Case study

Characterization of erosion and failure processes of spark plugs after field service in natural gas engines

H.T. Lin [a], *, M.P. Brady [a], R.K. Richards [b], D.M. Layton [b]

[a] *Metals and Ceramics Division Oak Ridge National Laboratory Oak Ridge, TN 37831-6068, USA*
[b] *Engineering Science and Technology Division Oak Ridge National Laboratory Oak Ridge, TN 37831-6068, USA*

Abstract

Microstructural and optical spectroscopic analyses were carried out on as-received and used spark plugs after field service in natural gas (NG) reciprocating engines. The objective of this work was to examine the corrosion and erosion mechanisms of natural gas engine spark plug as well as identify the primary life limiting processes during field operation. The optical emission spectroscopic analysis showed a strong Ca signal in the exposed spark plugs and scanning electron microscopy showed substantial formation of Ca-enriched glassy oxide phase(s) on the electrode surfaces. In addition, intergranular cracking was observed in the subsurface region of both iridium (Ir) and platinum–tungsten (Pt–W) alloy electrode insert tips. The coalescence and subsequent growth of these cracks would accelerate the wear of the electrodes and shorten the lifetime of the spark plugs. Also, extensive internal oxidation and subsequent crack generation occurred along the interface between Ni-base alloy electrode and Pt–W alloy tip insert during field service, which would result in substantial degradation in the ignitability and performance of the electrodes, and thus spark plug failure.
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Keywords: Spark plug; Natural gas reciprocating engine; Ir electrode; Pt electrode; Erosion

1. Introduction

Improved ignition systems have been identified by natural gas (NG) reciprocating engine manufacturers as one of the key technologies for achieving cost/performance/emission goals for lean and stoichiometric engines. Spark plug erosion and subsequent failure have been recognized as a major issue in the long-term durability of natural gas ignition systems. Current spark plug lifetimes are on the order of only 1000–4000 h, which results in loss of performance and necessitates frequent costly downtime for the plug replacement. Natural gas engine end users need spark plugs lifetimes on the order of ≥8000 h (approximately ≥1 year). It is recognized that as cylinder pressures, compression ratios, and ignition voltages increase, and combustion moves to more lean burn to reduce emissions, spark plug reliability and lifetime

performance is a critical limitation for further advances in engine development. Consequently, the present research was initiated under the Department of Energy Advanced Reciprocating Engine Systems (DOE ARES) program to characterize spark plugs after field service to gain insights into the corrosion/erosion processes that limit the spark plug lifetime. Ultimately the goal of this research effort is to increase the fundamental understanding of spark plug erosion and failure processes in NG reciprocating engines as a basis for improvements in long-term reliability and lifetime of spark plugs. This paper presents the results of the characterization of erosion and failure of spark plugs after field service.

2. Experimental procedures

Engine tested spark plugs near the end of their service life were obtained from the field and characterized by optical emission spectroscopic and microstructure examination. The

* Corresponding author. Tel.: +1 865 576 8857; fax: +1 865 574 6098.
  E-mail address: linh@ornl.gov (H.T. Lin).

spark plugs used in this study were acquired from Caterpillar Inc., part number 194-8518, in sets of 16. The spark plugs were exposed in several Caterpillar 770 ekW natural gas engines until significant wear was observed and replacement was required. Two sets of these worn spark plugs with operating service times of 2020 and 4386 h were characterized in the present study. Some of the spark plugs from these sets were found to have electrical breakdown in the dielectric and could not be used for optical spectroscopic studies, but were still available for metallurgical examination. A similar set of new spark plugs was also acquired for comparison. These are J-type spark plugs with the electrodes consisting of a nickel (Ni)-base alloy (∼nominal 90–95 wt.% Ni) with the tip insert for the center and ground electrodes being iridium (Ir) and platinum–tungsten (Pt–W) base alloy, respectively.

A test chamber with a quartz-viewing window was specially constructed for the spectroscopic investigation of spark plugs. This chamber can be pressurized up to 200 psig with air or selected gases relevant to engine environments. A voltage is applied to the spark plugs using a MSD ignition coil capable of operating at rates up to 40 pulses per second. Using a quartz lens, light from the spark plug is focused into a 6 m long ultraviolet transmitting optical fiber, 400 μm in diameter. The long fiber permits operation of a spectrometer at a sufficient distance from the spark plug to prevent electrical noise from interfering with the CCD array detector. The quartz optics allows transmission in the ultraviolet where many of the metals produce spectral emission lines. The output from the fiber is directed into an Ocean Optics model S2000 fiber coupled optical emission spectrometer. This instrument is computer operated for triggering control, data transfer, and data analysis at rates up to 40 spectra per second. This speed permits spectral measurements to be taken from individual and sequential spark plug arcs.

