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Characterization of Erosion Mechanisms for Natural Gas Engine Spark Plugs

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Abstract

J-type spark plugs composed of Ni-base alloy electrodes with a pure Ir tip in the center electrode and a Pt-W alloy tip in the ground electrode were examined as-manufactured and after use in natural gas reciprocating engines by spectroscopic and metallurgical techniques. The spectroscopic examination indicated Ni emission from the Ni alloy electrodes in new plugs, but a strong Ca signal in engine used plugs. This was confirmed by metallurgical examination, which showed the presence of Ca containing

glassy oxide phase(s) (with the electrode alloy components) in the used spark plug electrodes. Intergranular cracking was observed on the Ir and Pt-W alloy electrode insert tips. The interface between the Pt-W insert and the Ni alloy ground electrode also became a site for extensive cracking and oxidation during service. These oxidation/corrosion and metallurgical issues may represent a significant component of the wear mechanism of these plugs in natural gas engines.

Introduction

Natural gas (NG) reciprocating engine manufacturers have identified ignition systems as a key technology to achieve cost/performance/emission goals for lean and stoichiometric engines. Spark plug erosion is a major problem in natural gas ignition. As cylinder pressures, compression ratios, and ignition voltages are increased, spark plug reliability and lifetime performance will become even more of an issue and could limit further engine development. Therefore, a task was initiated under the Department of Energy Advanced Reciprocating Engine Systems (DOE ARES) program to characterize field-tested spark plugs to gain insight into the corrosion/erosion mechanisms. The ultimate goal of this effort is to increase fundamental understanding of spark plug erosion in NG reciprocating engines as a basis to improve spark plug life. This paper presents initial results of the characterization of erosion in field tested spark plugs.

Experimental Approach

Engine tested spark plugs near end of life were obtained from the field and characterized by spectroscopic and metallurgical examination. The emission spectra of new and worn spark plugs were examined during sparking in a pressurized air test chamber to determine the chemicals leaving the electrode surfaces due to the spark. Select plugs were then metallographically sectioned to examine and compare the microstructural features of the electrode erosion with the spectroscopic data.

Spectroscopy

A specialized test chamber (four inches long by three and ½ inches diameter) was constructed for the spectroscopic investigation of spark plugs (Fig. 1). This chamber can be pressurized up to 200 psig with air. Four ports are placed around this chamber for inserting plugs with different threads. A voltage is applied to the spark plugs using a MSD ignition coil (part number 8223) capable of operating at rates up to 40 pulses per second. A quartz viewing window makes up one end of the test chamber. Using a quartz lens, light from the spark plug is focused into a 6-meter long ultraviolet transmitting optical fiber, 400 microns in diameter and is shown in Fig. 2. 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 spectrometer. This instrument is computer operated for triggering control, data transfer, and data analysis at rates up to 40 spectrums per second. This speed permits spectral measurements to be taken from individual and sequential spark plug arcs.

Spark Plugs

The spark plugs used in this study were acquired from Caterpillar Inc. (part number 194-8518) in sets of 16, that were Champion spark plugs manufactured by Federal Mogul, Inc. The plugs were used in several Caterpillar 770 eKWatt natural gas engines until sufficient wear required that they be replaced. Sets of these worn plugs were obtained for operating times of 2,020, 2,200, 4,386, 5,280 and 5,388 hours. Some of the spark plugs from these sets were found to have electrical breakdown in the dielectric and could not be used for spectroscopic studies but were still available for metallurgical examination. For comparison, a similar set of new spark plugs was obtained from Champion, part number RB77WPCC as shown in Fig 3. These are J-type spark plugs with the electrodes consisting of a nickel-base alloy (~ nominal 90-95 wt.% Ni in the plugs examined) with the tip of the center electrode being iridium (Ir) and the ground, platinum-tungsten (Pt-W) base alloy (W content in the nominal range of 5 wt.% in the plugs examined).

