An experimental study of microfabricated spark gaps: wear and erosion characteristics

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Abstract

The objective of this work is to experimentally study the erosion and wear characteristics of microfabricated spark gaps. A microfabricated spark gap is a small-scale, low-profile ignition device that can be used, for example, for a small-scale combustion engine. Wear characteristics of this spark gap are important parameters to study to ensure long lifetime and trouble-free operation of the small-scale combustion engine. In this research, microfabricated spark gaps are made of metals—nickel, platinum, and silver—which are currently used in macro-scale spark plugs. A spark gap structure is built by microfabrication processes including photolithography, electroplating, and screen-printing processes. The finished spark gap is then repetitively cycled and optically measured for erosion and wear to determine the experimental volume erosion rate. Six experiments for observing the effects on spark erosion characteristics from six different parameters are constructed. These parameters are the spark gap distance, the electrode height and width, the spark energy, the source of spark energy, the method of fabrication, and the spark gap electrode material. It was found that all parameters except the spark gap distance affected the erosion characteristics of microfabricated spark gaps, and that the particle ejection could be an appropriate erosion mechanism at work for these microfabricated spark gaps.

1. Introduction

Recently, there has been much interest in the potential application of small-scale combustion devices for automotive and for power generation in microelectromechanical systems (MEMS) [1]. In some combustion processes, such as reciprocating devices or pulse combustion, ignition of the combusting mixture using an electrical spark at every cycle is used. For nonreciprocating devices, e.g., rotary engines and turbines, single sparks can be an effective way to initiate the combustion process. So it is applicable in a small-scale combustion engine, instead of a typical spark ignition device in a conventional spark plug, a small-scale, low-profile electrical spark ignition device, called a “microfabricated spark gap,” is used and fabricated by MEMS technology.

The objective of this research is to experimentally study the characteristics, especially wear and erosion, of microfabricated spark gaps, and to compare the results with literature theories on erosion and wear. Wear and erosion characteristics of these spark gaps are important parameters to study to ensure long lifetime and trouble-free operation of the small-scale combustion engine. Although there is much reference on some characteristics and erosion models of conventional arc discharge devices (2-27), because of the differing fabrication techniques and the small scales of MEMS spark gaps, these erosion characteristics should be determined on the MEMS gaps themselves.

In this paper, section 2 provides a detailed background and literature review of materials for microfabricated spark gap electrodes. In section 3, details of experimental methods and design used in microfabricated spark gap tests are presented. In section 4, a detailed overview of the experiments and their operating conditions are explained individually. These experiments have been conducted to determine the erosion characteristics of the microfabricated gaps as a function of six experimental parameters. These parameters are the spark gap distance, the electrode height and width, the spark energy, the source of spark energy, the method of fabrication, and the spark gap electrode material.
Section 5 presents the wear and erosion characteristics results as a function of the six experimental parameters, as well as some discussion of the results. Finally, conclusions regarding the microfabricated spark gap erosion and wear characteristics studied in this research are reached in section 6.

2. Materials for microfabricated spark gap electrodes

Spark gap materials have been carefully selected because the erosion characteristics of the spark gap depend directly on its material properties. Furthermore, it has been presented in the literature [11] that erosion rates of metals are not usually correlated with any single mechanical property. Gierke et al. [12] proposed that the erosion rates of ductile metals be tested, with the hardness of the eroded surface, with ductility, or with thermophysical properties, such as heat capacity, thermal conductivity and the melting point of these metals. In several papers [8, 13], it has been noted that metals with high heat capacity, melting point and good oxidation resistance tend to have a better resistance to erosion. Moreover, the spray width or erosion rate of a material depends on the melting point and boiling point values, which correlate with melting energy. H. Single et al. [14] have reported that another parameter which affects the wear characteristics of spark electrodes is the morphology of the material (i.e., its microscopic structure). This is especially true for composite materials and in ion-implanted fiber materials.

For all of the above results, when considering materials as candidates for spark gap electrodes, three important factors are the melting and boiling points of the material, the material's erosion resistance, and the microstructural characteristics of the material in combustion environments.