The electrode tip surfaces of new and worn plug were examined by optical microscopy and scanning electron microscopy (SEM), combined with qualitative compositional analysis by energy dispersive X-ray spectrometry (EDS) techniques. Selected spark plugs were also ground and prepared for SEM examination by standard metallographic techniques. Quantitative compositional analysis was performed on the polished cross-sections by electron probe microanalysis (EPMA) using pure element standards.

3. Results and discussion

The representative optical spectroscopic results are summarized in Fig. 1 where the emission spectra for both a new and used (4386 h) plug are compared. Sets of plugs with 2020 h of operation have also been examined and found to produce similar spectra to that shown in Fig. 1. Most of the spectral emissions observed for both new and used plugs consist of nitrogen and oxygen lines. For new spark plugs, emission lines from Ni were always observed in the shorter wavelengths region. On the other hand, no spectral lines of
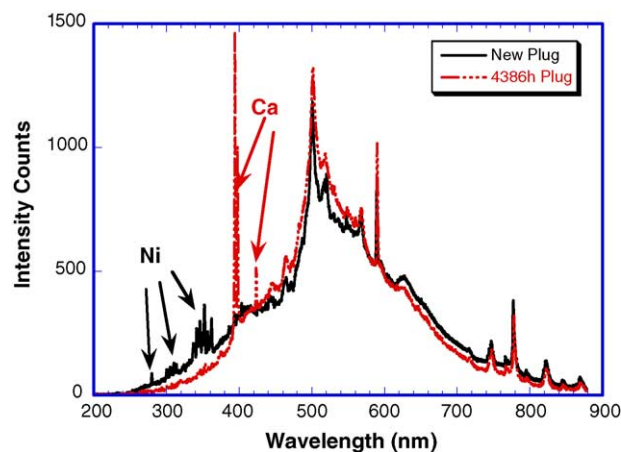

Fig. 1. Comparison of emission spectra from a new and used spark plug indicates the presence of Ca in the used plug that is not shown in the new plug.

Pt/W, and Ir, which were primary elements of ground and central electrode tip inserts, respectively, were observed during sparking. This may be the result of the superior sparking resistance of these materials compared to Ni; however, it is also possible that these elements are emitted as cluster of atoms during sparking and were not detected by the optical spectroscopic technique employed. For the used spark plugs, significant calcium (Ca) lines were observed, with little Ni and no Pt, W, or Ir element detected. There was no significant difference in Ca line intensity between 2020 and 4386 h tested spark plugs (based on 16 measurements for each set).

The observation of Ca lines in the used spark plug emission spectrum was confirmed by SEM and EDS analysis on the electrode side surfaces (Ni-base alloy) and Ir and Pt–W tip inserts of the spark plug after 4386 h field service (Figs. 2 and 3). The side surfaces of the Ni-base alloy ground electrode (Fig. 2a and b) were covered with a glassy phase enriched with Ca, Zn, P, and S. Oxide phase containing Pt and Ni was also observed with a significant quantity of Ca. In addition, the center electrode showed similar oxidation product, again containing significant quantities of Ca (Fig. 3a and b). Note that the Mn, Cr, and Si, minor alloying element components of the Ni-base alloy electrode, were also detected by EDS in these regions.