Metallurgical Characterization

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

Results and Discussion

The spectroscopic results are summarized in Fig. 4 where the emission spectra for both a new and used (4,386 hour) plug are compared. Sets of plugs with different hours of operation have also been examined and found to produce similar spectra to that shown with the blue curve in Fig. 4. Most of the spectral emissions for both new and used plugs come from air (nitrogen and oxygen lines). However, at the shorter wavelengths, several metal lines can be observed. With new spark plugs, emission lines from Ni are observed. For used spark plugs, the nickel lines become insignificant and calcium (Ca) lines appear. The more interesting result is the lack of lines from Ir, Pt and W. Such results would indicate that the Pt and Ir tips are producing the desired results in limiting electrode surface wear, although it is also conceivable that these elements are leaving as clusters of atoms and were not detected by the spectroscopic technique used.

The observation of Ca in the used plug emission spectrum was confirmed by SEM analysis of the electrode side surfaces (Ni alloy) and Ir/Pt-W tips of the 4,383 h used plug (Figs. 5 and 6). Although this observation is for plugs with 4,386 hours of use, the investigation of plugs involving 2,020 hours is in progress and initial observations on surfaces revealed similar features. The side surfaces of the Ni alloy ground electrode (Fig. 5a) were covered with a glassy Pt-W base oxide phase, with a significant quantity of Ca. The center electrode showed comparable features, with a Ir-Ni base oxide, again containing significant quantities of Ca (Mn, Cr, and Si were also detected in some regions) (Fig. 5b). Examination of the Pt-W tip showed evidence of extensive cracking and local melting (Fig. 6a and 6b), but no evidence of oxide-containing phase(s) formation. The absence of oxide formation at the Pt-W tip surface suggests its loss during the sparking process and that significant material loss during sparking may be occurring at the Pt-W ground electrode tip insert. At the Ir tip (Fig. 6c), cracking was also observed, although there were no signs of local melting and the surface was fully covered by the Ir-Ni-Ca oxide phase (Fig. 6d). The source of the Ca is speculated to be the engine lubricant, as Ca-containing compounds are an additive in low ash lubricants required for NG engines [1]. The formation of such Ca-containing oxide glass(s) may lead to enhanced wear as Ca is known as a glass former and can readily decrease the melting point of oxides.

A polished SEM cross-section image of a new plug is shown in Fig. 7a. Preliminary analysis by EPMA suggested significant interdiffusion of the precious metal tips with the Ni electrode alloy in the new plugs, particularly with the Pt-W tip. The polished SEM cross-section image of the 4,383 h used plug is shown in Fig. 7b. Wear of Ni is evident at the corners of the center electrode Ni alloy/Ir tip, which is consistent with the spectroscopic finding of Ni emission from the new spark plug. Significant loss of the Pt-W alloy tip insert material is also evident in the ground electrode, which is consistent with the local melting and absence of oxide at this tip surface (Fig. 6a and 6b).

Figs. 8a and 8b show etched cross-sections of the outer surface of the Ir and Pt-W alloy tips. Intergranular cracking is evident in both Pt-W and Ir tip. In addition to the typical surface erosion processes/material loss phenomena resulting from sputtering, melting, ablation, particle erosion, and related effects during sparking [e.g. 2, 3], the generation, growth, and coalescence of intergranular cracks would also result in significant material loss and accelerated erosion during service. Characterization of shorter term NG tested partially worn spark plugs is planned in an attempt to determine the relative contribution of this intergranular cracking to the loss of electrode tip material.

The absence of significant Pt in the emission spectrum of the used plug is consistent with loss of Pt-W alloy by cracking rather than directly during sparking, however, again, 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 used. The cause of this cracking is not yet known, although Pt alloys have been reported to be susceptible to intergranular cracking when exposed to carbon at elevated temperatures [4].

Figs. 9a and 9b show a higher magnification SEM image of the interface between the Ni alloy and the Pt-W alloy insert. An oxidized crack was found to extend along much of the interface, effectively nearly completely separating the Pt-W tip from the ground electrode. Such cracking has been observed in several end-of-life plugs, and may be the life-limiting final step in the wear process. Susceptibility at this location may be the result of interdiffusion or joining issues between the Pt-W tip and Ni alloy.

