Optimization of the Contact Material and Conductive Ink used for an Automotive Fuel Level Sensor

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Abstract

The initial design for a potentiometric, automotive fuel level sensor utilized a copper alloy contact (C770) sliding against both the conductive silver and resistive ink. Because the service environment required immersion in both gasoline and gasoline vapors, the sensor utilized thick film technology on an alumina substrate. The initial combination resulted in either excessive noise at low gram loading or ink wear at high normal forces. A test program, simulating the in tank service conditions, was undertaken to increase the cyclic lifetime of the sensor. By increasing the palladium content of the conductive trace, ink wear was eliminated. It was also necessary to change the layout of the thick film traces in such a way to eliminate sliding against the resistive ink. However, with these changes, contact wear was found slightly later in life. The contact wear is thought to be caused by residual glass components that remained near the surface after firing of the conductive ink. The introduction of a harder palladium based contact material allowed the use of lower normal loads and eliminated both the noise and wear problems. The combination of the Pd based contact material and a high Pd content, conductive ink resulted in a fuel level sensor capable of long life service under the aggressive conditions found in an automotive gas tank.

1. Background

Over the past 5-10 years, reliability in the automotive industry has made tremendous improvements. Long gone are the 2-year/24,000 mile, powertrain only warranties. Now, 10-year/100,000+ mile warranties with all-inclusive features are becoming far more common. Additionally, the costs of warranty issues are being pushed down from the car manufacturer to the component supplier. In order for these longer warranty claims to become reality, component suppliers must develop higher performance, longer life parts. This is the first in a series of papers outlining the steps taken to improve the contact system and overall performance of an automotive fuel level sensor.

As shown in figure 1, the sensor is part of the fuel pump module that is installed directly in the gas tank. The sensor is a rotary potentiometer connected to a float arm. The float arm moves with the fuel level, and its motion causes the rotation of a set of contacts within the potentiometer. Because of the corrosive conditions within the fuel tank, the normal polymeric materials used in most potentiometers would be dimensionally and electrically unstable. For this reason, the potentiometric circuit is made using thick film traces fired on an alumina substrate. The collector or ground trace is normally made from a Ag/Pd thick film conductor. The resistive trace is made from a mixture of refractory oxides in a glass/ceramic matrix. The contact acts as a shorting bar between the two traces, and its position along the resistive trace determines the device resistance. Performance targets for this stage in the program were a minimum of 1,000,000 cyclic rotations and noise spikes below 15 ohms.

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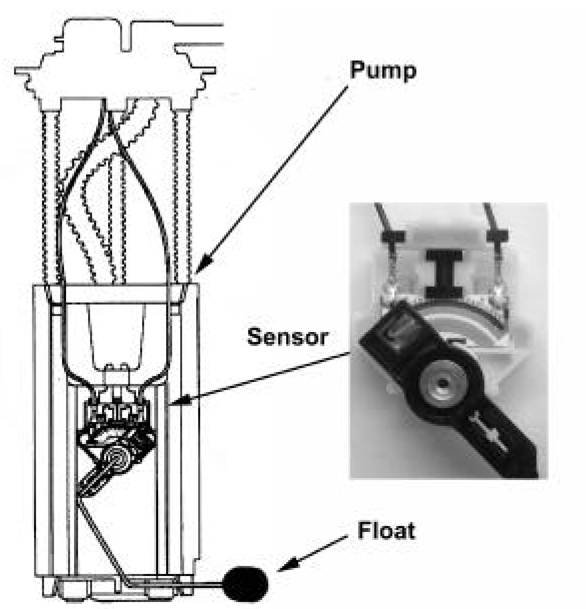


Figure 1) Schematic drawing of the fuel sender module showing a typical location of the fuel level sensor with an enlarged photograph of the sensor assembly

2. Materials

At the start of this program, the contacts were made from a copper-nickel-zinc alloy (CDA 770) and the conductive trace used a 6Ag::1Pd thick film ink. In the initial design, the contacts were designed as three individual fingers that were centered across the width of both traces. This combination provided a reasonable base line, but its optimal performance failed to reach the overall performance needs of the program. The contacts were in a spoon or knuckle geometry.

