The spark plug must therefore operate at the self-cleaning temperature, i.e. between 500-800ºC. This is quite difficult to achieve for all engine operating mode, because the heat received by the spark plug varies depending on the ignition advance, engine speed, proportion of gasoline in the fuel mixture, humidity of the intake air, etc.

Spark plug electrodes are consumed faster in two-stroke engines and when magneto ignition is used than in the case of four-stroke engines and coil ignition.

Optimal combustion keeps the combustion chamber walls, piston cap and spark plug clean. Most of the time it is enough to look at a spark plugs to know how well the engine works.

The spark plug is a very important part in the engine operating mode, without which the engine would not ignite and therefore would not even start.

3. Experimental investigations and results

In the present study, several types of spark plugs were investigated. Spark plug configurations with one, two, three or four lateral electrodes were considered. Both new and worn out spark plugs were optically investigated in order to visualize the central electrode wear pattern, [HOL16].

Using a NanoFocus µScan® laser profilometer, surface microtopographies of the central electrodes were mapped for both new and worn spark plugs. This allowed reconstructing 3D images of the electrode front surface as well as

The first investigated spark plug was a single lateral electrode configuration, as illustrated by Fig.1.

(a) *(b)*

Figure 1: *New (a) and worn (b) spark plug with single lateral electrode*

The central electrode surface was mapped by aid of laser profilometry for both the new and the worn out spark plug, and the 3D images of said surface were plotted as shown in Figs.2 and 3.

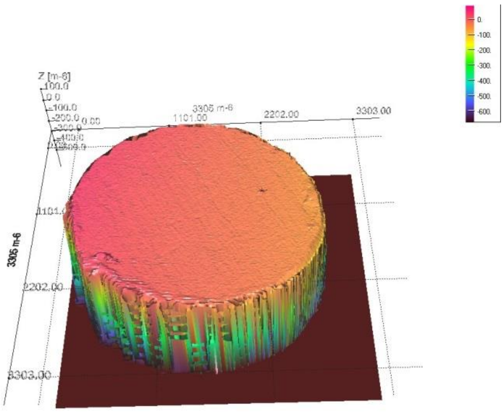

Figure 2: *3D surface representation for a new spark plug with single lateral electrode configuration*

It can be easily observed that in this configuration, the central electrode surface is initially flat and has a circular shape.

For the single electrode configuration, the ground electrode is bent over the central one (positive), in order to protect it from heat and oil contamination. This leads to lower temperature variations and less fouling of the central electrode.

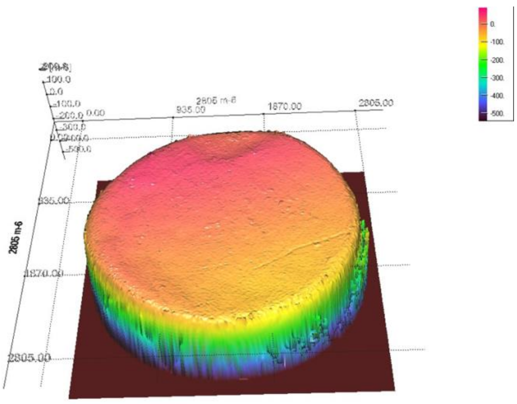

Figure 3: *3D surface representation for a worn out spark plug with single lateral electrode configuration*

From the 3D representation of the worn plug, Fig.3, it can be observed that the front surface remains relatively flat and clean, with the exception of a concave region, where the sparks were probably predominantly produced.

The obtained surface microtopograpy for the single negative electrode configuration, show that the electric discharges were not concentrated in the central region of the positive electrode, but rather in a more lateral position.

The second set of experiments considered dual lateral electrode spark plug configuration. In this case, there are two grounded electrodes placed symmetrically to the central electrode. Such a configuration can be observed in Fig.4.

