Reliability Improvements for an Automotive Fuel Level Sensor

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An experimental program was undertaken to improve the rotational life of an automotive fuel level sensor. The potentiometric design of this sensor utilizes a Pd based contact material sliding along two thick film, conductive Ag tracks. One track was the continuous ground or return leg, and the other track was composed of discrete segments radially terminated into the resistive leg. Abrasive wear of the contact sliding against the segmented track was found to determine the useful lifetime of the sensor. Previous work had shown that reductions in the contact normal force produced unacceptable noise due to a failure to break through the gasoline generated sulfide films on the inks. This paper reviews the efforts to improve the wear characteristics of the inks. Although some wear improvements were obtained by mechanical polishing after firing, this introduced output noise caused by sulfide films. More dramatic improvements were achieved by utilizing a different ink formulation that incorporated a finer frit. With the new ink and an optimized firing schedule, it was possible to achieve a smooth surface without the need for a post fire polish. The new ink produced a useable lifetime of over 4 million full cycle rotations compared to roughly 600,000 cycles with the older, rougher ink

1. Background

In an earlier paper[1], the authors introduced some of the electrical noise and contact wear issues associated with the performance of a fuel level sensor. The sensor, illustrated in figure 1, is attached to the fuel pump, and is located in the gas tank. It is designed to provide a low noise signal during exposure to both the liquid and vapor environments typical of an automotive gas tank environment. The sensor is a rotary potentiometer with the position of the contacts determined by the rotation of the float arm. Recently, a number of factors have combined that require performance improvement in these devices. First, automotive warranty periods are increasing. This requires much longer cyclic lifetimes. Second, the increased used of computerized data input for engine management functions requires much cleaner signals from the sensors. Momentary noise spikes are no longer tolerated.

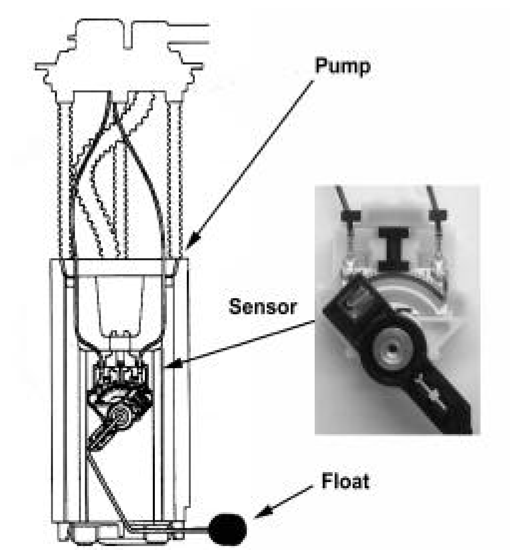

Figure 1. *Schematic diagram illustrating the fuel sender module and position of the level sensor.*

As noted in the earlier paper, very little information has been published regarding the wear characteristics of the thick film inks. These inks were originally developed to serve strictly as conductive circuit traces on ceramic substrates. In this regard, the three most important functions of the ink were: 1) develop a strong, adherent bond with the alumina substrate, 2) provide an electrically conductive circuit path, and 3) provide a solderable surface for additional internal or external circuit connections.

The inks are normally formulated by physical blending metal and glass powders, called frit. The glass provides the bonding agent to the ceramic and the metal provides the conduction path. The powders are mixed with a polymeric binder to allow patterned silk screening onto the substrate. The binder is driven off during a low temperature exposure at the early stages of the firing profile, and higher temperature exposures are used to sinter the powders. Firing is generally done in air to prevent reduction of the glass and to aid in complete removal of the binder through a combined volatilization /combustion process. Historically, firing schedules were developed to promote solderability by minimizing both surface glass exposure and oxidation of the ink components.

The most common conductive inks contain mixtures of Pd and Ag as the metal powders. Pd was used to improve the mechanical strength of the ink and reduce Ag migration. At the firing temperatures used to ensure proper adhesion to the ceramic substrates (typically in the 800^0 C range), the metal powders will sinter and therefore anneal; as such, the metal potion of the ink is expected to be extremely soft. However, as shown in the previous paper, the wear characteristics of the inks do not always follow what would be expected for a soft, ductile precious metal surface. The sensors studied previously failed by either excessive signal noise at low contact gram loads or by abrasive contact wear at high loads. It is the intention of this paper to further investigate the wear characteristics of the inks, and identify conditions for increased sensor life.

1. Materials

For this paper, two different ink formulations were used. As a starting point the 3 Ag ::1 Pd used in the last study was selected as a reference. In addition to examining the ink in as fired condition, this ink was also examined after a light mechanical polishing to reduce the surface roughness. A second ink was also used with slightly lower Ag level (2.6 Ag ::1 Pd). The second ink also had a smaller average frit size, prior to firing.

For all the work reported in this paper, the contact material is age hardened Paliney**®** 6. The contact was “U” shaped with two parallel cantilever beam style arms. At the end of each arm, the contact was split into a three finger design with a 10 gram normal force across all three fingers.

2. Experimental

For all three inks, sensors were fabricated from the circuit pattern shown in figure 2. Since the resistive ink is known to be very abrasive, the conductive spokes were added to provide resistance taps as function of relative position. The mating contact slides on both the segments and the common conductive track. The position of the sliding contact shorts the spokes to the ground track and its position acts to set the sensor resistance.

