Characterization of Erosion and Failure Processes of Spark Plugs After Field Service in Natural Gas Engines

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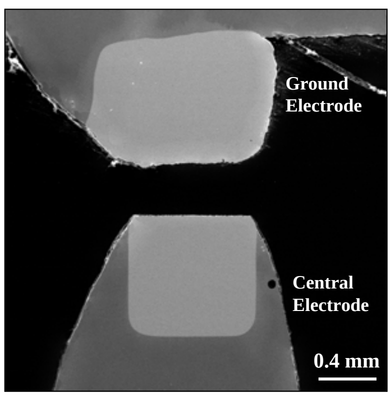
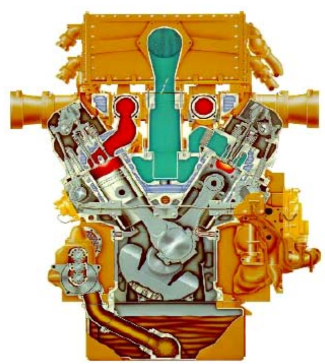
Outline

- Background
- Spectroscopic Investigations
- Metallurgical Investigations
- Summary of Observations
- New Materials Research

Background

- The Advanced ignition system is a key technology to achieve cost/performance/emission characteristic goals for lean and stoichiometric engines
- Corrosion/erosion of spark plugs limits the long-term reliability and performance of ignition systems and, thus also ARES
- Increase in cylinder pressures, compression ratios, and ignition voltages will further limit the ignition performance and ARES developments
- Improvement of high-temperature corrosion/erosion resistance of electrodes is a critical issue to maintain the durability of spark plugs





CAT® GAS ENGINES

Cummins

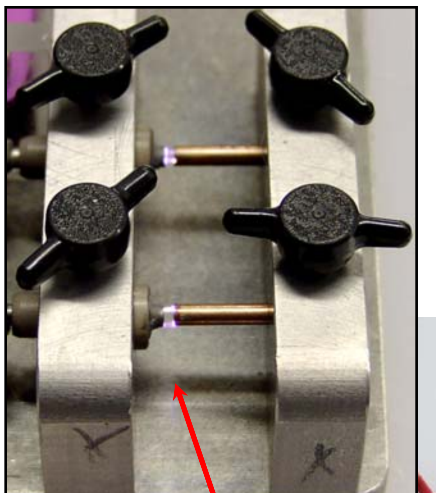
DRESSER Waukesha

Objective

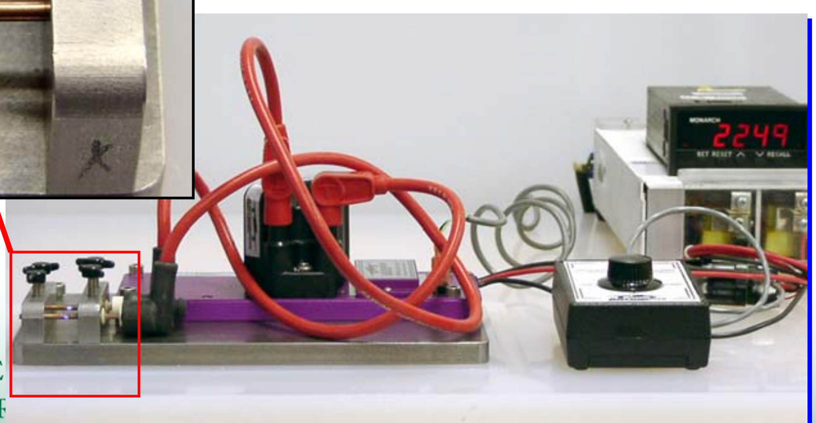
- Characterize optical spectra of spark plug arcs to evaluate the ignitability and erosion or age characteristics of spark plugs
- Characterize and measure spark plug erosion as a function of field-tested time
- Provide understanding of corrosion and erosion mechanisms of spark plugs in natural gas engine environments
- Provide design guidelines for ignition systems of Advanced Reciprocating Engine Systems
- Develop advanced alloys to improve the corrosion/erosion resistance and extend the lifetime of electrodes and spark plugs

Integrated Approaches

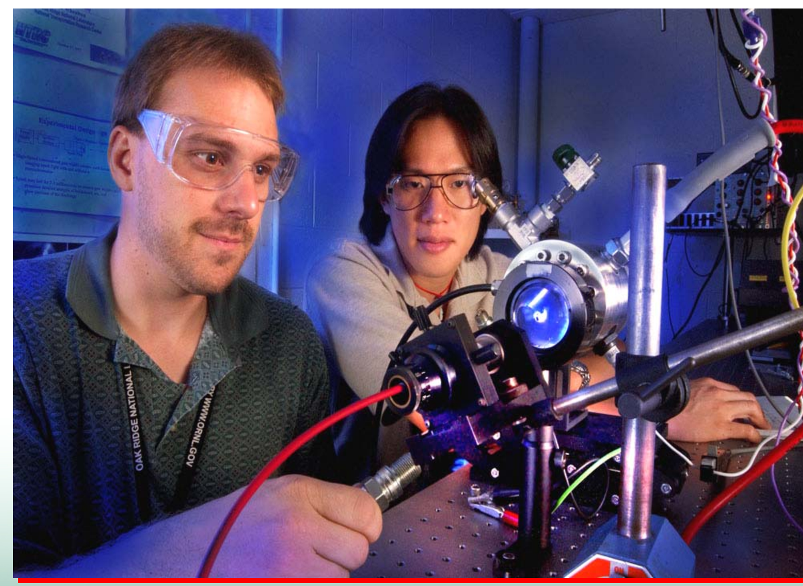
- Develop diagnostic tool for measuring shot-to-shot erosion
- Optical spectroscopy analysis for field-tested spark plugs acquired from gas engine companies, i.e., Caterpillar, Cummins, and Waukesha
- Identification of erosion/corrosion mechanisms of ground and center electrodes via systematic optical and SEM analysis
- Develop advanced alloys to significantly improve spark plug reliability and extend life performance



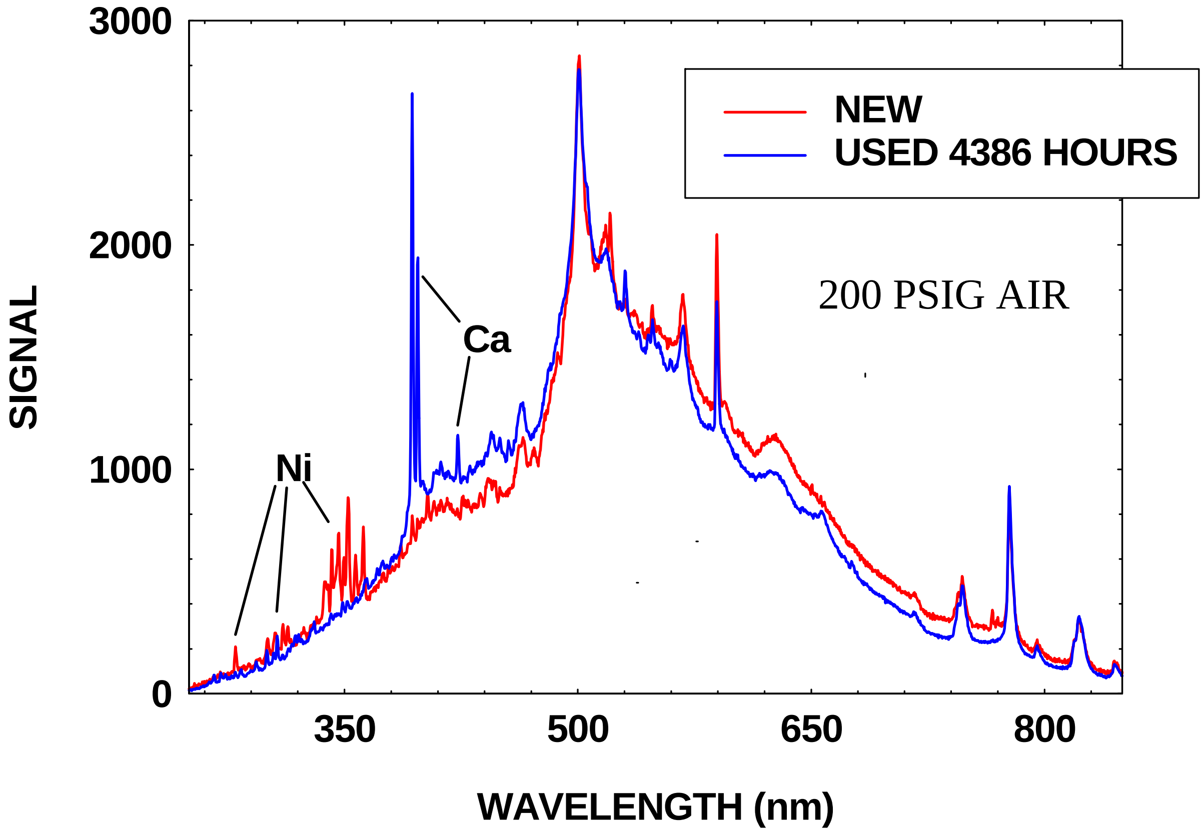
ORNL Electrode Screening Test Rig

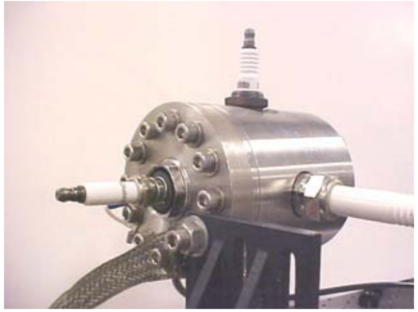


NTRC Optical Spectroscopy Chamber



Optical Spectroscopic Analysis Detected Substantial Amount Calcium Present in Field Tested Spark Plugs