The nest step in this investigation is the systematic analysis on plugs taken form engine prior to failure to establish a sequence of times correlated to the observations of wear/erosion. The goal is to understand the progressive evolution of oxide formation and crack generation.

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Figure Captions

Figure 1. Photograph of the test chamber showing the location of the spark plugs. The quartz viewing window is on the far side.

Figure 2. Photograph of the optical setup showing the test chamber, focusing lens, and the optical fiber.

Figure 3. Photograph of new spark plug, Champion, part number RB77WPCC. These are J-type spark plugs with the tip of the center electrode being iridium (Ir) and the ground side an alloy of platinum-tungsten (Pt-W).

Figure 4. Plot of the spectrum from a new (red) and used (blue) spark plug. The used plug was removed after 4,386 hours of operation. The most striking difference between these curves is the presence of emission lines from nickel in the new plug and the calcium in the used plug.

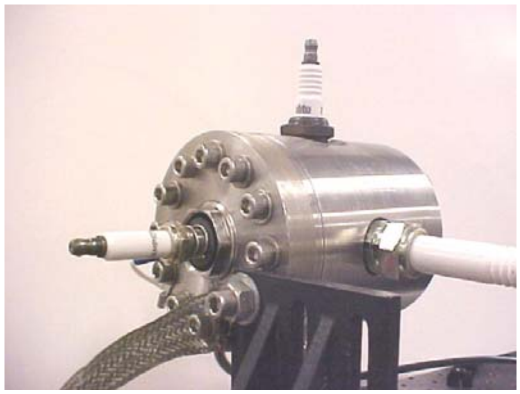
Figure 5. SEM micrographs show the side surface feature of Ni-based electrode on (a) Pt-W tip insert (anode) side and (b) Ir tip insert (cathode) side after field service. Note the inserts show the low magnification of both Pt-W and Ir tip insert. This plug had 4,386 hours of engine operation.

F**igure 6.** SEM micrographs show the top surface morphology of Pt-W (a, b) and Ir (c, d) tip insert after field service. Note that (b) and (d) are the high magnification of (a) and (c), respectively. This plug had 4,386 hours of engine operation.

Figure 7. Micrograph showing the differences between a new and used spark plug (4,386 hours); of note is the erosion of both the nickel base and the platinum electrode.

Figure 8. SEM micrographs show extensive formation of intergranular cracks in both Pt-W (a) and Ir (b) tip insert after field service. This plug had 4,386 hours of engine operation.

Figure 9. (a) SEM micrographs show extensive oxidation and crack formation at the interface between Ni alloy and Pt-W tip insert after field service and (b) a detailed view of the crack. This plug had 4,386 hours of engine operation.



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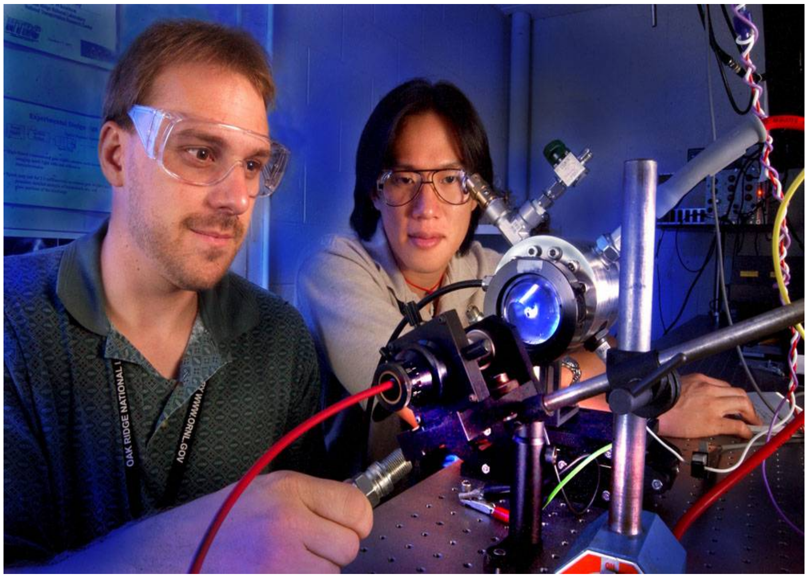