Examination of the Pt–W tip insert surface showed extensive cracking and local melting (droplet morphology), but no apparent surface oxide layer, as shown in Fig. 2c. The absence of oxide formation on the Pt–W tip insert surface suggested that the oxide phase was sputtered off during the sparking process, and thus significant material loss during sparking could occur at the Pt–W ground electrode tip insert. At the Ir tip insert (Fig. 3c), substantial intergranular cracking was also observed and the surface was fully covered by the glassy oxide phase containing Ir, Ni, and Ca. The presence of Ca, Zn, P, and S elements likely came from the lubricant used for NG engines, as they are common additives [1,2]. Note that introduction of Ca (well known as a glass modifier)
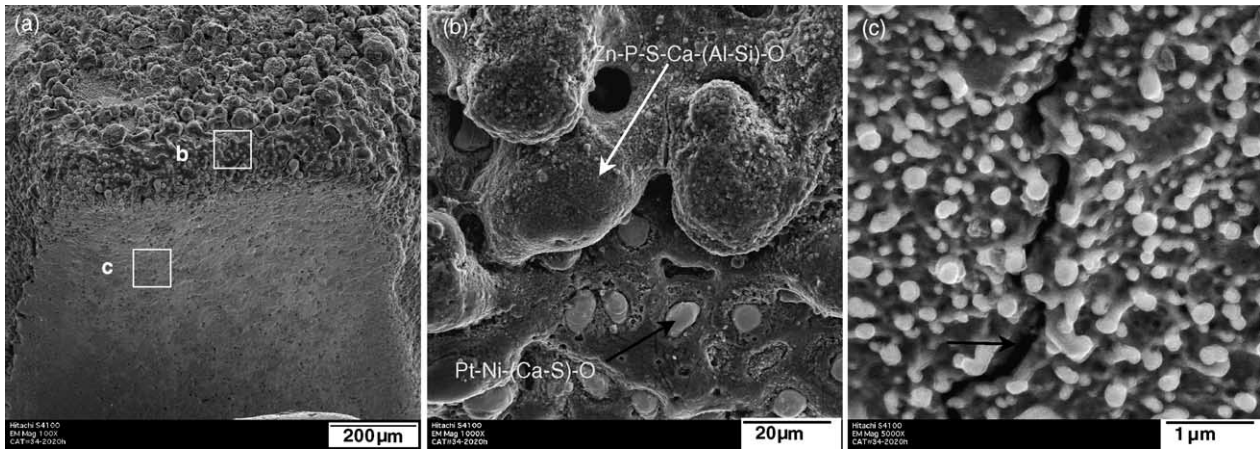
Fig. 2. SEM micrographs of Pt–W alloy ground electrode showing substantial formation of glassy phase enriched with Ca on electrode side surface (b) and crack generation and localized melting on Pt–W alloy tip insert surface (c).

into the surface oxide could significantly decrease the softening temperature and viscosity of any amorphous phase(s), thus possibly enhancing the surface erosion of the Ni-base electrode and Pt–W/Ir tip inserts during sparking at elevated temperatures. The SEM cross-section micrographs for a used plug after 4386 h field service are shown in Fig. 4. Significant wear of Ni-base electrode was observed at the corners of both the Pt–W ground and Ir central electrode, consistent with the optical spectroscopy analysis results of Ni emission from the new spark plug (Fig. 1). Comparison of surface areas of both Pt–W alloy and Ir tip inserts between new and used spark plugs showed significant area reduction ranging from 30 to 40% for the Pt–W and 10 to 15% for the Ir insert, indicating that the Pt–W insert wore at a much faster rate than the Ir insert. Also, substantial intergranular cracking was evident in both the Pt–W and Ir electrode insert. Some surface regions of the Ir insert were coated with Pt–W alloy, presumably due to the sputtering and melting of the Pt–W insert (Fig. 4c). In addition to the typical surface erosion processes/material

loss phenomena resulting from sputtering, melting, ablation, particle erosion and related effects during sparking [3,4], the generation, growth, and coalescence of intergranular cracks could also lead to significant material loss and accelerate the erosion process during field service.

The absence of significant Pt and Ir in the emission spectrum of the used plug is consistent with loss of both Pt–W alloy and Ir by crack initiation and growth rather than direct sparking and sputtering. However, the absence of these metals in the emission spectrum could be the result of clustering of atoms during sparking not registering with the spectroscopic techniques employed. Precious metals, particularly Pt, are reported to be susceptible to intergranular cracking when exposed to hydrocarbon environments at elevated temperatures [5]. Also, Ir can suffer from ductile-brittle-transition issues/cracking due to the segregation of impurities at grain boundaries [6,7]. Characterization of partially worn spark plugs with controlled short-term time intervals is needed in order to determine the relative contri-
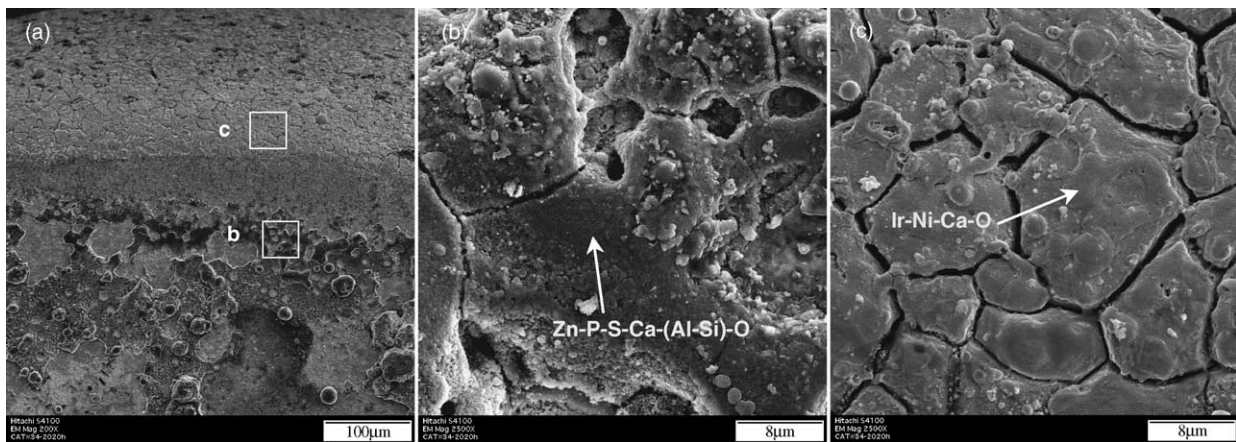