(a) *(b)*

Figure 4: *New (a) and worn (b) spark plug with dual lateral electrode*

For the new spark plug, the central electrode has the front surface shaped as a spherical cap, as shown in Fig 5. This is meant to ensure that the electric discharge takes place on the surface and not in midair.

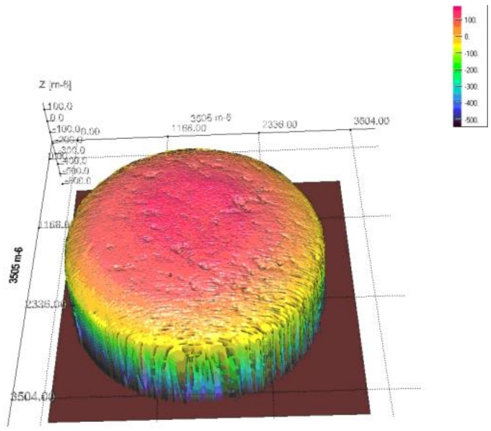

Figure 5: *3D surface representation for a new spark plug with dual lateral electrode configuration*

The front surface of the worn electrode, shown in Fig.6, is ovalized due to melting of material in diametrically opposed areas, corresponding to the two electrodes. The presence of a single central cavity could be explained by accidental discharges.

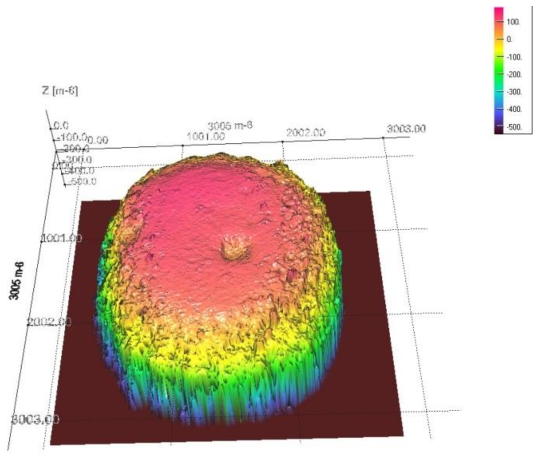

Figure 6: *3D surface representation for a worn out spark plug with dual lateral electrode configuration*

Experimental measurements continued with a triple lateral electrode spark plug configuration. The three electrodes are placed at 120° from each other, as illustrated in Fig.7.

For this configuration, the central electrode presents a similar spherical cap shape as previously. The difference is that in this case, the spherical cap is more convex than in the dual electrode configuration, as it can be observed in Fig.8.

(a) *(b)*

Figure 7: *New (a) and worn (b) spark plug with triple lateral electrode*

The reason for the more convex shape is linked to the fact that the three sparks must form on the spherical surface and not in midair.

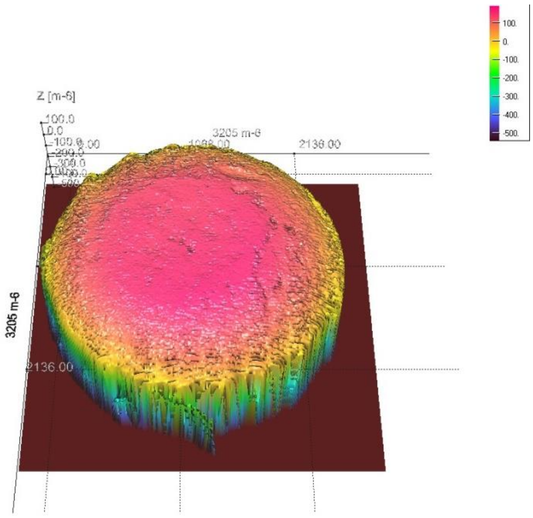

Figure 8: *3D surface representation for a new spark plug with triple lateral electrode configuration*

The worn surface of the triple electrode configuration, shown in Fig.9, has a rather triangular shape with significant rounding of the corners, due to the presence of three sparks

The observed unevenness of the worn surface suggests that the three discharges generated a very large amount of heat, which partially melted the central electrode. The cooling resulted after ignition is not as uniformly spread and leads to an unevenly solidified material.