There is a well-developed literature on materials for conventional spark plugs [2, 8, 9]. Appropriate microfabricated spark gap materials can be determined by considering which of the conventional spark plug materials are compatible with microfabrication and MEMS technology. An additional challenge in producing microfabricated spark gaps, as opposed to conventional spark plugs, is that since the total electrode volume is large, only very small amounts of erosion can correspond to large percentage increases in the electrodes.

In this research, nickel has been chosen as the base material to work with because of its high melting point, 1,452 °C [15], and well-developed fabrication processes [25]. Platinum is another material to study next because of its high melting point, 1,968 °C, and because fabrication processes for platinum are available. Moreover, platinum has been widely used for commercial conventional spark plug tips to improve corrosion resistance. The base material selected in this research work is silver. Although it has a relatively low melting point, silver is a conventional spark plug material and fabrication processes for silver are available. Therefore, it is appropriate to choose silver as one of the microfabricated spark gap materials to compare its results with nickel and platinum.

3. Experimental methods and design

3.1. Experimental parameters

These are many parameters of the microfabricated spark gap that affect its wear and erosion characteristics. Knowledge of the dependence of wear and erosion characteristics on different gap distances, and electrode height and width, will allow the optimization of an appropriate spark gap geometry which will provide good wear resistance over the micro-combustion regime life. Understanding how erosion characteristics are affected by different spark gap electrode material and methods of fabrication will also provide an optimal fabrication process and material for microfabricated spark gaps. Awareness of how the spark energy as well as its source may affect the erosion characteristic of microfabricated spark gaps is another important and interesting factor to study.

To study the effects of these parameters on wear and erosion characteristics, six selected experiments are conducted individually for all spark gaps important parameters. These parameters of interest are the spark gap distance, the electrode height and width, the spark energy, the source of spark energy, the method of fabrication, and the spark gap electrode material.

3.2. Method of fabrication

Conventional thin-film micromachining approaches, where the deposited film dimensions are of the order of microns, may not be appropriate for spark gap materials, as erosion will cause a much larger portion of material to be removed with each spark cycle, quickly eroding the spark gap (spark gap material).

MEMS-compatible procedures that result in thick deposited films should be used. Two attractive techniques that satisfy this criterion are electrophotography (electrophotography) and sputtering. In this research, a low-profile and small-scale spark gap structure is built using both of these techniques.

Spark erosion results from these two methods will be compared.

3.2.1. Electrophotography technique. Nickel has been chosen as the electrophotographic spark gap material due to the fact that nickel plating processes for MEMS are well-developed [26]. The microspark gaps are fabricated using a one-mask photolithography process on glass substrates. A pyrolytic graphite substrate forms the spark gap. The pyrolytic graphite substrate is removed using a standard photolithographic technique. After photolithography, a mask is used to form the microspark gap, and a photoresist is used to form the spark gap structure. The top Ti layer is then removed and the spark gap structure is completed. The fabricated spark gap electrode is shown in Figure 6. After photolithography, a mask is used to form the microspark gap structure. The top Ti layer is then removed, leaving behind the completed spark plug.
3.2.2. Screen printing technique. Three materials have been selected for the screen printed electrodes. The first material is nickel, in that direct competence can be made between the electrodeposited and screen-printed electrode materials. The other two materials, silver and platinum, have been selected as they are commonly used in either actual environments (surface-reactive metals) or actual spark gaps in automotive and other internal combustion applications (platinum).

In the screen-printing process, the desired metal ink is screen-printed through a patterned mask or screen onto a glass substrate, baked, and fired. All inks have been obtained from Dupont (part nos. 48429, 4938, and 9141).