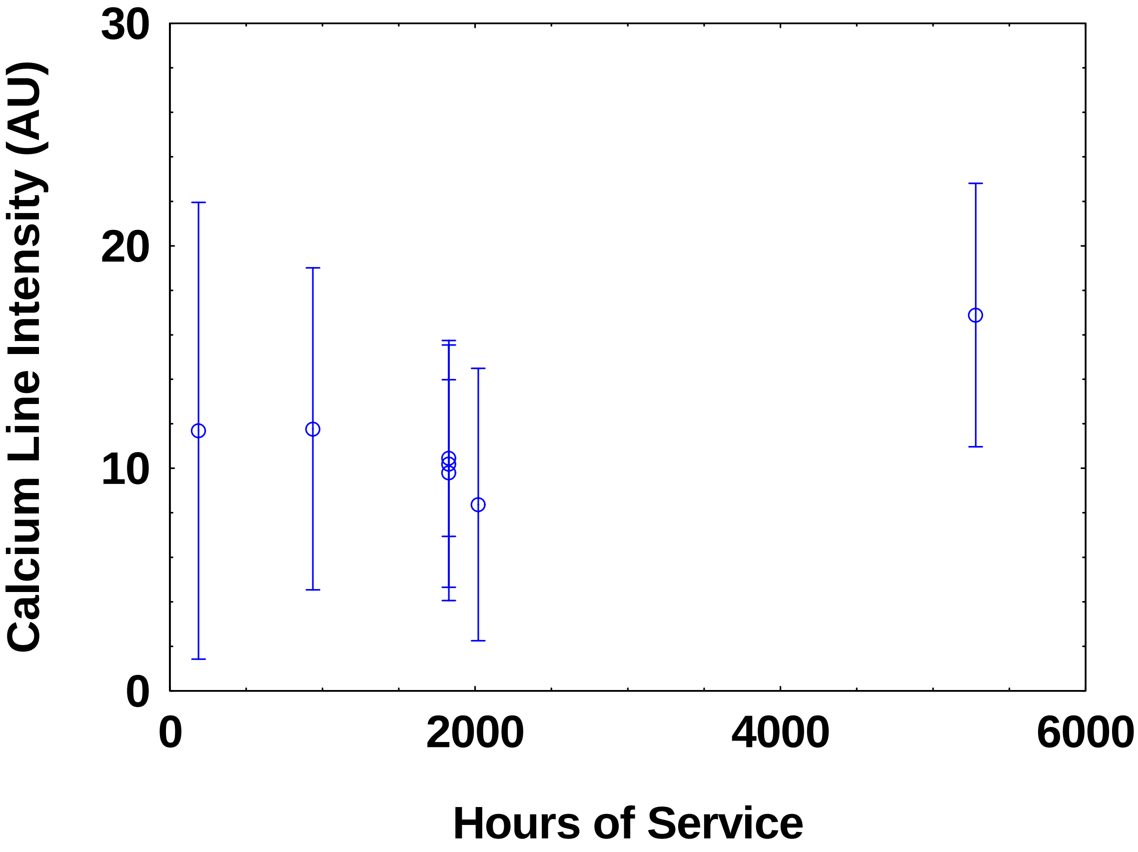


0-200 PSIG

- Ca from the engine oil
- No detection of Pt or Ir from electrode tips

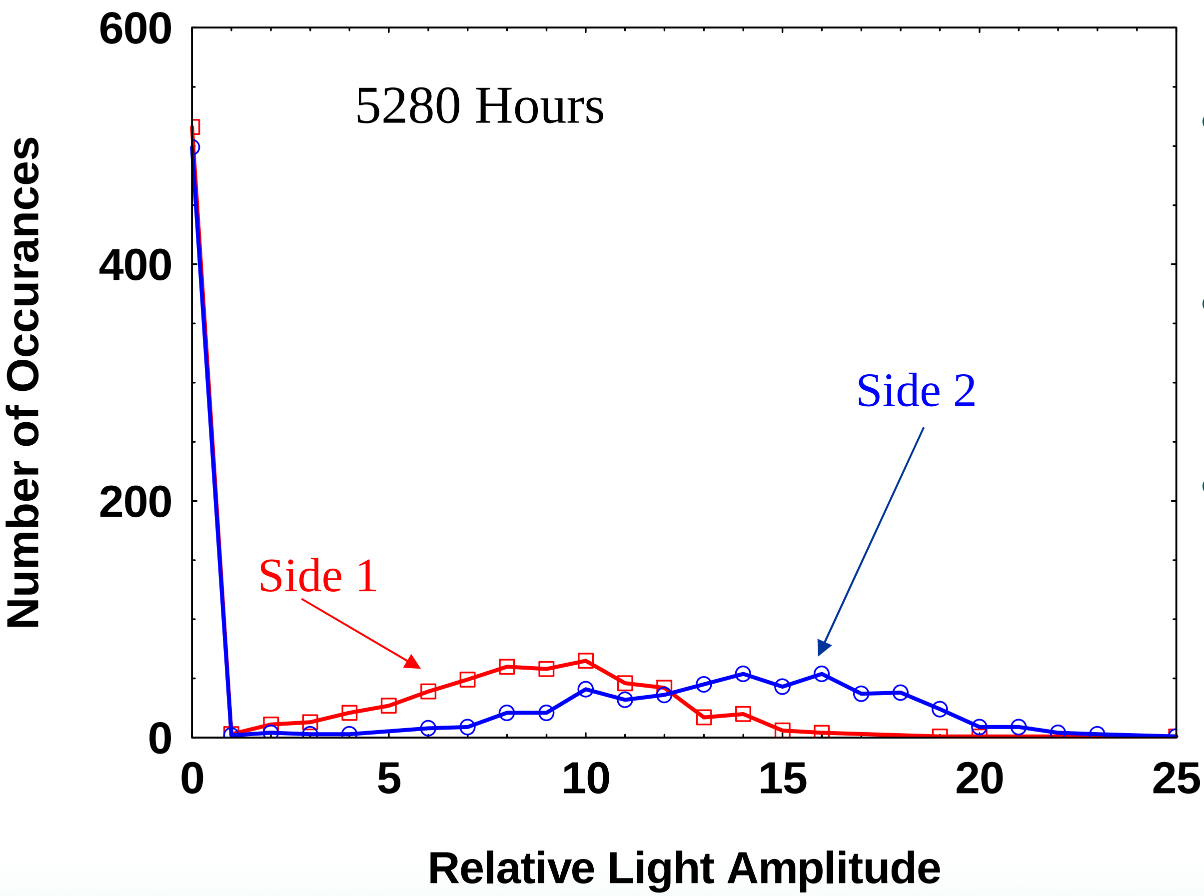
Detection of Ni in new spark plug suggests the erosion of Ni-based electrode due to sputtering process