Fig. 3. SEM micrographs of Ir central electrode showing substantial formation of glassy phase enriched with Ca on electrode side surface (b) and intergranular cracking and Ir–Ni glassy phase formation on Ir tip insert surface (c).
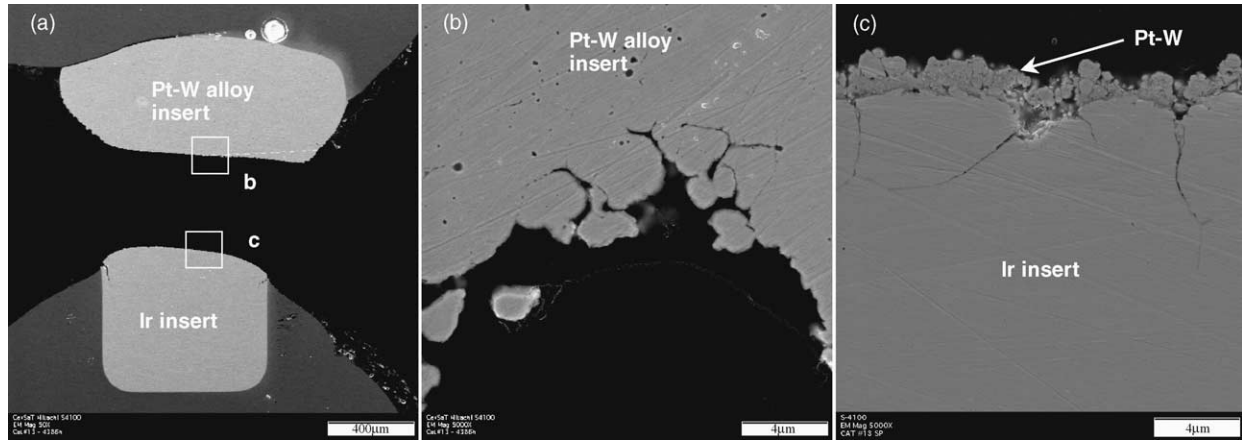
Fig. 4. SEM micrographs of polished cross section of 4386 h used spark plug showing significant generation of intergranular cracking in Pt–W alloy (b) and Ir insert (c).

bution of this intergranular cracking to the loss of electrode tip material.

