An Experimental Study of Microfabricated Nickel Spark Plug

Georgia Institute of technology
Atlanta, GA 30332-0250
Phone: (404) 894-9419 Fax: (404) 894"2776
e-mail:mark.allen@ee.gatech.edu

ABSTRACT

This paper presents experimental. results of the erosion and wear characteristics of micromachined nickel spark plugs for use in microcombustion applications, Two spark plug structures have been designed: one with a 175 micron gap, the second with a 2 mm gap. The devices are formed on glass substrates using electrodeposition through polymer molds. The nickel spark plugs are tested at 20 Hz using spark energies of 5 mJ and 10 mJ; these energies were chosen since they had been demonstrated to initiate combustion of hydrocarbon mixtures in small model combustprs. The erosion of the devices is measured optically. For comparison, the volume erosion r~te is determined for each energy and structure accordingly. Sputtering, melting and oxidation the electrodes were observed during the erosion testing. Typical erosion rates ranged from 0.03 - 0.25 cubic microns per cycle, depending on spark energies and electrode gaps.

INTRODUCTION

This work is an experimental study of electroplated nickel spark plugs. Recently there has been much interest in the potential application of small-scale combustion for MEMS, e.g., for actuators or for power generation [1]. In some combustion processes, such as reciprocating devices or pulse combustors, ignition of the combustible mixture using an electrical spark at every cycle is used. Even in non-reciprocating devices, e.g., rotary engines and turbines, single sparks can be a useful way of initiating the combustion process.

There is a well-developed literature on materials for conventional spark plugs [2]. Appropriate microfabricated spark plug materials can be determined by considering which of the conventional spark plug materials are compatible with micromachining. An additional challenge in producing microfabricated spark plugs is that large volumes of material are required in order to withstand erosion over the plug life.

When considering materials as candidates for spark plugs, the melting point of the material, the material sputter resistance, and the oxidation characteristics of the material in combustion environments are important factors. For example., tungsten (W) has an extremely high melting point, and very good spntter resistance, but relatively poor oxidation (esistance (3]. Platinum (Pt), which shows extremely good oxidation resistance, has a low melting point and is susceptible to sputter-removal, which may limit its use in microfabricated spark plugs unless relatively large volumes of material can be deposited (3].

Among rnicrofabrication processes available for the deposition of thick metal electrodes, electrodeposition is an attractive technique. By using electrodeposition, rnicromachined spark plugs of sufficient volume to be useful in microcombustion applications can be realized. Nickel was chosen as the first material to study due to its high melting point, 1453 °C [4], and since processes for the fabrication of electroplated nickel structures are well-developed [5].

DESIGN

The theoretical minimum ignition energy for stoichiometric mixtures of propane and fuel is 0.31 mJ [4.].. Additional energy is often required to initiate combustion due to hea:t..1osses and electrode oxidation so spark energies of 5 mJ and 10 mJ were chosen for extended testing. Two spark plug test geometries were designed and fabricated. The first test structure was a simple two electrode system with a 175 micron arc gap. This was an arbitrary gap width designed to test the wear of the nickel spark plugs by keeping both ends of the spark plug within the field of view of a single microscope objective. The electrodes were nominally 200 microns wide by 40 microns high, in order to produce a sample of sufficient volume to enable extended wear data to be gathered.

In spite of the relatively small size of this spark gap, these electrodes in qualitative tests demonstrated the ability to ignite a propane/air mixture at room temperature and pressure. These small-gap plugs were then tested in a high aspect ratio test combustion chamber (wall separation of approximately 3 mIn) for simulation of a micro combustion environment. In this chamber, it was found that the 175 micron electrode gap was not sufficient to ignite a stochiometric propane-air mixture. A second spark plug geometry was then designed with a 2 tmn arc gap. The electrodes of this device were nominally 200 microns wide by 80 microns high, and this device was successful in igniting the propane,.air mixture in the model combustor. Wear results from both geometries are presented.