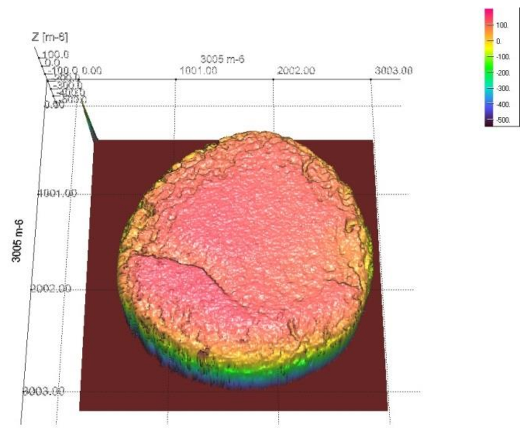

Figure 9: *3D surface representation for a worn out spark plug with triple lateral electrode configuration*

The fourth and final set of measurements was conducted on a four electrode configuration of spark plugs, where the electrodes are placed on the circumference, at 90° from each other, as seen in Fig.10.

(a) (b)

Figure 10: *New (a) and worn (b) spark plug with quadruple lateral electrode*

The front surface of the central electrode for the new spark plug is very similar in shape with the triple electrode configuration, as easily observed from Fig.11.

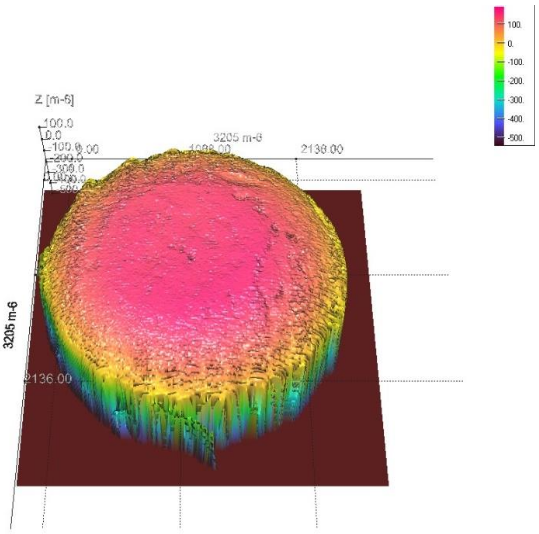

Figure 11: *3D surface representation for a new spark plug with four lateral electrodes configuration*

The worn surface however is completely different from the previous cases.

The shape of the worn front surface of the central electrode in a quadruple negative electrode configuration was found to be conical, with a rounded tip, as shown in Fig.12.

The explanation for this shape could be related to the fact that the four sparks surround the electrode like a torus. The generated heat is uniformly melting the central electrode on the lateral surface and in the joining area with the spherical cap. Due to the vertical positioning of the spark plug, the molten material then flowed under the action of gravity, solidifying uniformly.

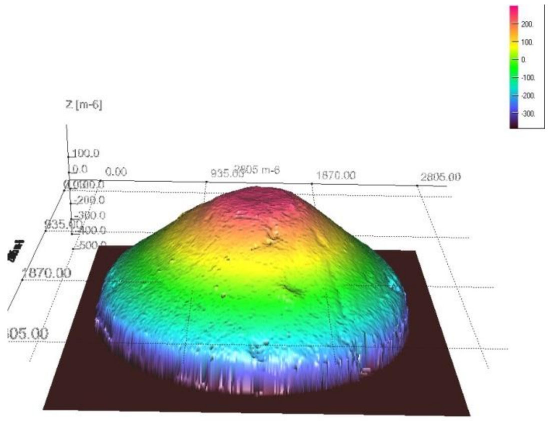

Figure 12: *3D surface representation for a worn spark plug with four lateral electrodes configuration*

The plane representations of the central electrode surfaces permit evaluations of its circular shape and dimensions. Measurements of the electrode circumference were conducted for both new and worn electrodes, as illustrated in Fig. 13.