Typical firing temperatures and times for different materials are listed below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>550-600</td>
<td>30-60</td>
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<tr>
<td>Ag</td>
<td>550-600</td>
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<td>Ag</td>
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3.3. Source of spark energy

3.3.1. Dual transformer approach. The first spark igniter using system studied in this research was a dual transformer approach. The first transformer (called the primary) is used to increase the voltage to about 360 V. The secondary of this transformer is connected to a bank of capacitors and diodes. The capacitors are charged to the desired energy, and when triggered by the SCR switch, the spark energy in the capacitors is discharged to the secondary transformer. The secondary transformer (24 V pulse transformer) can increase the voltage up to about 20 kV, which is used as a high-voltage pulse to jump the arcs across the gap of the spark plug. The SCR switch is triggered by a TTL pulse from the 24 V pulse generator (HP/Agilent Model 735A). It is a rate of 2 times, and results in 20 Hz spark pulses at the spark gap.

If losses in the secondary transformer can be neglected, the energy in the spark can be set by the energy stored in the capacitor bank. This energy is determined by the charge stored in the bank of capacitors. Assuming the capacitors are linear, equation (1) below expresses the energy stored in the capacitors, where \( E \) represents the energy, \( C \) represents the capacitance, and \( V \) represents the voltage across the capacitor.

\[
E = \frac{1}{2} CV^2.
\]

The theoretical maximum ignition energy for stoichiometric mixtures of propane and air is 0.5 J (1). Additional energy is often required to initiate combustion as a result of electrical losses, heat losses, and electronic ionization. Therefore, in this research, two secondary capacitors were used in a push-pull arrangement, which correspond to a charging voltage of 340 V and capacitance values of 60 and 80 mF, respectively. However, actual commercial value capacitors used in this circuit are 62 and 150 mF, it has been reported in the literature (10-13) that this approach can result in very low energy transfer efficiency, 1% or less. Most of the energy is lost in the transformer due to its connection to the spark gap and in the spark gap itself.

3.3.2. High-voltage capacitor approach. Because of the difficulty of accurate energy measurement in the transformer approach, an alternative approach based on the direct discharge of a high-voltage capacitor was developed. In this research, a high-voltage amplifier model 9701 from Tektronix is used to supply the high-voltage signal. This high-voltage amplifier has a power 1000 and maximum output of 10 kV. To achieve this high voltage amplifier is a programmable function generator (Tektronix). It is used to make a spark pulse every 30 ms (20 Hz), the function generator is set to a square wave with frequency of 20 Hz and a duty cycle of 0.6% as a peak voltage of 1.8 kV. Power from this amplifier is supplied to the connecting RC circuit to charge the capacitor. It is then tested with another high-voltage capacitor, 330 µF. Between the high voltage amplifier output and RC circuit to isolate the external action from the amplifier. The voltage across the capacitors, or also across the spark gap, is slowly ramping up with a known time constant, \( \tau = RC \), where \( R \) is the resistance and \( C \) is the capacitance. At the moment that the voltage across the spark gap reaches the breakdown voltage, the spark jumps across the PP.

Assuming that the time constant of the RC circuit is much longer than the spark period, the energy in the spark can be set by the capacitance of the capacitor and the voltage across the gap at the inception of the spark. In this paper, a 20 MG, resistance and 40.7 µF, capacitance, which will give a time constant of about 1 ms, is used. Compared to the spark duration (which is the order of microseconds), the energy that is supplied to the spark can be assumed to be equal to the energy stored in the 40.7 µF capacitance. The expression of equation (1) is used to calculate this energy. For two parallel-connected spark gaps, the breakdown voltage in air ranges experimentally from 5.7 to 6.2 kV. Because the capacitors do not completely discharge, the maximum voltage drops suddenly from the breakdown voltage to a measured voltage of 1.25 kV and then recovers again, equation (1) must be modified to equations (2), equation (2) replaces \( V_0 \) in equation (1) by \( \frac{V_0 - V}{\tau} \), where \( V_0 \) represents the upper bound of capacitor voltage and \( V \) represents the lower bound of capacitor voltage.

\[
E = \frac{1}{2} CV_0^2 - \frac{1}{2} \frac{V_0 - V}{\tau}^2.
\]

Therefore, with \( V_0 = 4.0 \), \( 3.75 \), \( 3.5 \), \( V = 1.25 \) kV, 48.8 J, the spark energy in this approach will range from 330 to 695 microjoules (µJ). The actual spark energy may be more than that reported here because of the additional current from the high-voltage amplifier that can be delivered to the spark gap, however, because of the long time constant of charging the discharge capacitor, this current is assumed to be negligible.