FABRICATION

The micro spark plugs were fabricated using a one- mask process on glass substrates, using electrodeposi ti on -through -polymer-mold technology. A Cr/Cuffi, electroplating seed layer, 500/2000/1000 A in thickness, was first deposited on the glass using electron-beam evaporation. An SU-8 photosensitive epoxy mold was spin cast to the desired thickness, either 40 microns or 80 microns, and photodefined to form molds for the spark structures. The top Ti layer was then removed and the spark plug structures were electroplated through the mold at a current density of 5 *mNcm2* in a standard Watts Ni plating bath [5]. After electroplating, the epoxy mold was removed using reactive ion etching. The uncovered seed layer was then removed leaving behind the nickel spark plugs. Figures 1 and 2 show photomicrographs of the 175 micron and 2 ~ spark structures, respectively.

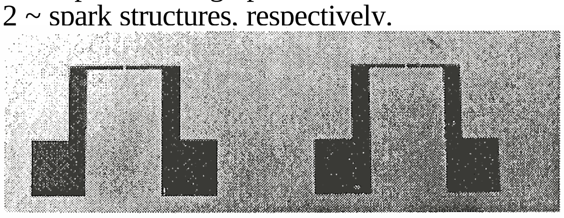


Figure 1 - Photomicrograph of theU5 micron gap nickel spark plugs.

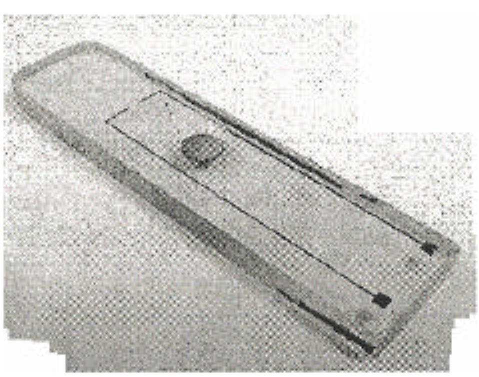


Figure 2 -Photomicrograph of the 2 rom gap nickel spark plug.

TESTING AND RESULTS

The spark ignition system uses a dual-transformer approach. The first transformer is used to step up the voltage to -500 V. The secondary of this transformer is connected to a bank of capacitors. The capacitors are charged, and when triggered, the stored energy in the capacitors is dumped to the second transformer. The second transformer steps the voltage up to -10 kV which is used to jump the arc across the gap of the spark plug. Assuming that there are very low losses in the second transformer, the energy in the spark can be set by capacitance of the capacitor bank and the voltage to which the capacitor bank has been charged. Actual energies achieved at the spark gap may be lower than those reported here due to potential inefficiencies in the second transformer.

All spark data described in this work were gathered in laboratory air. In both the small and large gap structures, the qualitative optical micrographs of the wear for S and 1.0 mJ energies appeared similar as a function of time; with the SmJ micrographs exhibiting less wear. Thus, only optical and SEM micrographs for the 10 mJ excitations are shown. However, quantitative measurement data for both energies are given below.

Small-Gap Structures

Figure 3 shows typical photomicrographs of the small gap spark plug tested at 10 mJ as a function of the number of cycles.

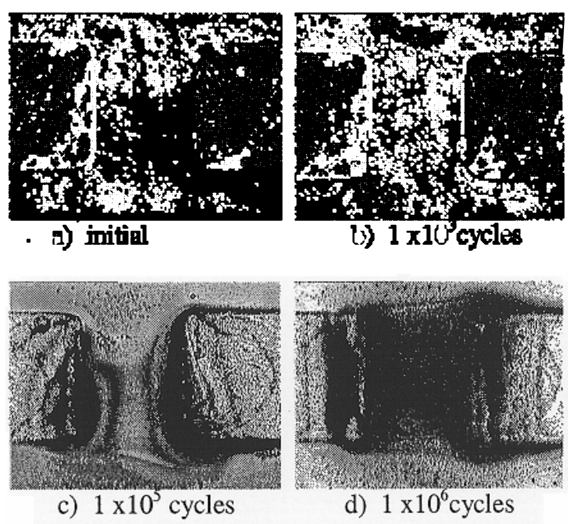


Figure 3 - Progression of the spark plug wear

The electrodes had dimensions of 200 x 40 microns. In this test, the gap width increased by 36 microns after the first 5xloS cycles. Similar results are found in the case of the 5 ri1J tests; however, the severity of the erosion is less. Figure 4 shows the gap width as a function of number of cycles. From this graph, a linearized volume erosion rate as a function of spark energy is calculated and given in Table 1. Error limits in Table 1 represent sample- to~sample variation.