Variation of Calcium with Hours of Service



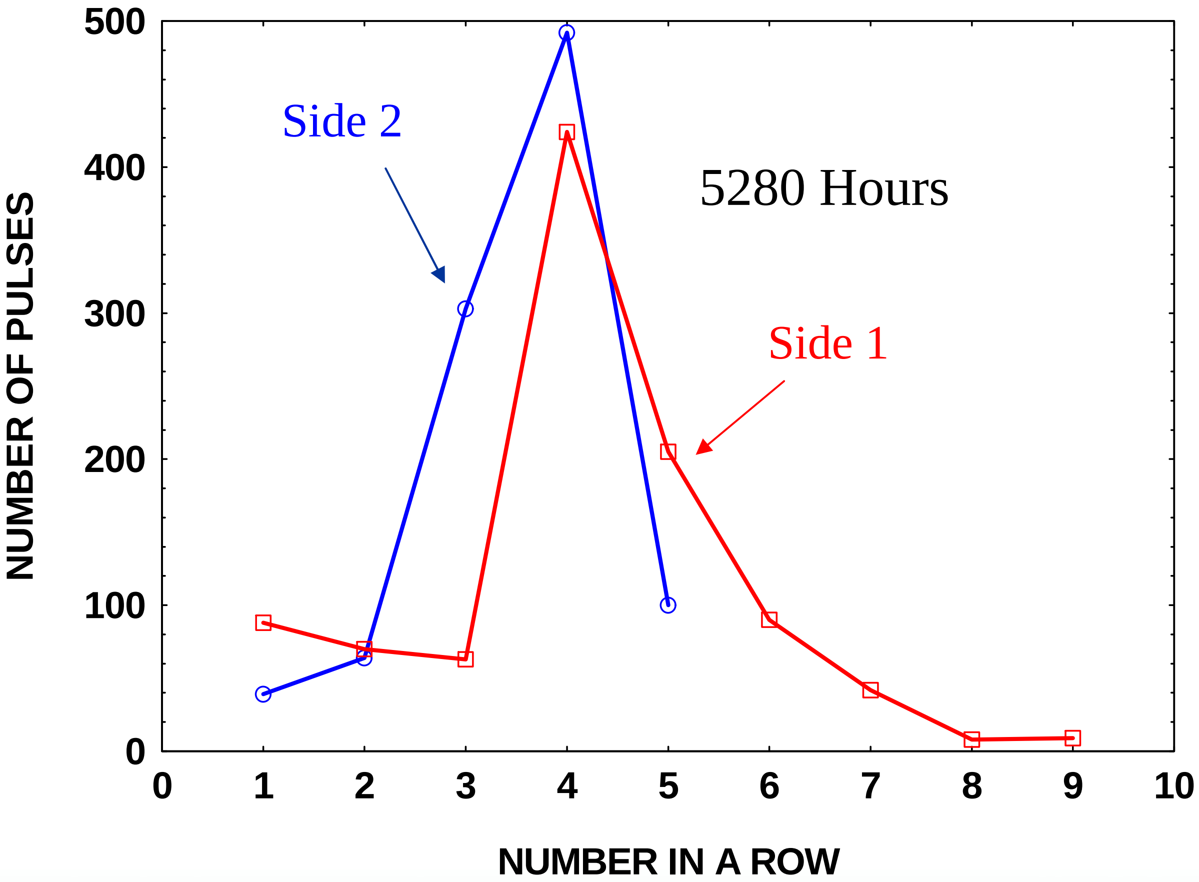
- Large variation plug-to-plug
- Rapid saturation of calcium

FOR 1000 CONSECUTIVE ARCS HALF PRODUCE NO SPECTROSCOPIC SIGNAL

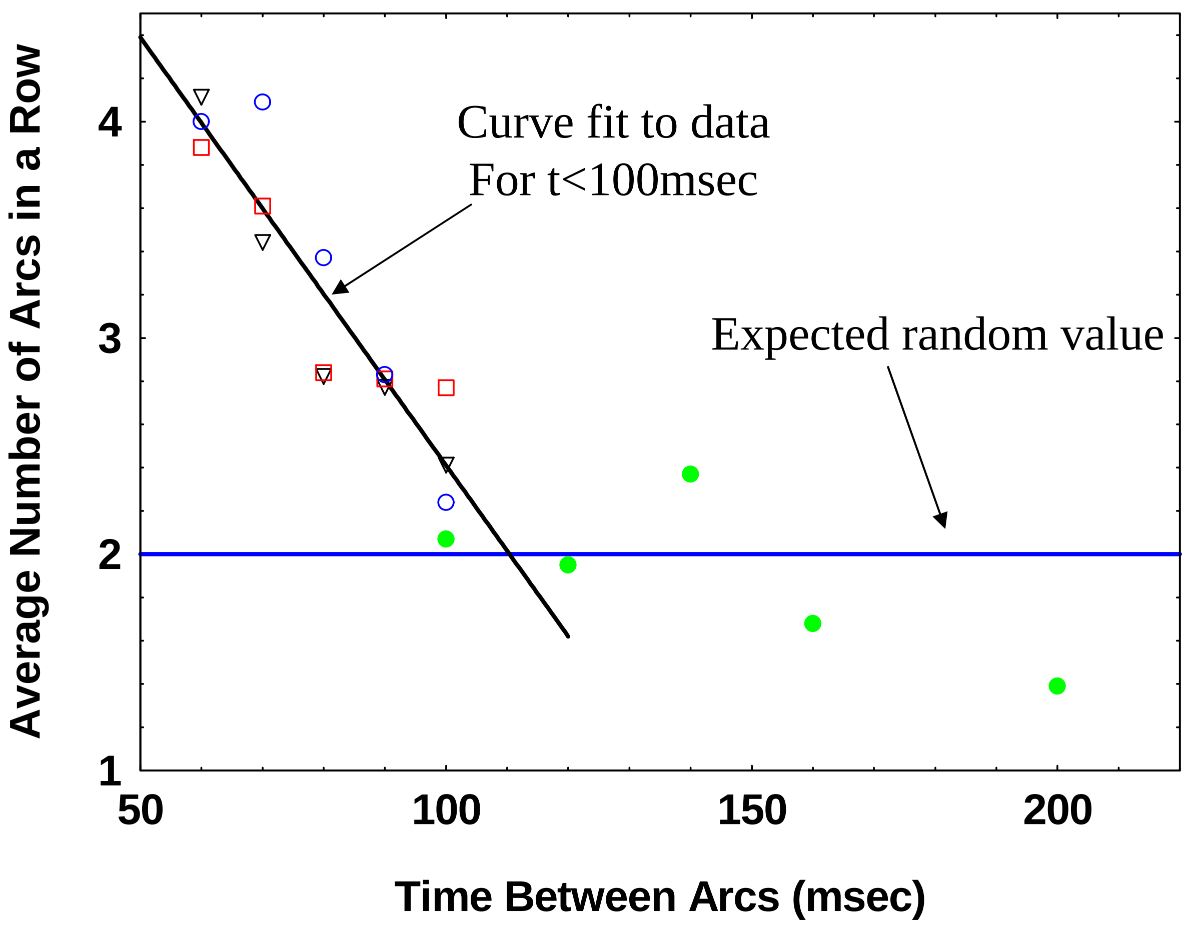


- Light still present – misses collecting optics
- Two distinct spatial points of light from each side of plug tip
- Amplitude can be used to see where breakdown occurred