The experimental program utilized three different combinations of contact material and conductive ink. The C770 alloy was tested against conductive inks with 6Ag::1Pd ratio as well as a 3Ag::1Pd ratio. Additionally, in an effort to eliminate contact wear problems, tests were also done using a Pd based contact material, Paliney® 6.* Table 1 lists the pertinent properties of the two contact materials. Although not given in the table, all other relevant mechanical properties such as yield strength (YS) and ultimate tensile strength (UTS) would rank in the same approximate ratio as the hardness. All combinations of contact material and conductive inks were tested over a range of normal forces from 8 to 15 grams.

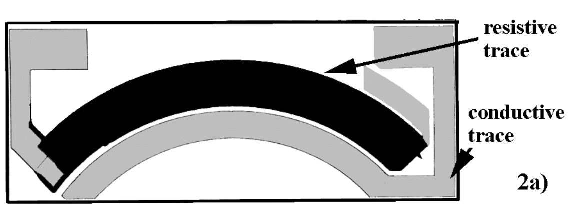
Table 1
Mechanical Properties of Contact Alloys

Alloy	Composition	Temper	Hardness Knoop (100g)
C770	Cu-27Zn-18Ni	Hard	205
Paliney® 6	44Pd-38Ag-16Cu-1Pt-1Ni	Age Hardened	330

3.Design Changes

During the initial tests of the C770 versus the 6::1 ink, the sensor lifetime was limited by wear of the resistive track. Reduction in the resistive ink thickness produced a linear increase in the overall device resistance and an eventual high resistance failure. In an effort to overcome the wear problem, a spoke-like arrangement of conductive arms was added to the resistive trace.[1] These segments were basically electrical taps set at uniformly spaced resistive values and create a step function output. The segment spacing, contact orientation, and contact radius were designed to ensure make before break transitions between adjacent segments. This allowed the sliding contact to maintain metal to metal contact without fear of arcing or opens. With this design, the resistive ink could also be changed to meet any desired resistive value, without impacting the electrical noise or contact wear performance. The segmented approach can also be used on the collector trace in an effort to reduce the overall requirements for precious metal. Schematic drawings of both circuit designs are shown in figure 2.

**Paliney is a registered trademark of The J. M. Ney Company*



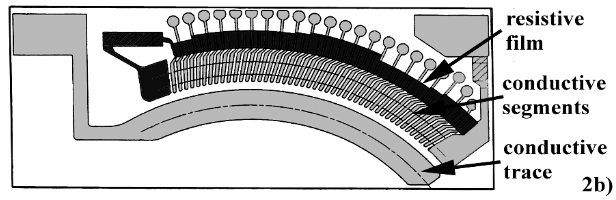
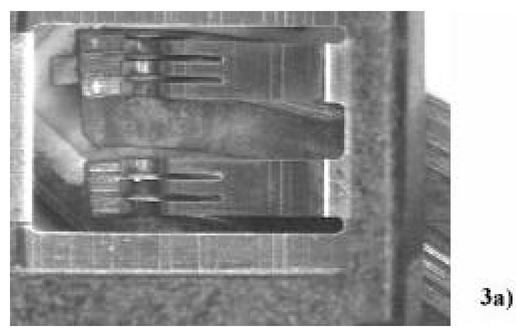


Figure 2) Schematic diagrams of the circuit traces
2a) Original design
2b) Segmented design

Although the mechanical properties of the inks were not directly measured, contact wear of the C770 indicated that the higher Pd level inks were harder. Figure 3a shows an overview of the sensor with the original circuit design after 300,000 rotation cycles. A normal force of 15 gram was deflecting the cantilevered contacts. The contacts remained intact but there is evidence of severe wear in both the resistive (upper) and conductive (lower) track. Figure 3b shows reflective laser profilometer readouts taken across the width of both thick film traces after the 300,000 cycles.