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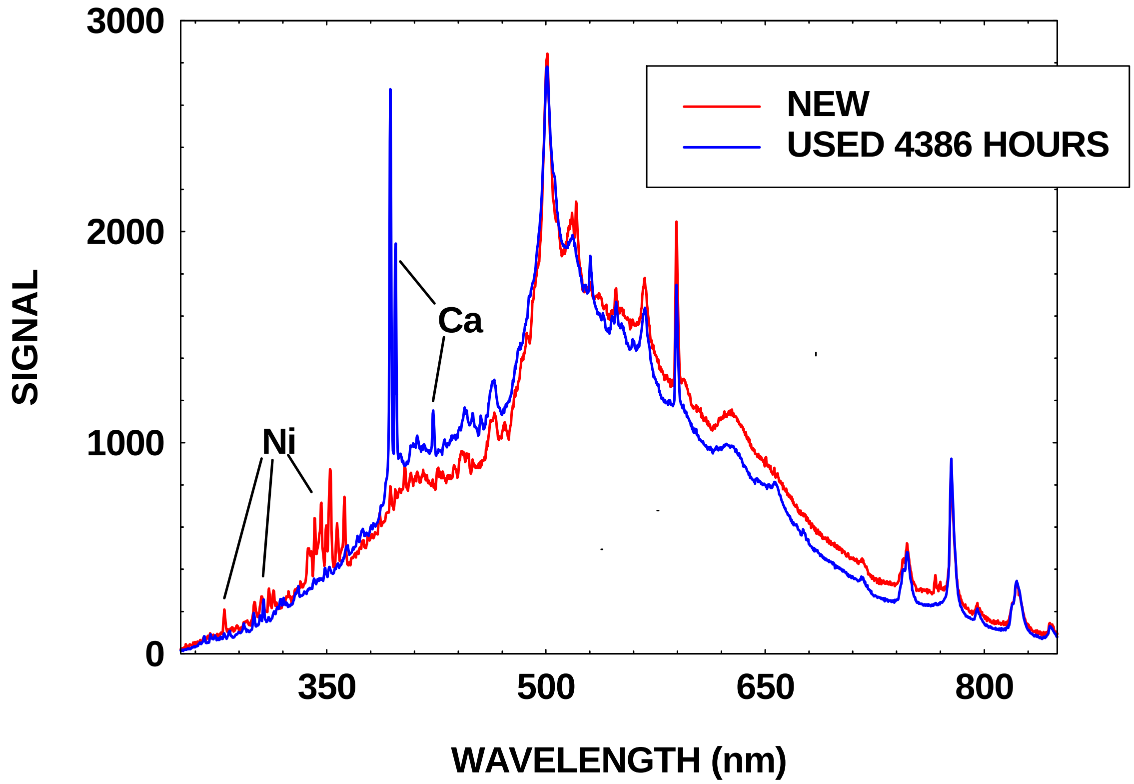