ARC LOCATION IS PREDICTIVE – AFTER 4 CONSECUTIVE BREAKDOWNS AT SAME LOCATION THE ARC MOVES TO THE OTHER SIDE

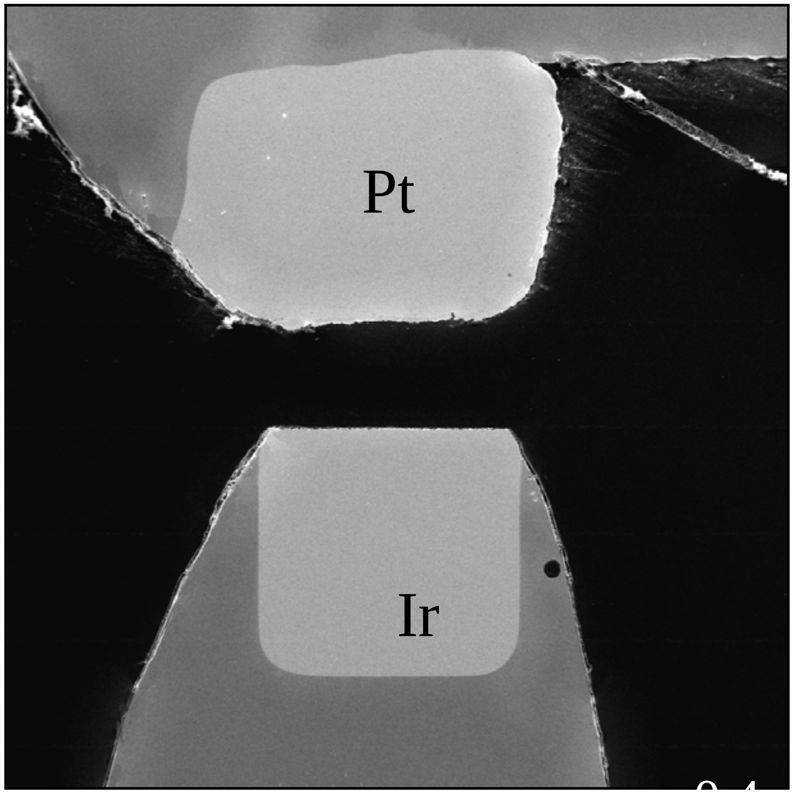


Spark Variation with Rate

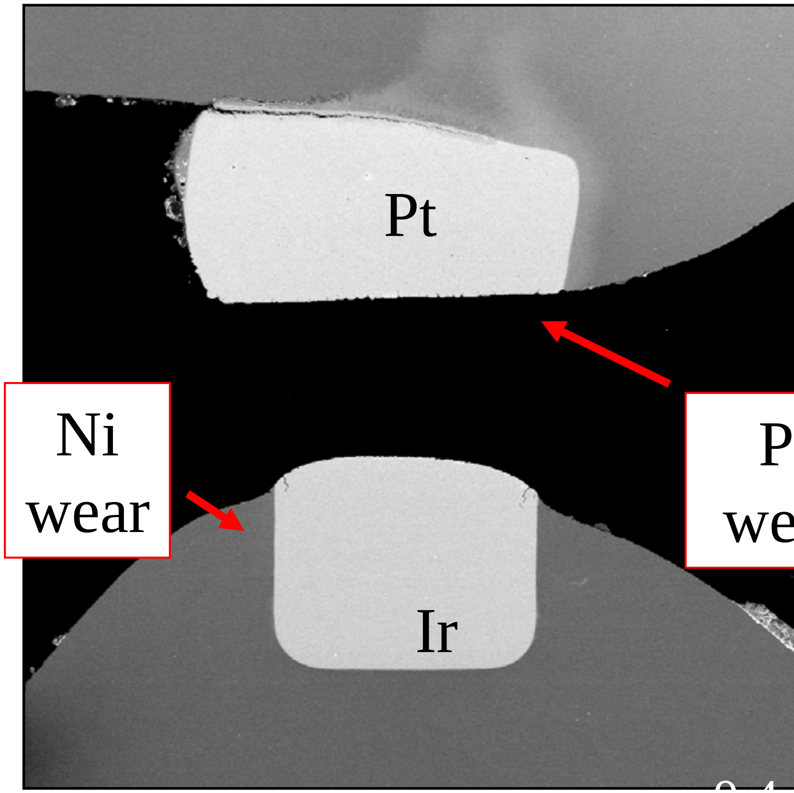


- Some variation plug-to-plug
- Expect a value of 2 for random events
- Trend toward random arcs for longer times
- A longer time allows the plug tip to cool

Spark Plug Erosion



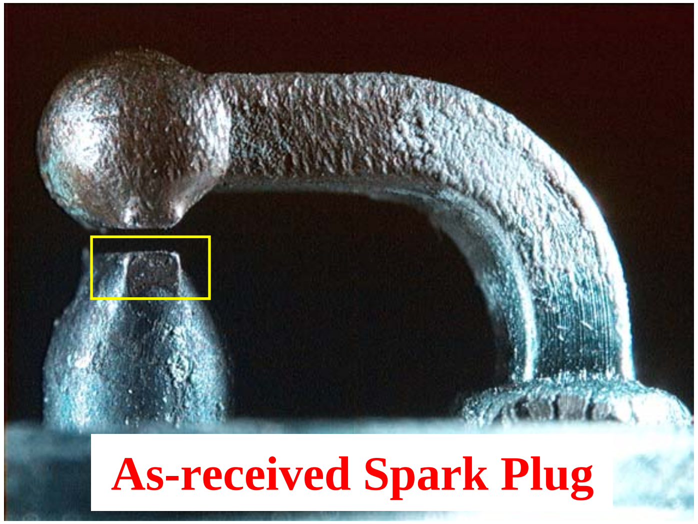
New

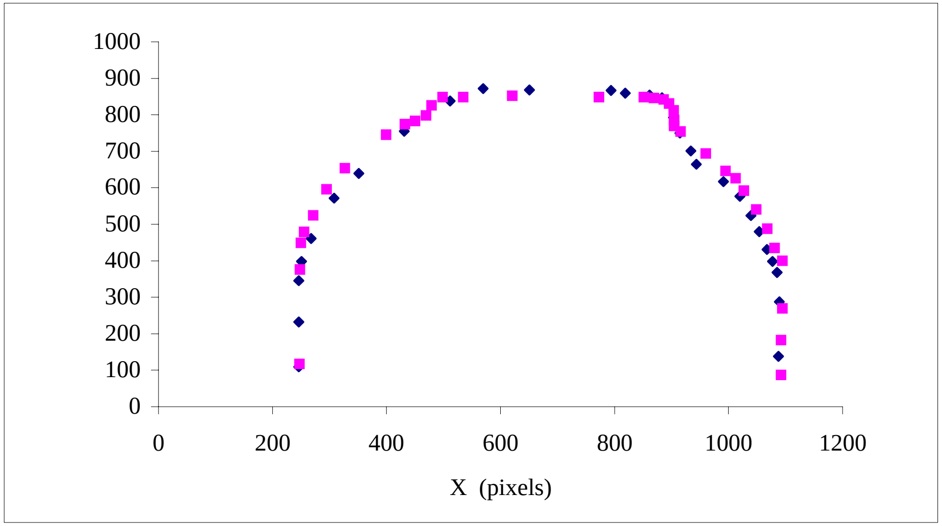


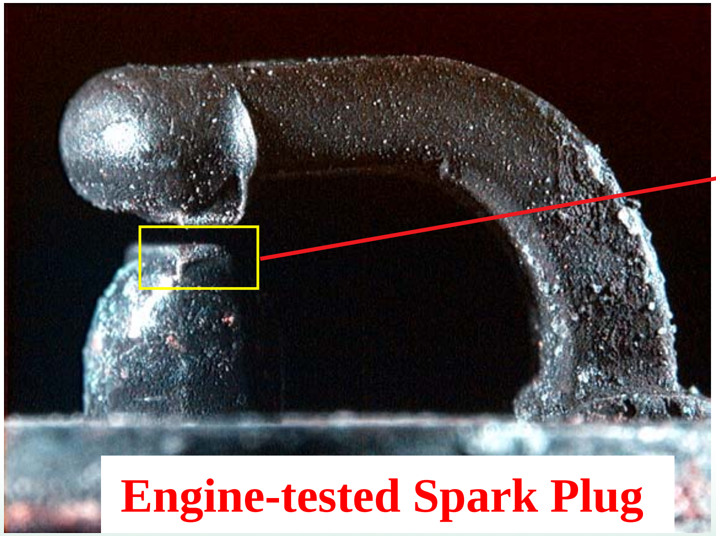
Used 4,386 hours

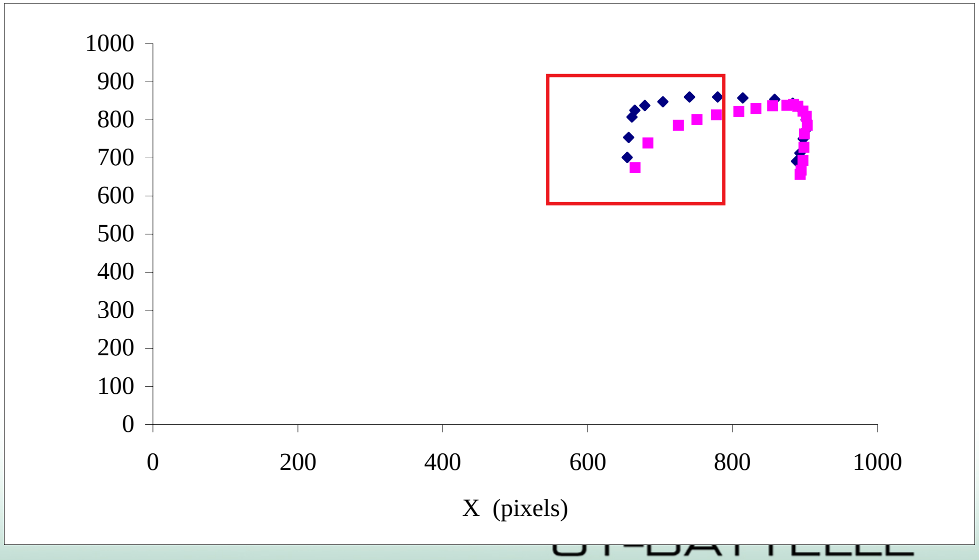
The tips of the spark plugs wear away until the gap distance is too large for the plug to fire.

Polynomial Curve-Fitting of Macro Spark Plug Photos Illustrates Erosion of Engine-Tested Plug