It is read that to measure the breakdown voltage, a resistance voltage divider is used. Series connected resistors (100 MG ohm) are connected parallel to the spark gap and a voltage across the small resistor (400 kΩ) is measured using a TDS 220 oscilloscope (Tektronix). This shows the measurement of \( V_0 \) and \( V \) for equation (2).
3.4. Erosion measurement

3.4.1. Quantitative erosion measurement: erosion rate. In this paper, for erosion and wear optical measurement, or optical microscope (OM) is used to measure heights, widths and removal lengths of both sides of spark electrodes after the spark gap has been run for a specific number of spark cycles. The multiplications of those widths and removal length values provide removal rates of the spark gap. Then, a volumetric rate of volume erosion is calculated by multiplying the removal area by the heights of the spark gap. By plotting many values of volume erosion as a function of the number of spark cycles, a volume erosion graph can be obtained. This volume erosion ratio is the slope of the graph. The rate of volume erosion rate is cubic meter per cycle.

3.4.2. Qualitative erosion measurement: surface erosion characteristics. Although the optical microscope measurement method described above yields quantitative information about erosion rate, additional information regarding the erosion mechanism can be obtained by a detailed study of the surface morphology of the spark gap materials. This is done by observation in a scanning electron microscope (SEM) (Hitachi). By using this tool, it may be possible to determine not only the structure of the discrete surface after sparking, but also to study the pattern of ejected material from the electrode surface that has sublimed on the glass. From these measurements, a qualitative comparison to literature theories of wear and erosion can be made.

4. Detailed outline of experiments

The six parameters of interest studied in this research are the spark gap distance, the electrode height and width, the spark gap energy, the source of ignition energy, the methods of fabrication, and the spark gap electrode material. Both qualitative and quantitative measurements are chosen to determine wear and erosion characteristics of micro-debused spark gaps affected by these parameters. The microscopic and spark gap test, a test and a removal removal for each spark gap is typically measured repeatedly up to 1 million spark cycles or until spark gap rise (literature).

By using the quantitative optical measurement, an experimental volume erosion rate can be determined. Also, after the experiments, the spark gaps are examined qualitatively in an SEM to observe the surface morphology of the spark gap materials.

Several experiments are conducted in this study. Erosion characteristics affected by different spark gap distances are investigated in experiment 1. Two spark gap distances, a 175 micron gap and a 2 mm gap, are used in this experiment. In experiment 2, the effect of different electrode heights and widths on erosion characteristics will be studied. Two 175 micron spark gaps that differ in height are tested. Also, two sets of 2 mm spark gaps with a difference in height and width are assessed. In experiment 3, six spark gaps are tested at two different spark energy, 3 and 10 ml, to observe the influence of spark energy on erosion characteristics. In experiment 4, both spark ignition circuits, the dual transformer approach and the high voltage capacitor approach, are used to run four spark gaps. This will determine erosion characteristics as a function of the source of spark energy. Erosion characteristics as a function of the method of lubrication are studied in experiment 5. Both the electro-deposition and screen-printing processes are chosen to lubricate the spark gap in this experiment and the results on wear and erosion characteristics from both techniques will be compared. Finally, in experiment 6, three different materials (aluminum, platinum, and silver) are chosen as screen printing spark gap electrode materials, to study how erosion characteristics are affected by electrode materials. Each of these parameters of interest and the experimental details are presented and described here.

4.1. Experiment 1: spark gap distance

The first spark gap structure is a single two-electrode system with a 175 micron gap (figure 1). This is an arbitrary gap distance designed to see the wear of spark gaps by keeping both ends of the spark gap within the field of view of a single microscope objective. The electrodes are nominally 105-125 microns wide by 40 microns high to produce a sample of a sufficient volume to enable reliable wear data to be gathered.