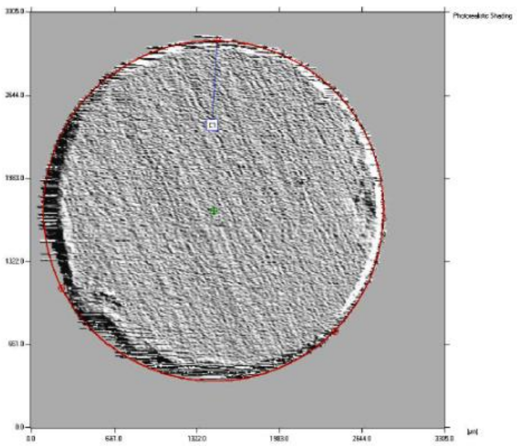

Figure 13: *Sample plane representation and circumference measurement of the central electrode for a single electrode spark plug configuration*

The obtained radii lengths for all the investigated spark plugs are found in Table 1.

From the investigated surfaces, single profiles were extracted, as shown in Fig.14.

The Ra and Rz roughness parameters were then determined according to EN ISO 4287 standard. The obtained roughness parameters for all the considered spark plugs were also centralized in Table 2.

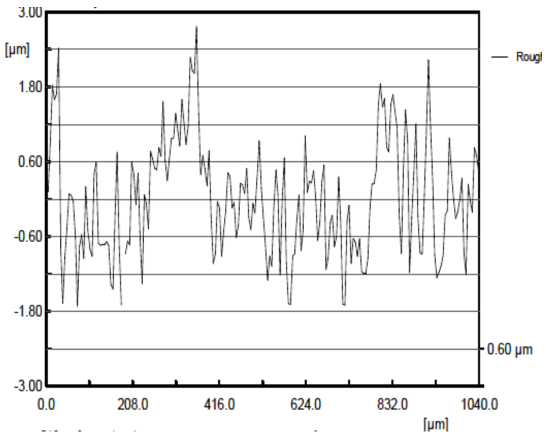

Figure 14: *Sample roughness profile representation for a single electrode spark plug configuration*

Table 1: *Central electrode measured radii*

Spark plug Configuration	Investigated State	Measured Radius [µm]
Single electrode	New	1360
	Worn	1274
Dual electrode	New	1468
	Worn	1319
Triple electrode	New	1325
	Worn	1279
Quadruple electrode	New	1358
	Worn	1181

Table 2: *Central electrode roughness*

Spark plug Configuration	Investigated State	R_a [µm]	R_z [µm]
Single electrode	New	0,755	4,943
	Worn	0,899	6,043
Dual electrode	New	0,965	7,144
	Worn	1,244	14,221
Triple electrode	New	1,553	9,937
	Worn	0,824	7,410
Quadruple electrode	New	0,803	3,589
	Worn	1,489	8,986

From the measurement data in Tables 1 and 2, it can be easily observed that the electrode front surface circumference diminishes for the worn spark plugs, while the roughness parameters R_a and R_z increase with wear.

4. Conclusions

Seeing that the spark plug is a very important part in the engine operating mode, without which the engine would not ignite and therefore would not even start, the present study experimentally investigates the wear of the central electrode on several types of spark plugs used in automotive ignition systems.

The aim was to highlight the wear produced on the central electrode after a period of use.

The damage occurring to the central electrode in several types of spark plugs was analyzed using laser profilometry.

Four types of spark plug configurations were tested, and the new and worn out central electrode surface was analyzed.

The central electrodes of investigated worn spark plugs showed little or no discoloring and from their surface measurements no material deposits were found, but only normal wear due to high temperatures and electric discharges. It can be therefore concluded that the engines from which the tested spark plugs were taken, worked in normal parameters, and the plugs were mostly maintained in the 500-800°C temperature range.

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