Fig. 5 shows SEM micrographs of the interface between the Ni-base alloy and the Pt–W alloy insert. An oxidized crack was found to extend along much of the interface, ranging from 30 to 75% of interface length, nearly completely separating the Pt–W tip from the ground electrode. Formation of Pt–Ni oxide and significant intergranular cracking in the Pt–W alloy insert were observed in front of the crack tip (Fig. 5b and c). Such cracking plus oxide formation have been consistently observed in many end-of-life used plugs, and thus are suspected to be the key life-limiting final step in the wear process. Susceptibility to oxidation and crack initiation and growth at this location could result from interdiffusion between the Pt–W tip and Ni alloy during initial joining and manufacture of the spark plugs. Electron probe microanalysis of a new spark plug showed significant interdiffusion of the precious metal tips with the Ni electrode alloy in the new plugs, particularly with the Pt–W alloy tip insert, as shown in Fig. 6. The size of this interdiffusion zone var-ied from 300 to 500 μm between the Ni-base electrode and the Pt–W alloy insert. The interdiffusion zone formed was smaller ($\sim$150 μm) between the Ni-base electrode and the Ir insert. Therefore, there may be a significant material incompatibility issue between the selected Ni-based electrode and tip insert materials. It has been well recognized that both Pt and Ir alloys form a solid solution with Ni [8] at elevated temperatures. Thus, this Pt–Ni solid solution interdiffusion zone would readily oxidize and form Pt–Ni oxide phase at interface. The formation of the Pt–Ni oxide plus crack generation could have significant impact on the subsequent spark plug ignitibility and performance. The crack would initiate at the Pt–Ni oxide due the thermomechanical stress induced during engine operation plus thermal expansion mismatch between Pt–W insert and Ni-base electrode as well. The progressive formation of Pt–Ni–O phase by oxidation reaction and crack growth would result in a substantial increase in electric resistance and thus breakdown voltage for ignition to continue. When the crack reaches a critical length it would ultimately cause dielectric breakdown and failure of the spark plug.
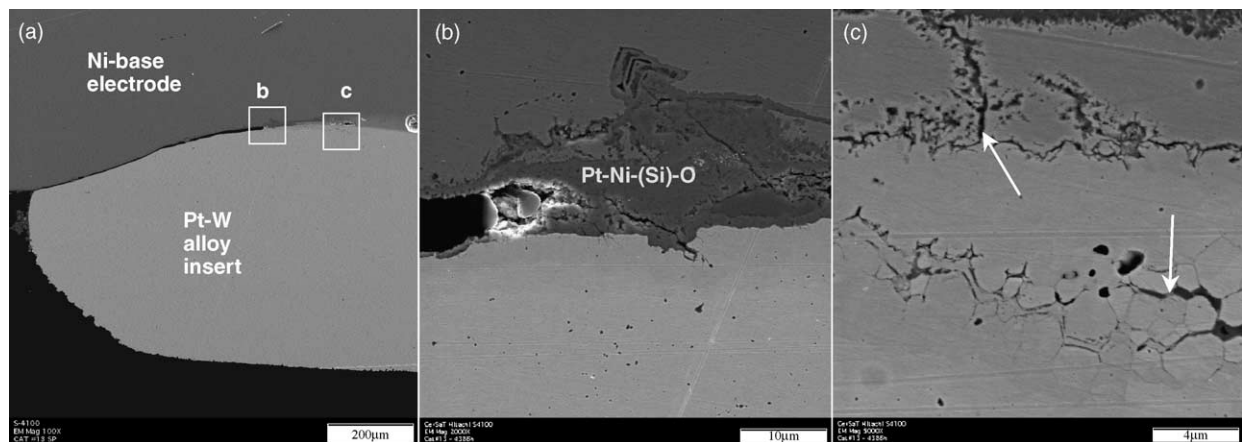

Fig. 5. SEM micrographs of Pt–W alloy insert showing crack extended 50% along the Pt–W insert and Ni-base electrode interface (a), crack and Pt–Ni oxide phase at the crack tip (b), and substantial generation of intergranular cracking in Pt–W insert in front of the crack tip (c).
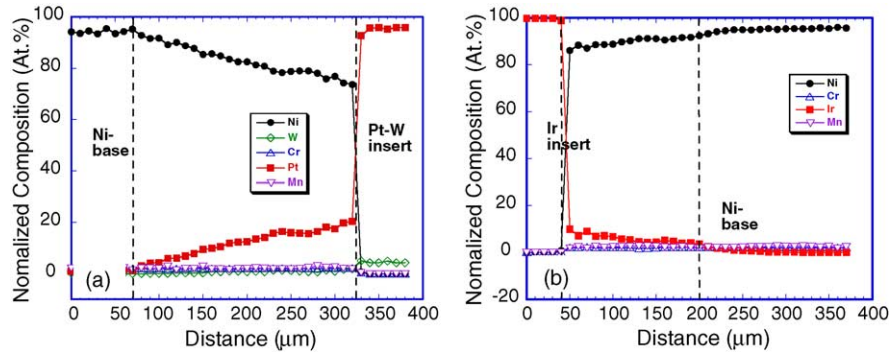
Fig. 6. Electron probe microanalysis of (a) Pt–W insert and Ni-base interface and (b) Ir insert and Ni-base electrode.

4. Conclusions

The spectroscopic and metallurgical analysis of the new and near-end-of-life NG exposed spark plugs showed a substantial formation of Ca-enriched glassy oxide phase(s) on the electrode surfaces. The presence of low melting Ca-enriched glassy phase could enhance the erosion of Ni-base electrode as well as Pt–W alloy and Ir tip inserts during engine operation. In addition, substantial intergranular cracking was observed in the surface region of both Ir and Pt–W alloy electrode insert tips. The coalescence and subsequent growth of these cracks could result in flake off of large amount of insert material and consequently accelerate the wear of electrodes during sparking. Extensive oxidation and subsequent crack generation occurred at the interface between the Ni-base alloy electrode and the Pt–W alloy tip insert during service. The progressive Pt–Ni oxide formation by oxidation combined with crack growth due to thermomechanical stress induced at the interface could result in substantial degradation in ignitability and performance of the electrodes, and thus spark plugs.

Acknowledgments

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