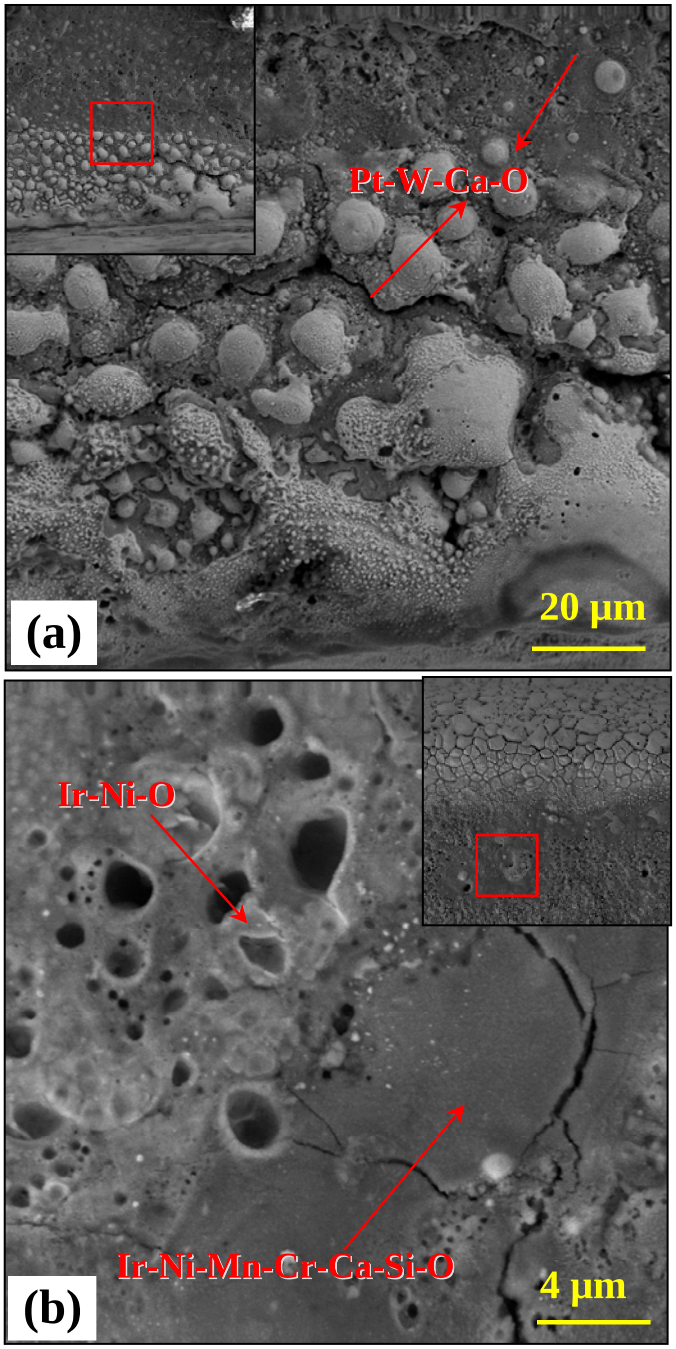
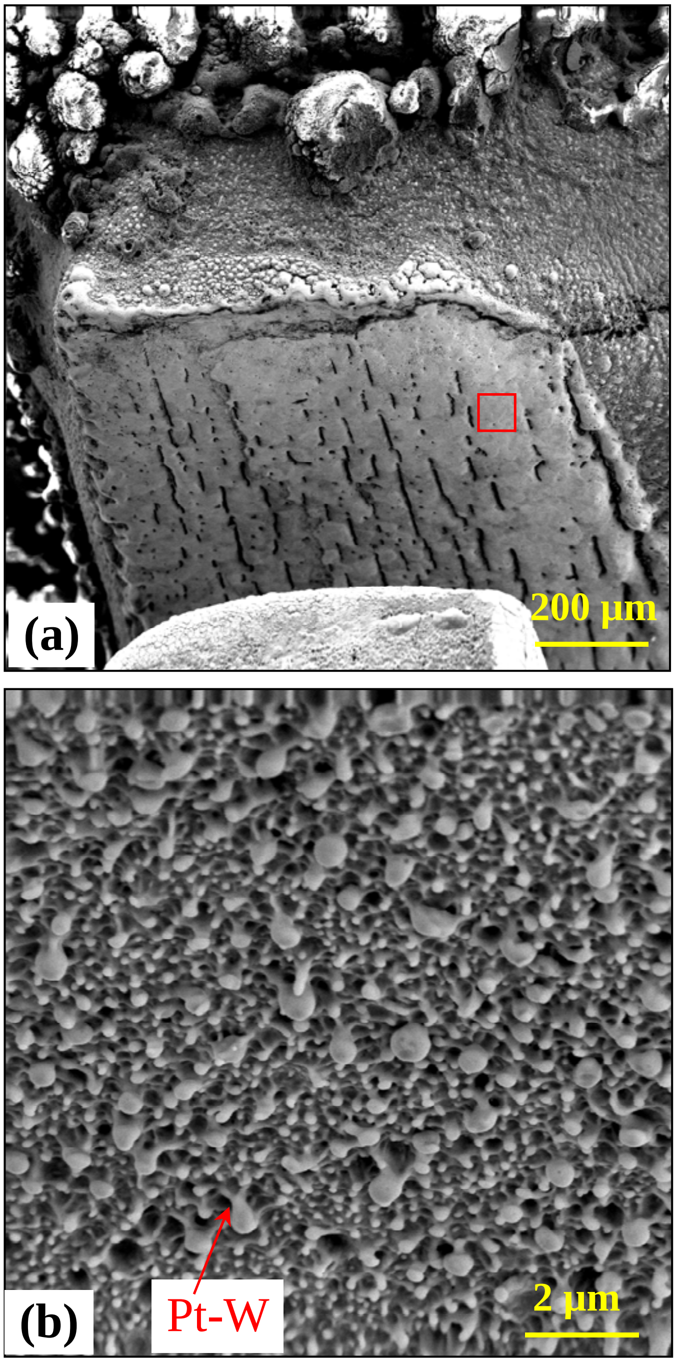