The second spark gap geometry is designed with a larger gap of 2 mm (figure 2). A combination experiment indicated that a 2 mm gap distance was an appropriate gap for repetitive and reliable ignition of propellant mixtures. The electrodes of this device are nominally 330-350 microns wide. The height of the device is varied between 40 and 90 microns.

Both 175 micron and 2 mm spark gaps are fabricated using the same material identically, and the same lubrication process (treatment). All spark data are gathered in laboratory air using the dual transformer approach. The ignition circuit is triggered with a 20 Hz pulse signal, resulting in 20 Hz spark.
pushes at the spark gap. All spark gaps are tested up to 1.5 million spark cycles. For 175 micron spark gaps, one spark gap is tested with 5 nJ energy and the other is tested with 10 nJ energy. For 2 mm spark gaps, two samples are tested with 5 nJ energy and the other two are tested with 10 nJ energy.

4.2. Experiment 2: electrode height and width

To assess the effect of electrode height and width on erosion characteristics, electrodes of two different heights and widths, with gap lengths of 175 microns and 2 mm have been designed and built using the same material (nickel) and the same electrodeposition process. All spark gaps in experiment 2 are wound in laboratory air with the dual transformer approach at the calculated 10 nJ energy. All spark gaps are tested up to 1.5 million spark cycles at 20 Hz spark pulse rate.

For the 175 micron length spark gaps (Figure 1), two heights, one 40 microns and the other 100 microns, are tested. For the 2 mm length spark gaps, these two structures are used. The first two electrodes are designed to have a much smaller electrode size, 100 microns wide by 20 microns high, as shown in Figure 3.

It is noted that these smaller 2 mm spark gaps also have reference lines next to the spark electrodes. These lines are located 250 microns away from the tips. These lines are used as a reference point in measuring the erosion lengths. As a result, it is believed that this new design will provide a better and more accurate technique in measuring electrode removal lengths.

4.3. Experiment 3: spark energy

The effect of varying spark energy on wear and erosion characteristics is another interesting parameter to study. Two spark energies, 5 nJ and 10 nJ, are used for this experiment. All spark gaps are the same electrode material (nickel) and the same fabrication process (electrodeposition). The dual transformer approach is used as a source of spark energy. All spark data are gathered in laboratory air and tested up to 1.5 million spark cycles (20 Hz spark pulse). Two 175 micron spark gaps (Figure 4), and four 2 mm spark gaps are investigated (Figure 2).

4.4. Experiment 4: source of spark energy

A difference in source of ignition energy can also affect the wear and erosion characteristics of spark gaps, according to the literature [10]. In this experiment, a nominal energy of 10 nJ for both sources of ignition energy has been attempted. To obtain the 10 nJ energy from the high voltage capacitor approach, a relatively high capacitance value of 1000 pF must be used. However, because there is a very high current discharge when using this large capacitor in the high voltage capacitor approach, a 20 Hz spark pulse cannot be obtained continuously using the available equipment. Spark gaps are therefore tested using a lower energy (on the hundreds of pF range) when using the high voltage capacitor approach. With the dual transformer approach, energy is held at a nominal 10 nJ level (although actual energies are lower due to losses inherent in this topology).

Two 2 mm spark gaps are tested with a dual transformer approach. The other two 2 mm spark gaps are tested with high voltage capacitor approach. All tests are run in laboratory air at a spark rate of 20 Hz. All spark gaps are built with the same electrode height and width using the same electrode material (nickel), and the same electrodeposition technique. All spark data are gathered up to 1 million spark cycles.