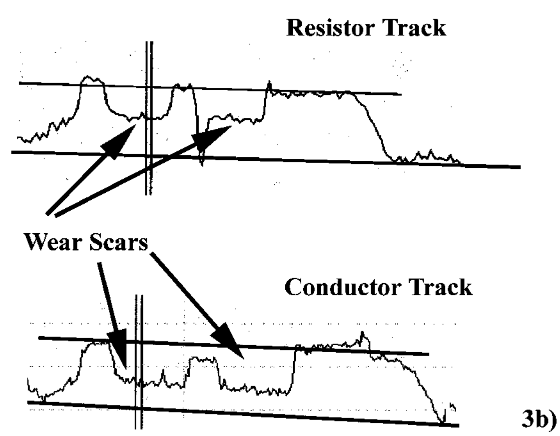
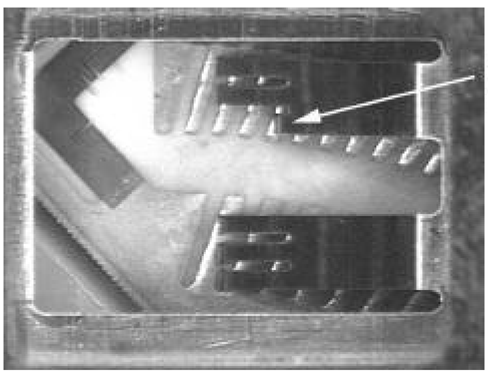


Figure 3) Wear characteristics of the original design, fuel level sensor after 300,000 rotations with a 15 gram load.
3a) Photograph showing acceptable contact life
3b) Profilometer traces across width of both tracks

Figure 4a shows the level of contact wear with the C770 contacts sliding against the 3::1 ink after 600,000 cycles. This test used the spoke design and a normal force of 10g. In this figure, five of the six fingers have worn through the contact knuckle and were found to have only a chisel point profile at the point of contact. (Note that in figure all the contact fingers are significantly shorter than those in figure 3.) On the sixth finger, (see arrow), the worn contact caught against one of the conductor segments and bent under the remainder of the contact arm. Figure 4b shows a Scanning Electron Microscope photograph of the worn contact tips in figure 4a. (Note: Metal on upper finger has been worn so thin that is actually curled into a spiral, just before separation.)



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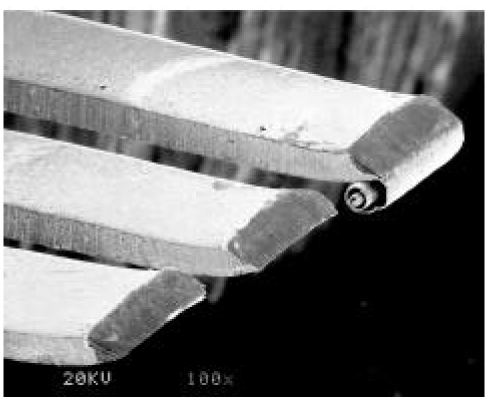
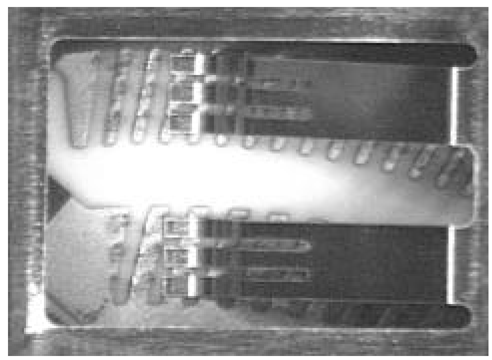


4b)