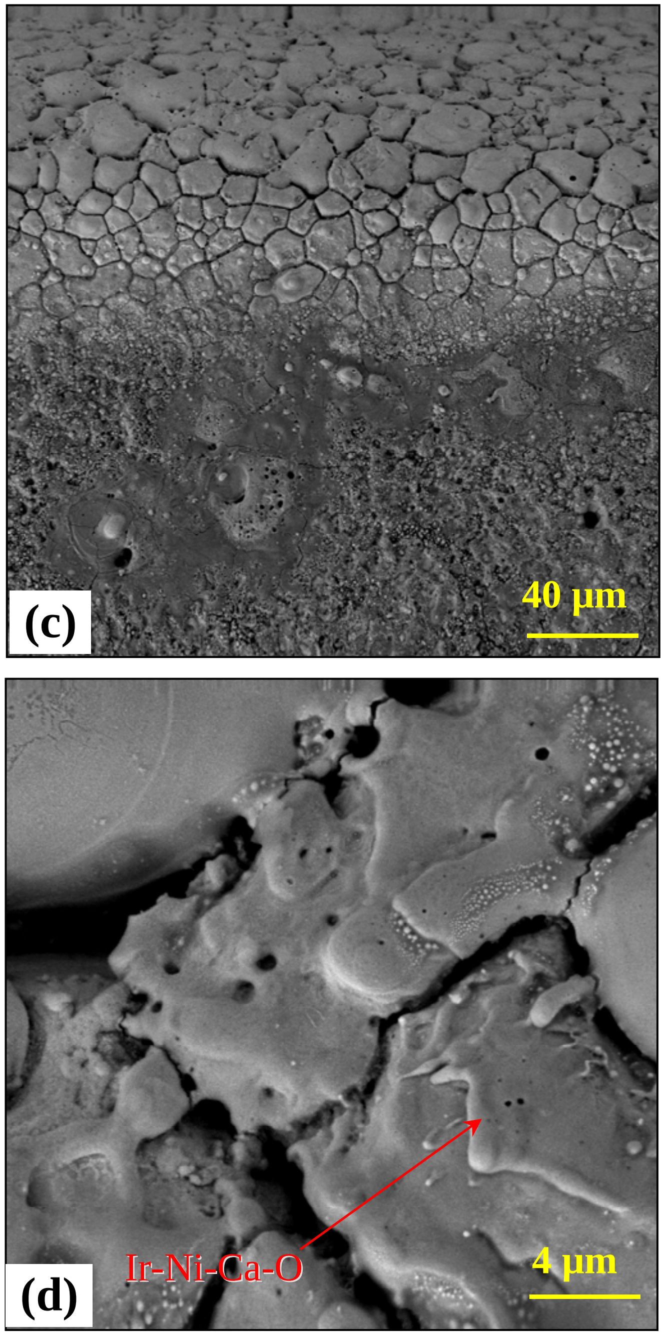
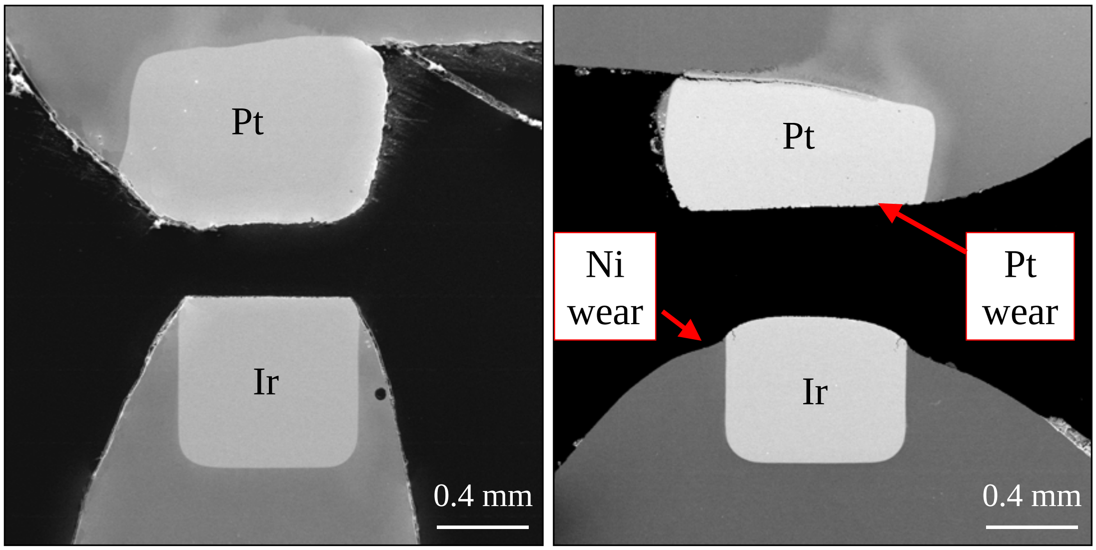