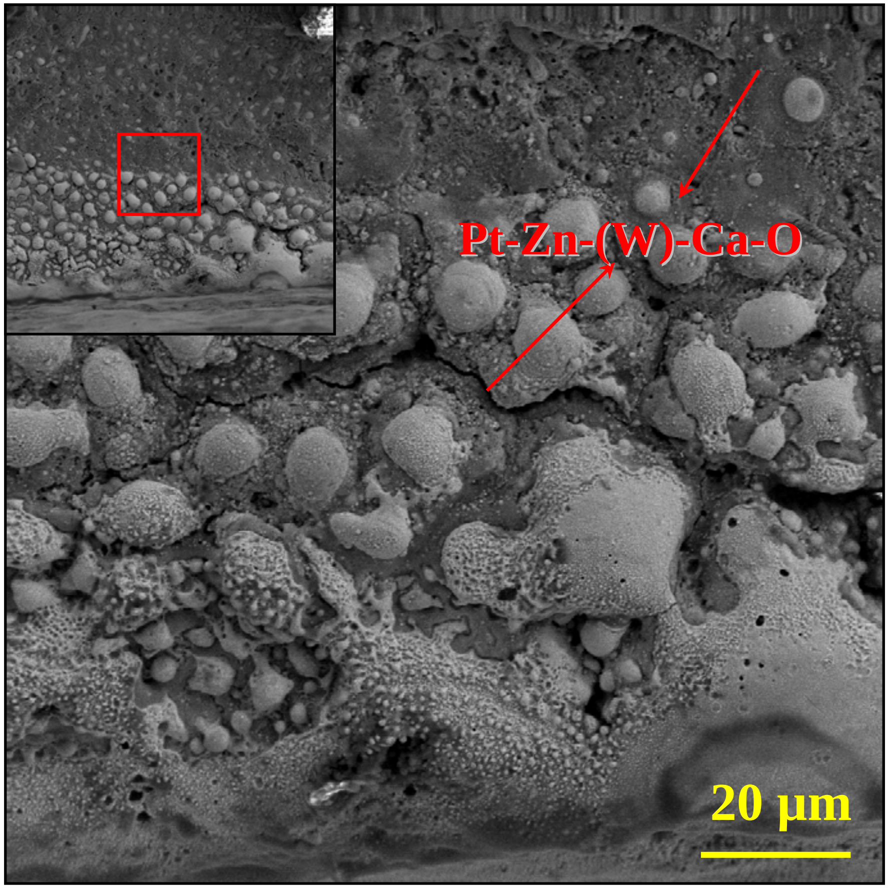


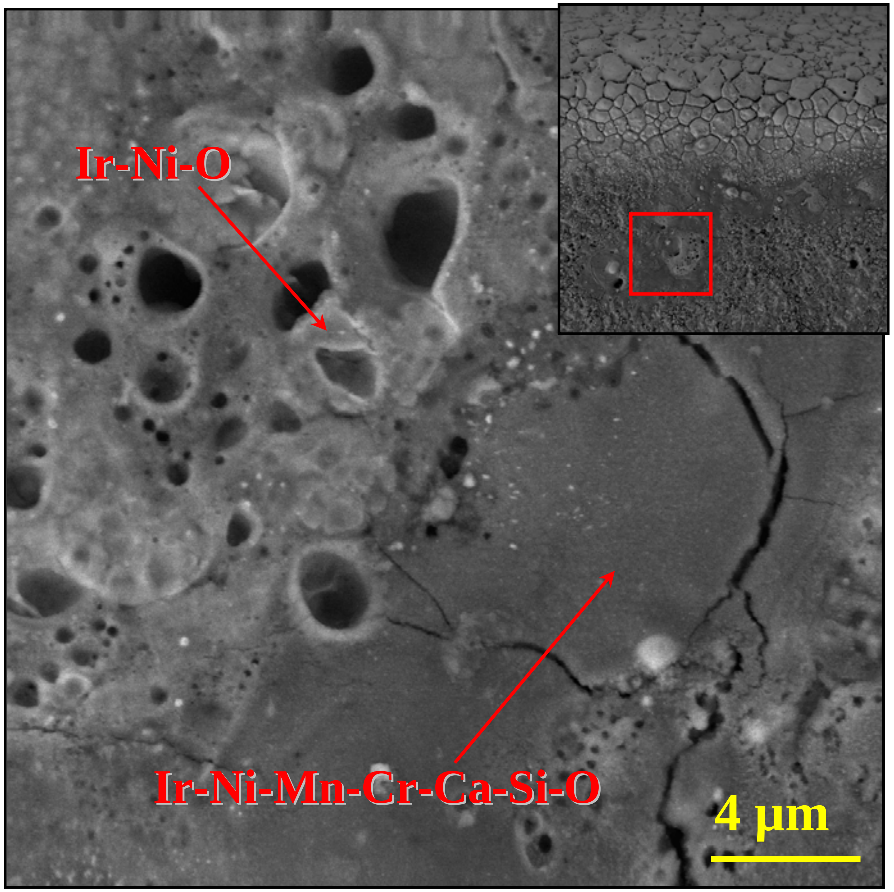






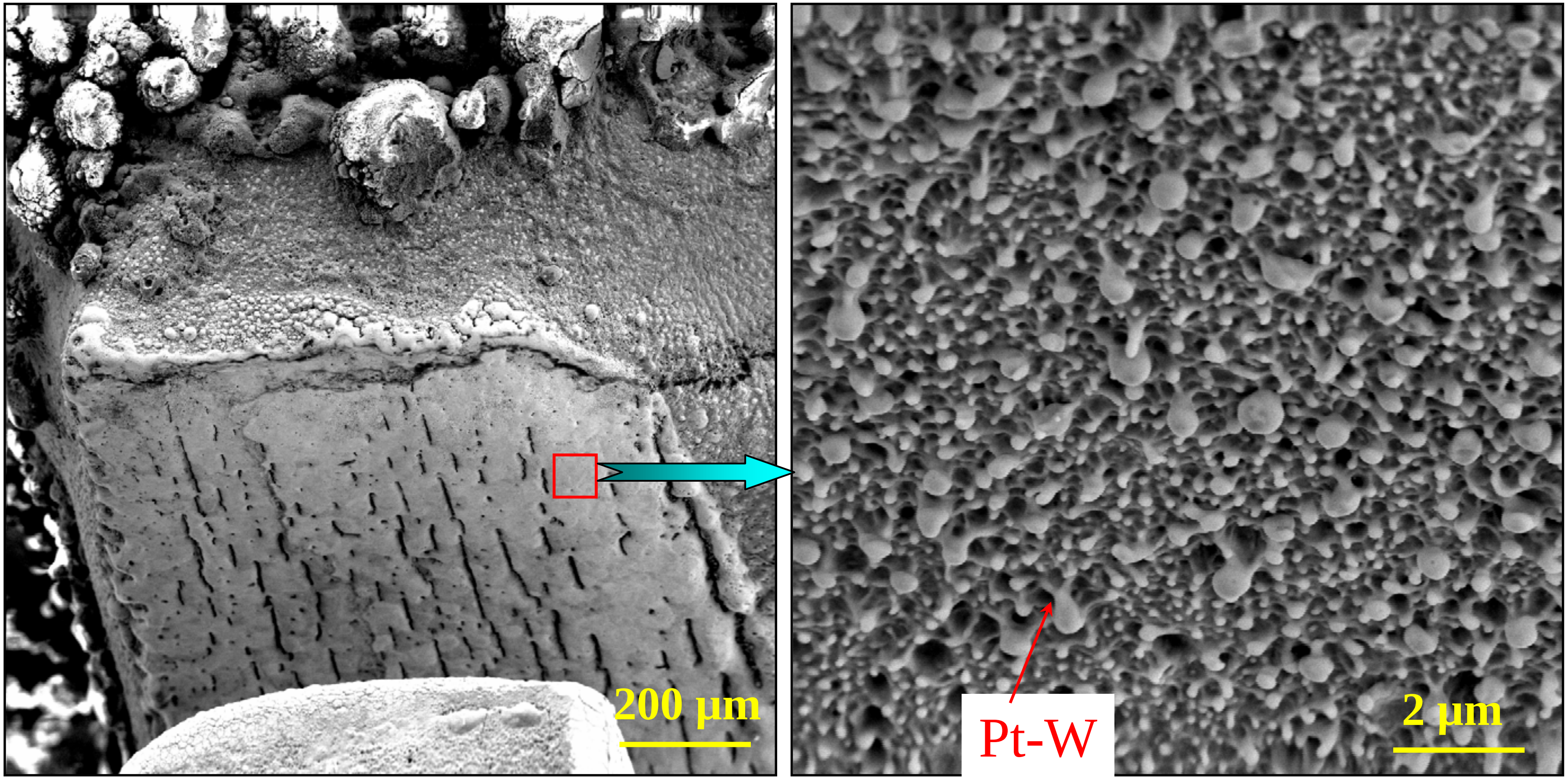
Substantial Oxidation Plus Glassy Phase Formation Observed in Both Pt-Alloy and Ir Electrode Side Surfaces After Field Service