Figure 4) Severe contact wear after 600,000 cycles at 10 grams using the segmented track with C770 contacts
4a) Photograph showing contacts completely worn through
4b) SEM photomicrograph chisel tips formed by abrasive wear of the contact by the 3::1 conductive ink



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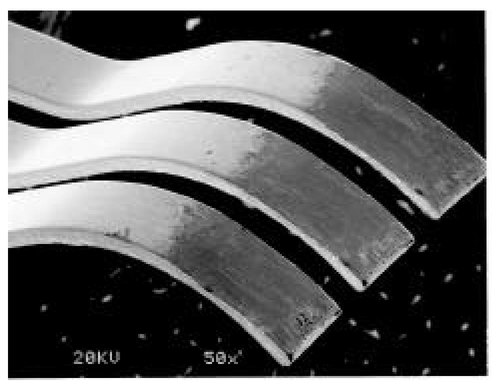


5b)

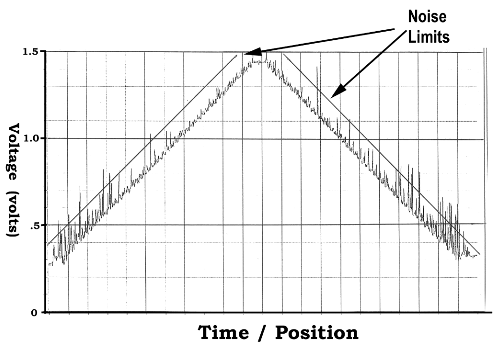
Figure 5) Minimal contact wear found after 1,125,000 cycles at 12 grams normal load using the segmented track and Paliney® 6 contacts
a) Overview showing acceptable contact wear on both contacts and ink traces
a) SEM photomicrograph showing only limited wear on the back of the spoon contact

Figures 5a and 5b show the significantly reduced wear found when the Paliney® 6 contacts slides against the 3::1 ink. These photomicrographs were taken after 1,125,000 cycles at a 12g normal load.

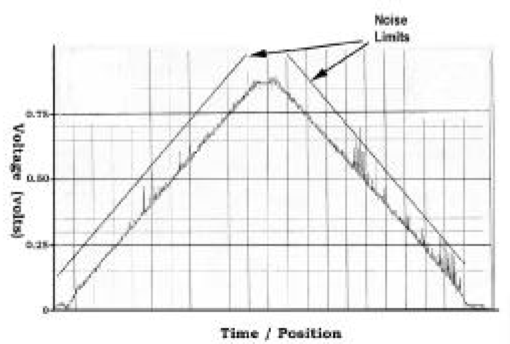
4. Electrical Test Procedures and Results

Samples were mounted into test fixtures within a sealed kettle. The kettle is filled with gasoline to a level well above the sample. Although four different gasoline sources were used in the study {standard US diesel, CARB phase II (a low sulfur fuel formulation), Howell "EEE", and Brazilian E-20}, no major differences could be assigned to the type of gasoline tested. The test fixture was connected to a computer controlled drive motor. The motor travel is set at a rate of 25 cycles per minute, with each cycle consisting of a sweep from the empty to full position and full reversal to empty. Tests were done at ambient temperatures and run until either electrical or mechanical failure occurred. Electrical failure was defined as any noise spike in excess of 15 ohms. Mechanical failure was defined as the wear through of the knuckle on two or more fingers. All six fingers in figure 4a are considered to have exceeded the definition of mechanical failure.

Figures 6a-c show the level of noise found on the various sensor designs after cycling. The electrical sweeps were done with a constant current of 10 ma. As with the wear tests, the units were cycled from empty to full and back to empty at a frequency of .42 Hz (25 cycles per minutes). Since the overall resistance values for each unit were different, different units are found on the vertical scales. The 15 ohm noise limits are drawn on each plot for ease of comparison.