3000
2000
1000
0
SIGNAL
350
500
650
800
WAVELENGTH (nm)
NEW
USED 4386 HOURS
Ca
Ni


Pt-W-Ca-O
20 µm
(a)
Ir-Ni-O
Ir-Ni-Mn-Cr-Ca-Si-O
4 µm
(b)

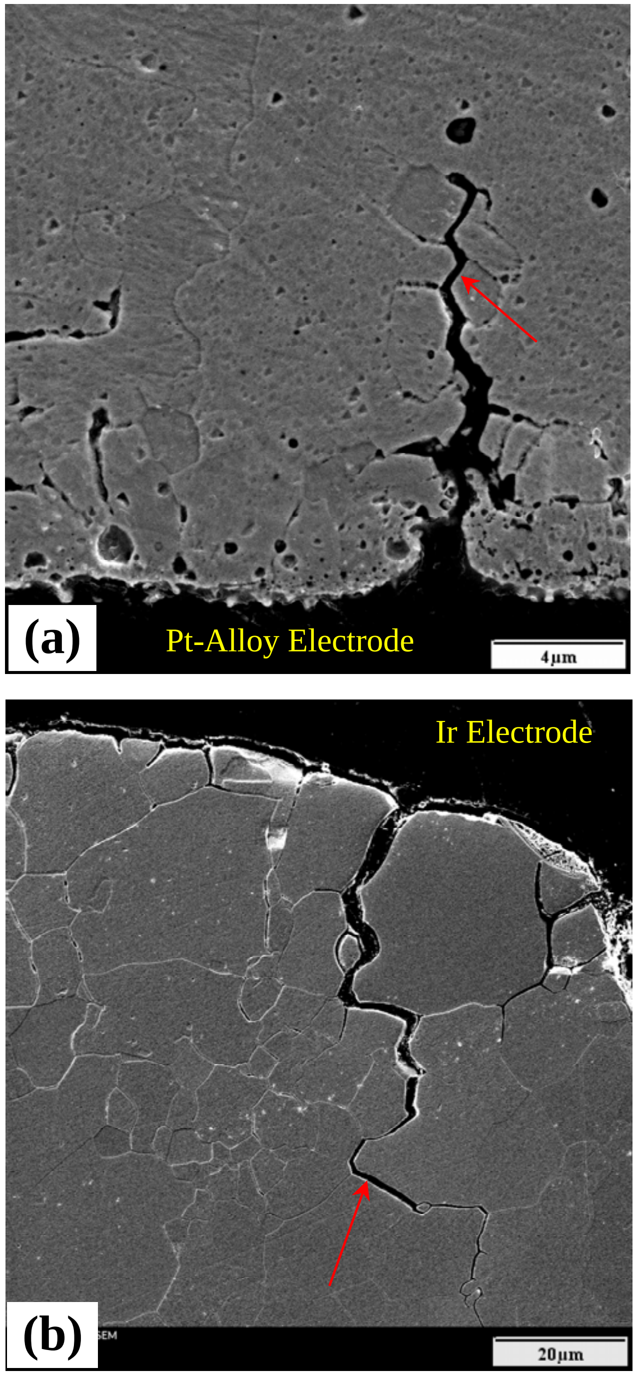

(a)
200 µm