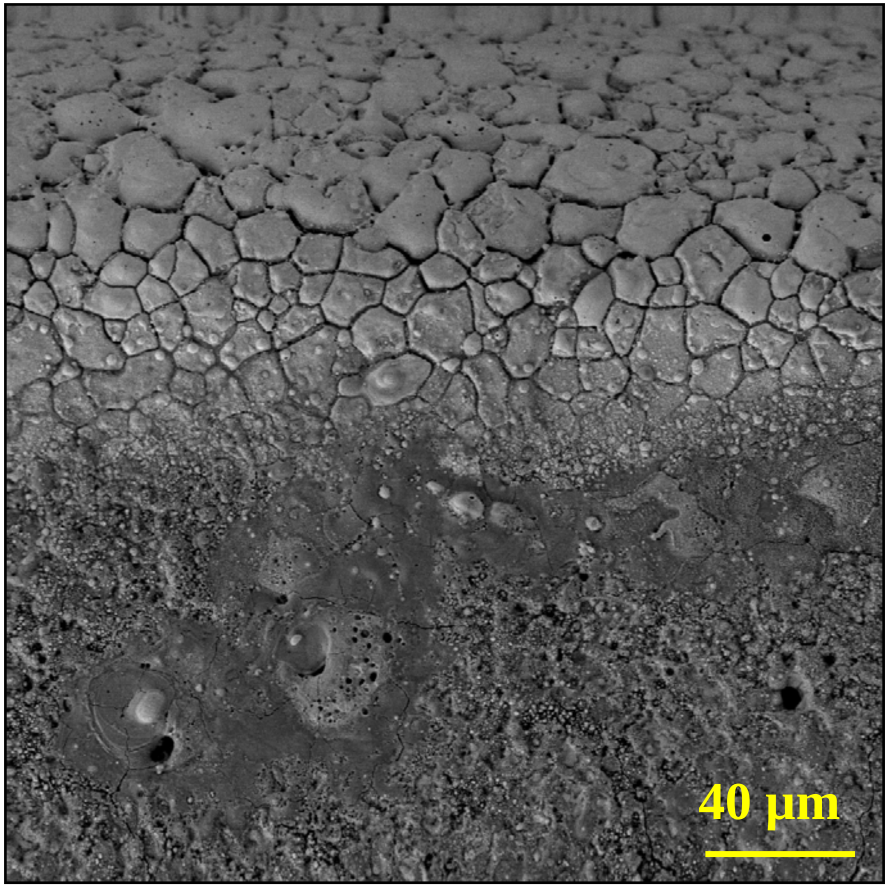
The Ca content in glassy phase is significant, and the presence of Ca could reduce the softening point and viscosity of glass, possibly enhancing the erosion process

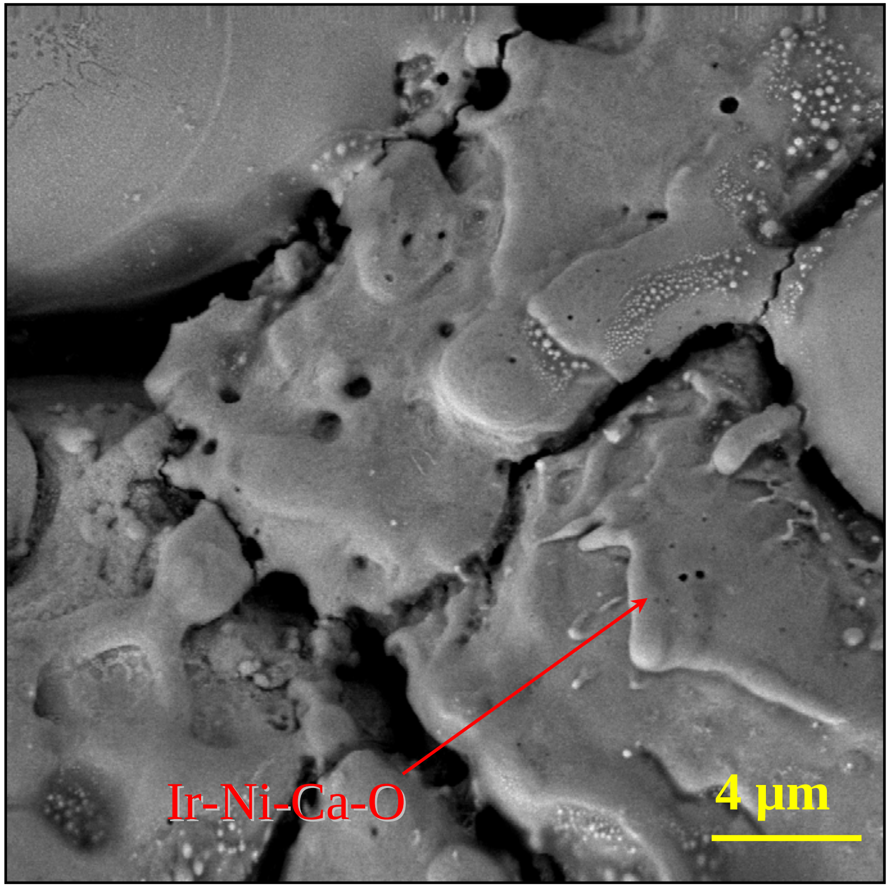
Substantial Line-Cracks Observed on Pt-Alloy Electrode Surface After Field Service



Formation of droplet-like morphology likely from local melting of the Pt-W Alloy

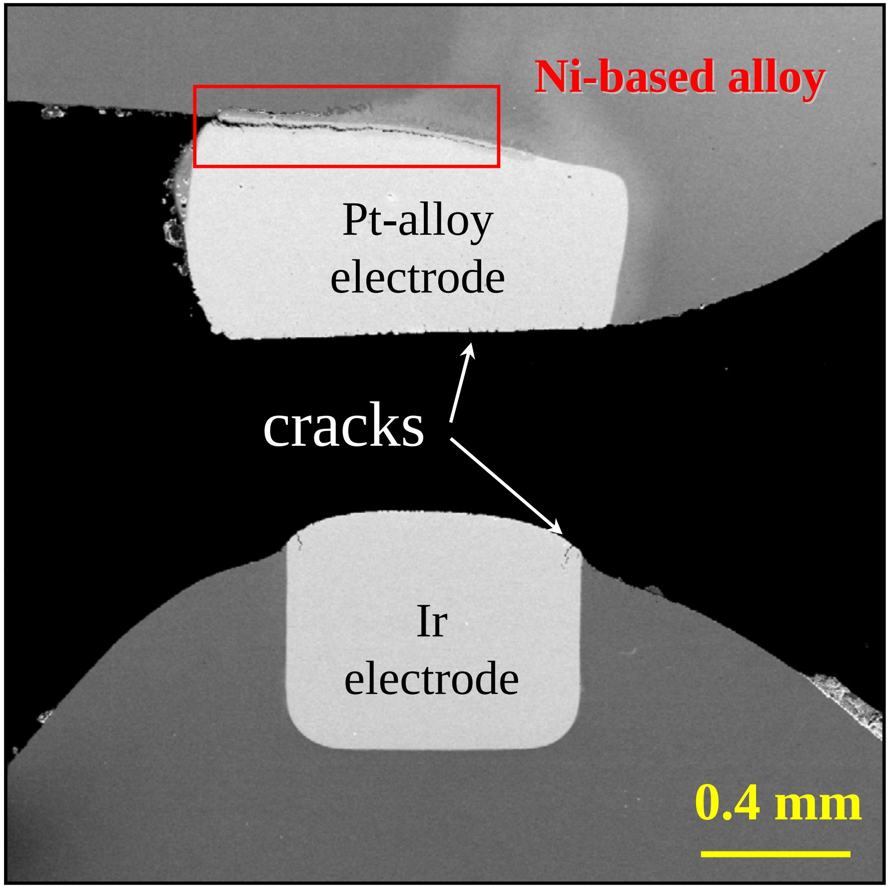
Substantial Oxidation With Crack Formation of Ir Electrode Surface Observed After Field Service

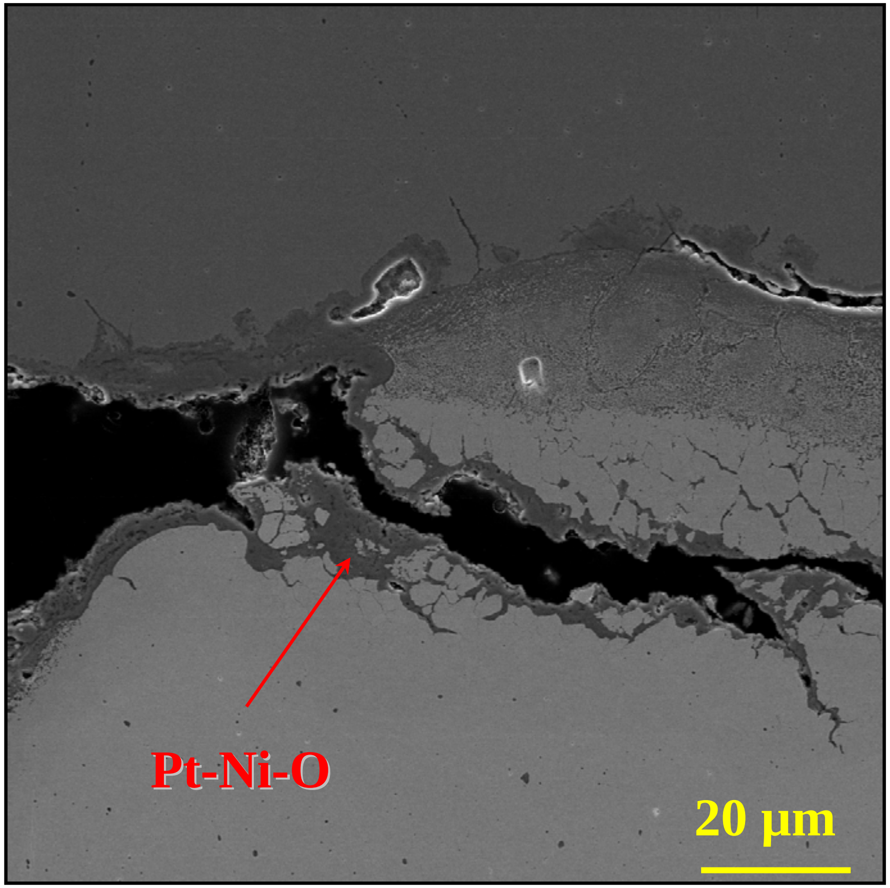




Mud-crack morphology of Ir electrode is significantly different from that observed on Pt-W alloy electrode