Table 1 - Data points taken after $1x10^6$ cycles

	5 mJ	10 mJ
175 µm gap	.04 μm^3/cycle	.13 ± .01 μm^3/cycle

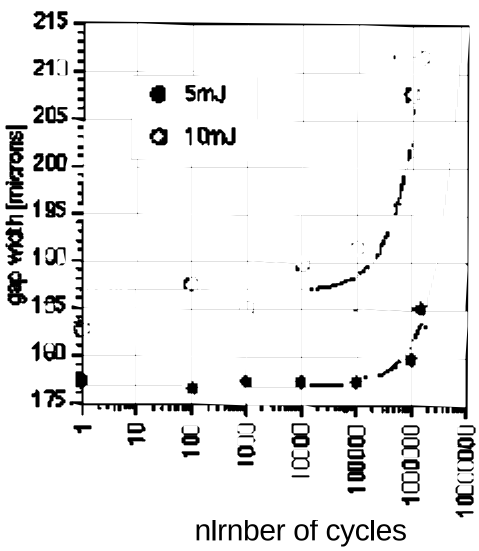


Figure 4 - Plot of the gap width vs. the number of spark cycles for the 175 micron gap structures, as parameterized by spark energy.

One device was tested to failure; failure occurred at approximately 5xlO6 cycles. The observed failure mode for this device was shorting due to deposition of sputtered material (Figure 5). Energy Dispersive Spectrometry has been used to analyze the material at the face of the electrode. It was found that there is a much higher concentration of oxygen at this surface after the testing.

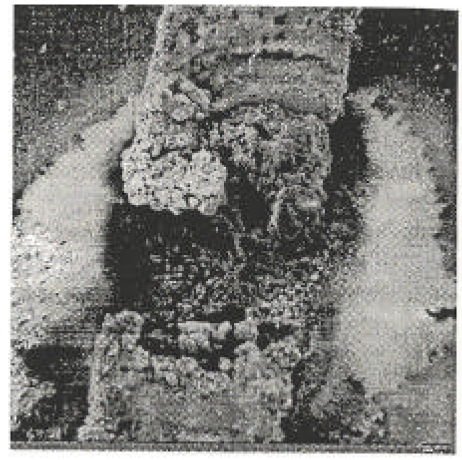


Figure 5 - A SEM picture showing a shorted narrow- gap spark plug that failed at 5xl06 cycles. This device was excited with a spark energy of 10 mJ per cycle.

Large-Gap Structures

The 2 mm gap structure test results are similar to those of the 175 micron gap results (Figure 6)

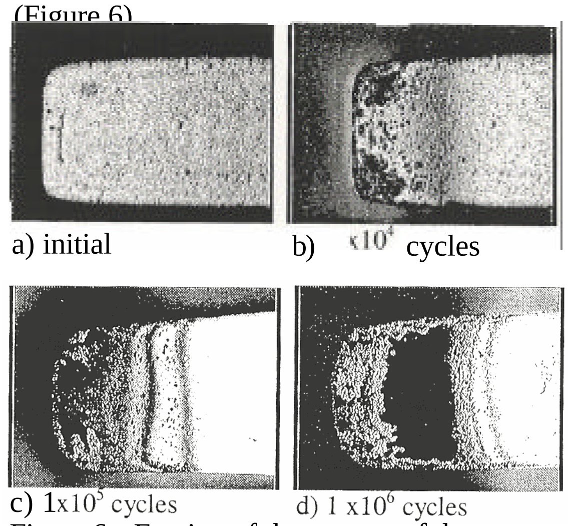
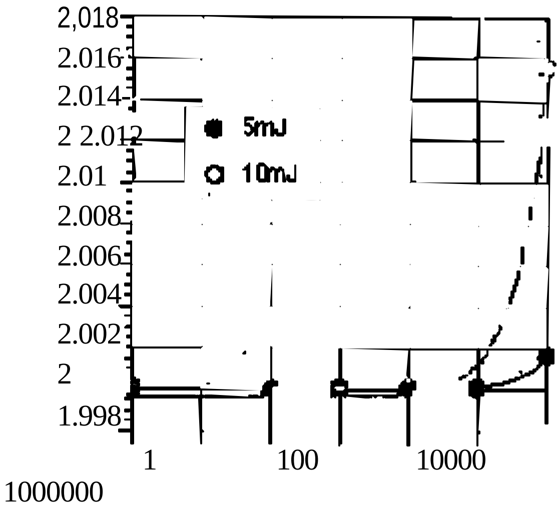