4.5. Experiment 5: method of fabrication

Nickel spark gaps fabricated by both the electrodeposition and screen-printing techniques are compared. The gap distance for these spark gaps is 2 mm. Every spark gap is tested at 10 nJ spark energy as supplied by the dual transformer ignition circuit. All spark data are gathered in laboratory air up to 1 million spark cycles. The nickel electrodeposited spark gap electrodes are 100 microns wide by 20 microns high. The nickel screen printed spark gap electrodes are 300-350 microns wide by 50 microns high.
4.6. Experiment 5: spark gap electrode material

In this research, nickel, platinum, and silver have been known as sintered-sintered spark gap electrode materials to study the effect of material on erosion. Two nickel, two silver, and three platinum sintered-sintered spark gap electrodes were fabricated using the screen-printing technique. Spark gap electrodes were nominally 200-250 microns wide by 5-35 microns high. Variations in the width and height of these spark gap electrodes are due to different sintered-sintered metal ink properties for different materials. All spark gaps were tested at 10 kV with a dual transformer approach circuit at a rate of 20 Hz spark pulse. All spark data were gathered in laboratory air up to 1 million spark cycles.

5. Results and discussion

5.1. Experiment 1: spark gap distance

Volume erosion data are plotted as a function of the number of spark cycles and as an experimental volume erosion rate as a function of spark cycles is equal to the slope of the graph. For 175 micro spark gaps, the volume erosion rate is equal to 0.16 cubic micrometers per cycle in the 175 micro spark gap case and 0.1 cubic micrometers in the 10 kV case, for 2 mm spark gaps, the volume erosion rate is equal to 0.05 x 0.05 cubic micrometers in the 6 kV case and 0.2 cubic micrometers in the 10 kV case. It is observed that the higher the number of spark cycles is, the higher the value of the volume erosion. Moreover, there is not much difference in the erosion rate when spark gaps are of a different gap distance for both 5 and 10 kV spark energies. Therefore, it is assumed that the erosion characteristics of the spark gaps in experiments 1 operating conditions are independent of the spark gap distance. First SEMs obtained from an optical microscope, the longer the period of time the spark gap devices are run, the more the electrodes are. This is because the electric field between the electrodes is higher at the sharp edges so that the spark tends to jump to and from these sharp points more than other areas. This results in more erosion at these sharp edges. This effect has also been reported in the literature [2], a metal removal of spark gaps manifested itself by a rounding of the electrode edges, which widens the spark gap. Furthermore, figures 4 and 5 show SEM images of both 175 micro and 2 mm spark gaps. Both pictures appear similar in the sense that both show the particles depositing around the tip of each electrode. Also, they both illustrate the similar melting like damaged surfaces at the tip for the 175 micro and the 2 mm spark gaps. It is believed that the erosion mechanism for all spark gaps in this experiment is the same and that the difference in gap distance does not affect the erosion mechanism.

5.2. Experiment 2: electrode height and width

Volume erosion data are plotted as a function of the number of spark cycles and as an experimental volume erosion rate as a function of spark cycles is equal to the slope of the graph. For 175 micro spark gaps, the volume erosion rate is equal to 0.18 cubic micrometers in the thicker electrode case and 0.01 cubic micrometers in the thinner electrode case. For 2 mm spark gaps, the volume erosion rate is equal to 0.01 cubic micrometers in the larger and thinner electrode case and 0.06 x 0.06 cubic micrometers in the smaller and thinner electrode case. In the 175 micro spark gap case, there is not much difference in the volume erosion rate for two spark gaps that differ in height. However, with the same volume erosion rate, but a difference in height, the removal length of the two samples are different. When SEM images of these two spark gaps are observed, their erosion appearances are different. It is observed that the thicker the spark gap is, the shorter the removal length and the less particle deposition on the spark gap electrode. For the thinner spark gap, the removal length is greater, and more particles are spattered around the electrodes. In the 2 mm spark gap case, a large difference in the volume removal rate can be observed for two spark gap electrodes that differ in height and width. The smaller electrode spark gap electrode has a much higher erosion rate compared to the larger one. It has been reported in the literature [3, 5, 26] that the smaller the electrodes are, the higher the erosion rate. This is because smaller electrodes receive a higher spark energy concentration that larger ones. Comparing the 2 mm and the 175 micro spark gap results, it is unclear why the effects of electrode height and width on