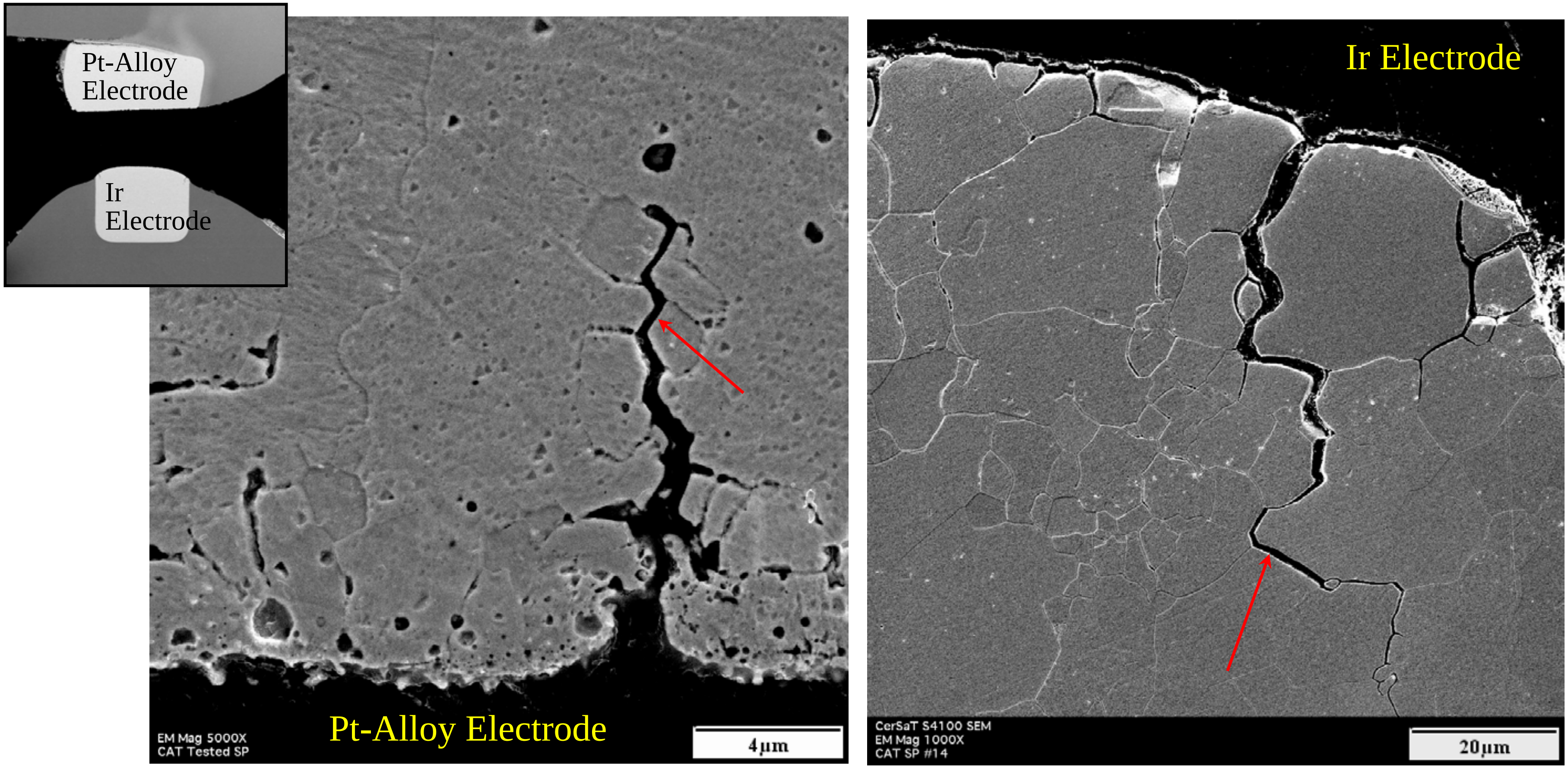
Substantial Crack Generation and Growth Observed Between Pt-alloy and Ni-based Electrode After Field Service





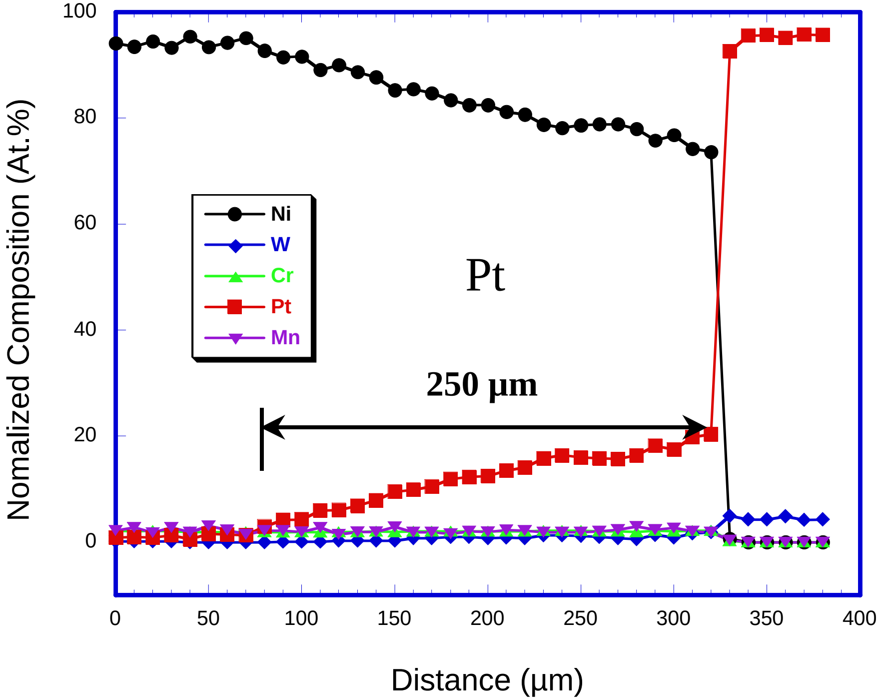
An oxide-based (Pt-Ni-O) reaction zone, which is brittle in nature, formed between Pt and Ni-based electrode. Crack generation and growth and oxide-based interface could significantly degrade the ignitability and performance of spark plugs

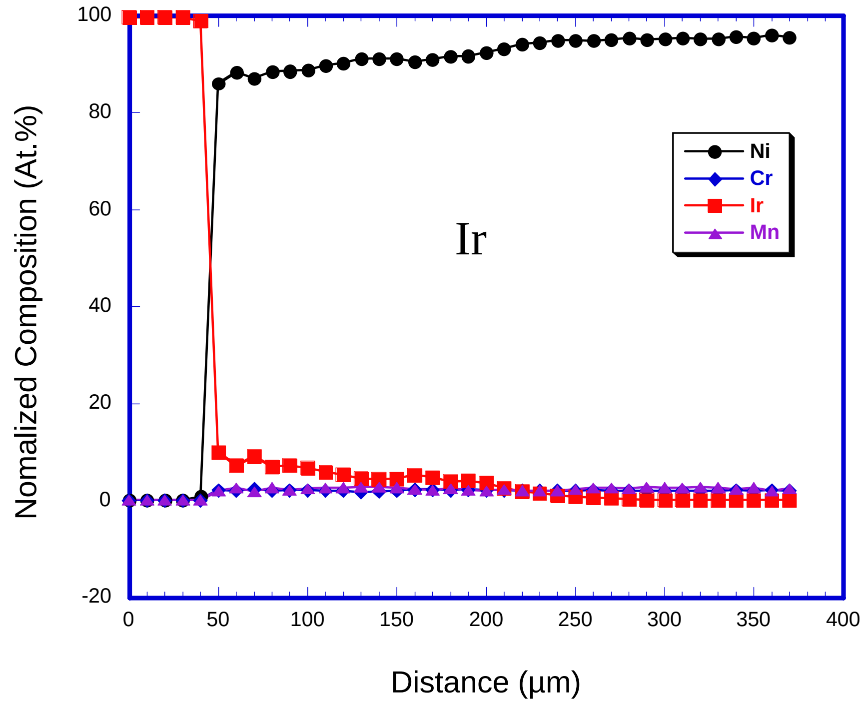
Substantial Intergranular Cracking Occurred in Both Pt-alloy and Ir based Electrode After Field Service



Coalescence of intergranular cracks and subsequent material flake-off in Pt and Ir electrodes would further accelerate the erosion process and limit the long-term durability and performance of spark plugs