Figure 6 - Erosion of the corners of the electrodes

The increase in the width of the gap is not as dramatic due to the difference in the height of the two structures. The calculated volume erosion rate is shown in Table 2, with error limits again representing sample-to-sample variation. Sputtering and oxide-formation are similar to the 175 micron gap structures.

Tabe 2 - Volume erosion rates calculated after
lxlO6 cycle



number of cycles

Figure 6 - The plot of the gap width YS. the number of sparks for the 2 mm gap structures.

For both the small and large gap structures the wear of the electrodes was greater at the corners. The result is a rounding of the electrode (Figure 5). One possible explanation for this effect is enhanced electric field intensity at the comers of the devices. Figure 8 shows the pattern of the sputtered material left behind on the surface of the glass substrate. The evidence of the arc jumping from comer to comer can be seen here.

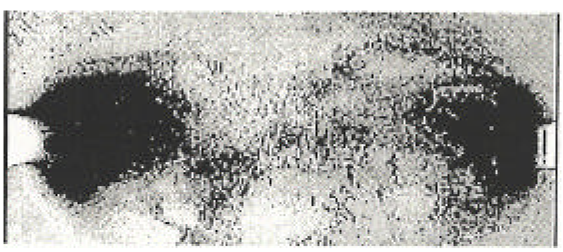


Figure 8 - Sputtered material on the surface of the substrate.

CONCLUSIONS

Electroplated nickel spark plugs have been designed and fabricated for use in a micro combustion environment. The 175 micron and 2mm gap structures have been tested with 5 mJ and 10 mJ spark energies at spark repetition rates of 20 Hz. Volume erosion rates ranging from 0.03- 0.25 cubic microns per cycle were observed depending on spark energy and gap width. The primary causes of erosion seem to be from sputtering, oxidation and melting, as expected.

ACKNOWLEDGMENTS

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA), under contract DABT 63-98-1-0009. Microfabrication was carried out in the Georgia Tech Microelectronics Research Center, with the assistance of the staff. The authors would like to thank David Scarborough, Jason Faulkner, and Professor Jeichel Jagoda of Georgia Tech for helpful technical discussions regarding combustion on the small scale, as well as running the model combustor experiments to determine appropriate spark energies; and Thomas Critten<;ien and Jin Park for the design of the spark generation circuitry used in this work.

REFERENCES

[1] A. H. Epstein, et. al. "Power \1EMS and Microengines," The 9 th International Conference on Solid State Sensors and Actuators (Transducers'97), Chicago, illinois, pp. 753-756, 1997

[2] F. Meyer and H. Bauer, Automotive electric/electronic systems, Bosch, Stuttgart, 1988

[3] K. Nishio, T. Oshima, H. Ogura, "Study on Spark Plug Electrode Shape" Int. J. Veh. Des., vol. 15,pp. 119-130, 1994

[4] R. C. Weast, S. M. Selby, CRC Handbook of Chemistrv and Physics, Cleveland, OR, The Chemical Rubber Co., 1968

[5] Frederick A. Lowenheim, Modern El~tro12lating, John Wiley & Son Inc., New York, 1974

[6] S. R. Turns, An introduction to combustion: concepts and a12plications, McGraw-Hill, New York, 1996

~