6a)



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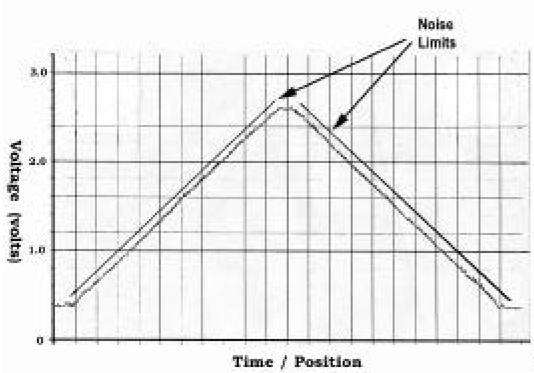

6c)

Figure 6) Voltage versus time plots for all three designs showing differences in noise levels
6a) C770 contact, 6::1 ink, original design, 15g, 300,000 cycles
6a) C770 contact, 3::1 ink, segmented design, 10g, 600,000 cycles
6a) Paliney® 6 contact, 3::1 ink, segmented design, 12g, 1,125,000 cycles

5. Discussion

With the initial design of this sensor, a C770 alloy contact rode directly on both the resistive and conductive thick film traces. The useful lifetime of the design was limited by ink wear. As shown in figure 3, the wear had extended roughly 50-60% through both inks by the 300,000 cycle level. Although continued wear of the conductive trace would have eventually placed the contact riding on the alumina substrate, wear at the level seen in figure 3 would not have caused any loss of electrical function. This Pd/Ag trace serves as a collector or common leg in the potentiometer. Since these sensors carry very small current loads, typically on the order of 10 ma or less, even very small cross sections of the conductive Ag/Pd layer are sufficient. However, once the alumina was even partially exposed, abrasive wear on the contact would proceed rapidly and result in the defined mechanical failure (wear through at the point of contact).

Wear in the resistive trace is far more damaging to the sensor performance. The bulk resistance, R, of any conducting media is given by the equation:

$$R = \rho \frac{\ell}{A} \qquad 1)$$

where ρ is the specific resistivity (a material constant- generally expressed as ohms/□), ℓ is the length and A is the cross sectional area. Wear acts to reduce the cross sectional area, and increase the measured resistance. The actual resistance increase is inversely related to the total area of the original trace minus the sum of the cross sectional areas from the three wear scars.

In addition to the wear problem, the original design also demonstrated unacceptably high noise (figure 6a). Since the wear debris from the resistive track was the most likely source for much of the noise, the first attempt to solve this problem was to transfer all wear from the resistive ink to the conductive ink. This was accomplished by a redesign of the silk screened traces and the introduction of a spoked conductor pattern attached to the resistive trace. (figure 2) Each spoke acted as an electrical tap for a specific resistance value. By having the sliding contact ride only on the spokes, this eliminated wear of resistive trace. By transferring the sliding to only the conductive ink, the overall system resistance did not change with wear through the thick film. Additionally, since the trace was conductive, it would seem logical that any wear debris generated should be more conductive than the debris from the resistive trace. Therefore, although some wear would occur, it was hoped that overall effect of the more conductive debris would be to lower the noise level.

Since as shown in figure 3, the original conductive ink had lost nearly 60% of its thickness in only 300,000 cycles, it was felt that harder conductive ink would be needed. As shown in figure 4, the change from a 6Ag::1Pd to a 3Ag::1Pd brought the desired change of a much harder ink. Actually in reviewing photographs in figure 4, it is evident that this change was so dramatic that it actually transferred the wear from the ink to the contact.