Interdiffusion of Pt with Ni but not with Ir





Results of EPMA showed that there existed a significant interdiffusion zone of Pt-W tip insert with the Ni-base electrode.The size of interdiffusion zone ranged from 250 to 300 µm and no apparent interdiffusion zone was observed between Ni-base electrode and Ir tip insert

Summary of Observations

- Pt and Ir tips are eroding but not sputtering
- Large amounts of Ca present around the tips
- Oxide scale containing Pt-W-Ca-O observed on both electrode side surfaces
- Periodic crack-lines formation due to localized material corrosion/erosion observed on Pt-alloy electrode tip surface after field service
- Substantial oxidation plus mud crack formation also observed on the Ir central electrode tip surface region
- There are metallic elements from the sputtered Ni-base electrode that deposit on the Ir and Pt surfaces and react with Ca and O producing a significant glassy phase (Ca-M-O) formation
- Generation and coalescence of intergranular cracks could accelerate the material erosion process of electrodes and further limit the lifetime of spark plugs

Issues to be Investigated

- The evolution of intergranular cracks and formation of Ca-containing glasses in both Pt and Ir electrode as a function of field test time and engine environments-Are they life limiting?
- The kinetics of crack generation and growth and its relationship to application environments
- The governing life limiting process of electrode and thus spark plugs
- A cooperative effort with engine companies has been proposed and will be carried out to systematically evaluate the above stated issues

Provide important guidelines for alloy development efforts

Key Observations for Alloy Design From Worn Plug Characterization Effort

- **Oxidation/Cracking at Ni Electrode/Pt Insert Interface**
  - -Expect gains via improved electrode alloy selection
  - -Ir attacked less but manufacturability limits use

- **Oxide Formation on Pt/Ir Inserts**
  - Pt group alloy inserts not inert in this environment
  - Alloy design to control oxide surface chemistry

- **Intergranular cracking of Pt/Ir Inserts**
  - Metallurgical variables important
    - i) impurity control
    - ii) microalloying of grain boundaries
  - Hydrocarbon grain boundary attack?
    - i) protective scale-forming additions?

Initial Materials Classes of Interest

- **Modification of Existing Pt/Ir Insert Alloys**
  - Improve manufacturability of Ir to allow use at both electrodes

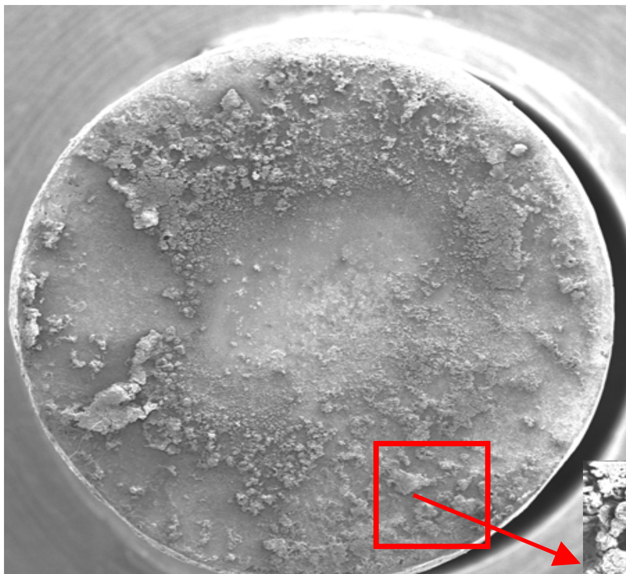
- **Dispersed Structures (Introduce Fine Precipitates)**
  - Well established to improve erosion resistance

- **New Refractory Metal Alloy Bases**
  - Initial focus on Cr-base alloys
    - i) melting points >1800°C- (volatility concerns)
    - ii) corrosion resistant, some ductility
  - High melting point refractory metal bases (W, Ta, …)
    - i) superior erosion resistance but rapidly oxidized
    - ii) gage potential to improve oxidation (500-900°C)

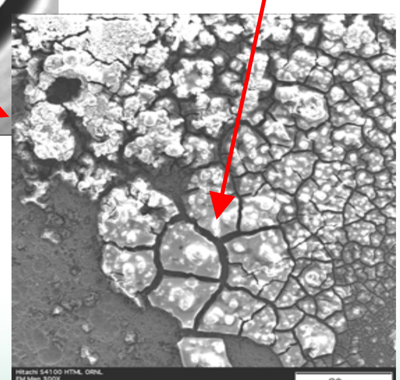
Nano Precipitates Limited Extent of Oxidation in Bench Top Sparking Test

"+" Sparking Surface of Stainless Steel Test Rods
$2x10^6$ Shots/Air/0.1" Gap (same alloy composition)

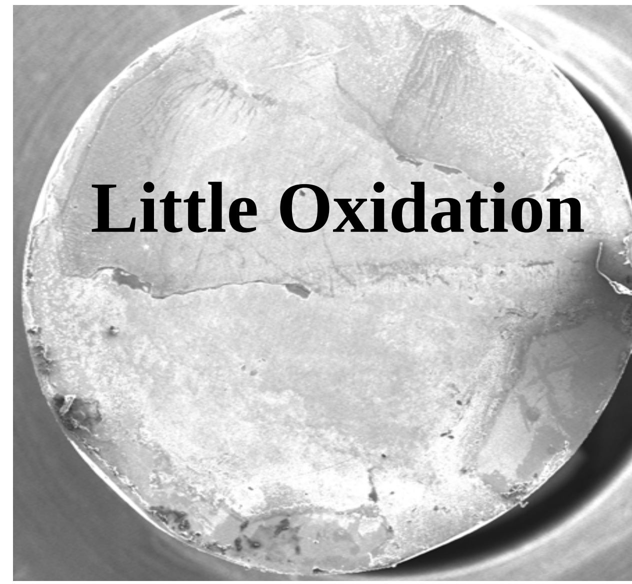
No Precipitates



Fe-Cr Oxide



Nano Precipitates

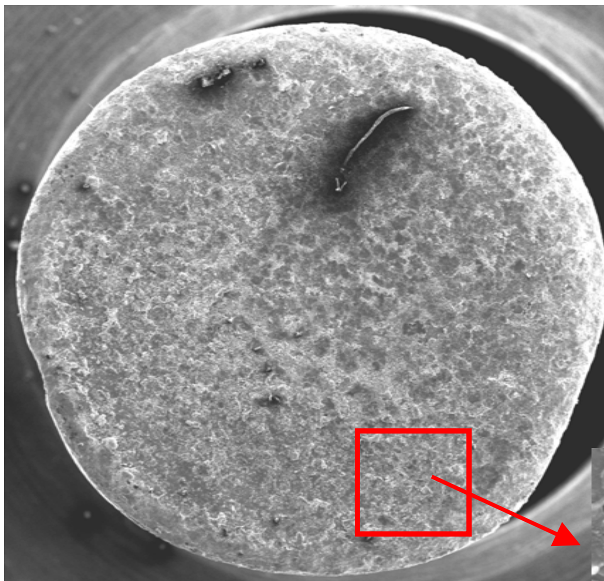


- Potential use in electrode alloys

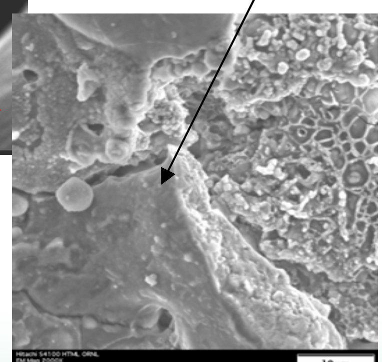
Little/No Attack of Modifed Cr-Base Alloy in Bench Top Sparking Test

+ Sparking Surface of Two Developmental Cr-Base Alloys
$2x10^6$ Shots/Air/0.1” Gap

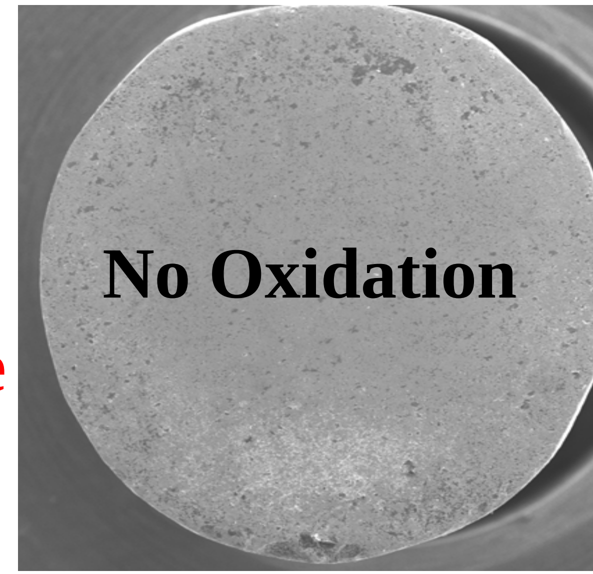
Baseline



Cr-Base Oxide



Modifed Baseline



• Potential replacement for Pt/Ir inserts