(b)
Pt-W
2 µm

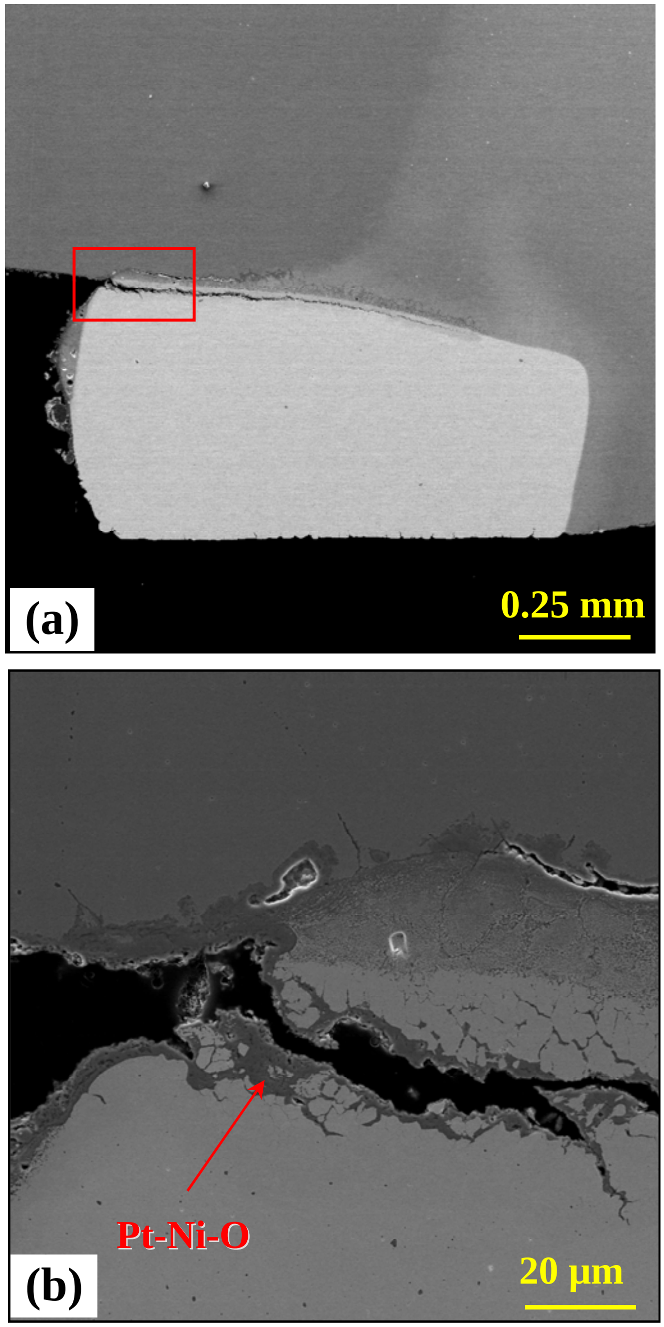

(c)
40 µm
(d)
Ir-Ni-Ca-O
4 µm



New

Used 4,386 hours


(a)
Pt-Alloy Electrode
4μm
Ir Electrode
(b)
20μm


(a)
0.25 mm
Pt-Ni-O
(b)
20 µm