Although increasing the Pd level in binary Pd-Ag alloys is known to increase strength and hardness[2], it was not anticipated that the increase would be large enough to cause contact wear. A quick examination of the properties of wrought Ag-Pd alloys shows that some other mechanism is likely causing the aggressive contact wear seen in figure 4. As a wrought material, binary Pd-Ag alloys are relatively soft in comparison to alloys typically used as contact spring members. Table II compares ultimate tensile strength values for a 6::1 (14% Pd) and 3::1 (25% Pd) binary alloy with that of the two contact materials used in this study.[3,4,5]

Table II
UTS of the Ink Formulations
And Contact alloys

Alloy	% Pd	Temper	UTS	
			(N/mm^2)	(psi)
6::1 ink	16	Annealed	68.5	9,947
3::1 ink	25	Annealed	115.5	16,768
C770	0	Hard	689.2	100,000
Paliney® 6	44	Age Hardened	1,171.6	170,000

Since hardness and shear strength tend to be somewhat proportional to UTS, it would seem unlikely that either conductive ink would abrasively cut or wear these contact materials. This is especially true since the firing temperature of the thick film inks is high enough to completely anneal the binary Pd-Ag alloys and reduce them to their softest state.

A close look at figure 4b indicates that the contact wear is abrasive and not adhesive. This suggests the possible presence of a hard substance dispersed in the softer Pd-Ag matrix. It is our belief that these hard particles are very small, residual pieces of the glass frit from the original ink formulation. Further study of this wear mechanism is the subject of the next paper in this series.[6]

Although this design had severe wear problems, it did show some marginal improvements in the noise response for the sensor (compare figures 6a and 6b). However, there were still a number of noise spikes above the 15 ohm threshold. Therefore, the last phase of this program required identifying a contact material that could resist the abrasive wear of the ink and also contribute to lowering the noise level even further. The fact that abrasive wear was present eliminated a plated solution, and the noise concern acted to eliminate the use of unplated, high strength copper alloys.

Unfortunately, little information existed regarding the contact resistance characteristics of candidate contact materials in gasoline. Therefore, a search was undertaken to identify contact materials used in other aggressive automotive environments. As shown in Table 1, Paliney® 6 was found to offer the higher hardness needed. This alloy was also used as the sliding contact in two other potentiometric automotive sensor applications- throttle position sensor (TPS) and Exhaust Gas Recirculation sensors (EGR).[7] Although not an exact environmental match, these applications were aggressive in their own right. The TPS is mounted right on the throttle body and with current engine designs must endure temperatures over 150^0 C. The EGR valve directs the flow of hot exhaust gases from the combustion chambers, and although the EGR position sensor is not designed for continuous, direct exhaust gas exposure, there likely is some backstreaming of the exhaust gas into the sensor area. Additionally, these applications require the contact to travel millions of cycles.

Based on its success in these other applications, Paliney® 6 was chosen as the contact material for the third iteration in this program. As with most sliding systems, there is a trade off between wear and noise.[8] Higher gram forces tend to produce low noise but higher wear. Lower gram forces reduce the wear, but are prone to noise from either skating over surface films or mechanical lifting. However, at the 12 gram level, this system produces an acceptable tradeoff between the two competing processes. As seen in figure 5, the increased hardness of the Paliney® 6 reduced the wear to a very manageable level. Additionally, as shown in figure 6c, the noble chemistry of the alloy reduced the noise well below the 15 ohm threshold.

The future studies in this program will examine how to further extend the cyclic lifetime of this potentiometric fuel level sensor.

6. Conclusions

The objective of this study was to increase the reliability of a potentiometric fuel level sensor. The original sensor design used a C770 contact sliding against a resistive and conductive thick film trace. At about 300,000 cycles, this design was prone to failure because of both electrical noise and excessive wear of the resistive ink.

In order to achieve the desired life of at least 1,000,000 full cycle rotations it was necessary to make three significant changes to the initial design. These included a redesign of the circuit layout to prevent wear of the resistive ink, the use of a harder conductive ink, and a change to a harder, more noble material, Paliney® 6, for the contact. With these changes, the useable lifetime of the sensor was increased from slightly under 300,000 to over 1,100,000 cycles.

This study also raised some interesting questions regarding the actual mechanisms responsible for contact wear. A better understanding of these phenomena should lead to further improvements in the reliability of these sensors.

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