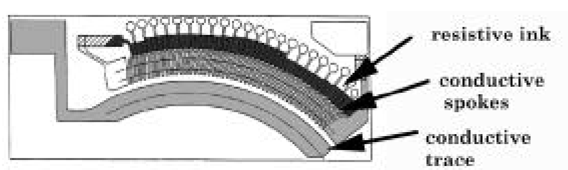

Figure 2. *Schematic diagram of the circuit traces.*

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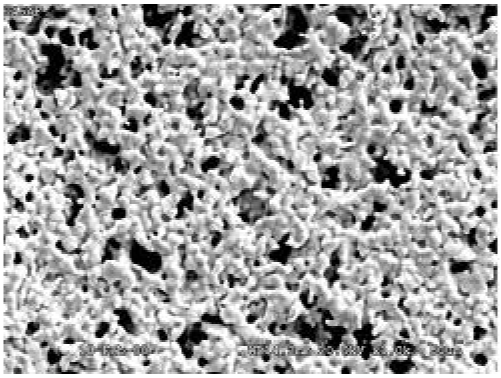


3a)

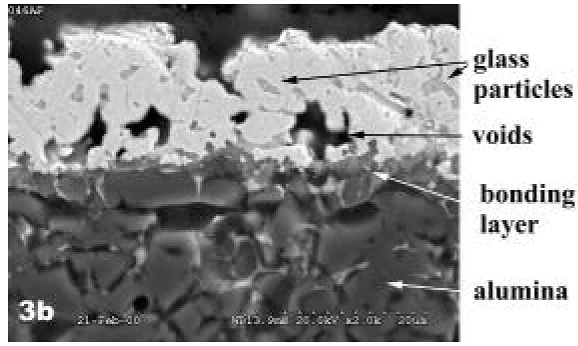
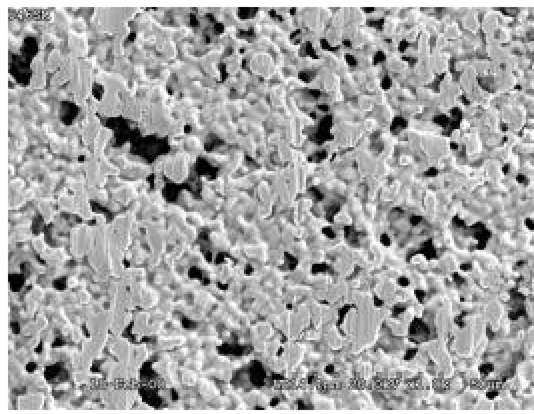


Figure 3. *SEM photomicrographs of the surface (3a, 1000x) and cross sectional (3b, 2000x) views of the as fired coarse frit ink.*

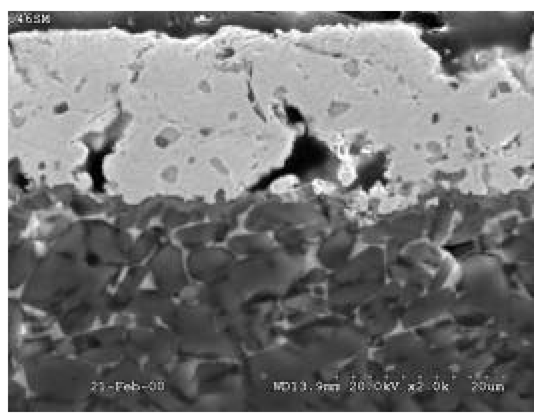
Operating sensors were mounted into test fixture within a sealed kettle. The kettle was filled with gasoline to a level well above the sample. Although a number of different gasoline sources were used in the study {including standard US diesel, CARB phase II (a low sulfur fuel formulation), and Brazilian E-20}, no major differences could be assigned to the type of gasoline tested. The test fixture is 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 two or more fingers. The surfaces of the inks and the contacts were examined with the Scanning Electron Microscope (SEM), both before and after cyclic testing in the kettle. Additionally, samples of the various inks were metallographically cross sectioned and examined in the SEM. Electrical readouts were taken periodically throughout the tests using a 10 ma current.

3. Results

Figures 3-5 show surface and cross sectional views of the three inks, prior to testing. The original ink (figure 3) shows a very rough topography with significant porosity. In some cases, the surface voids were found to reach all the way to the alumina substrate. The surface polishing (figure 4) produced some slight smearing of the surface, but it failed to close all the pores.



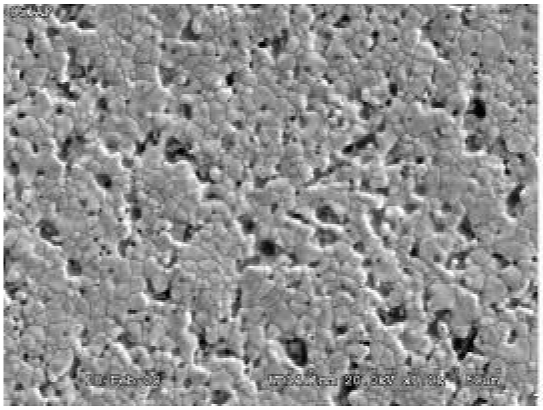
4a)



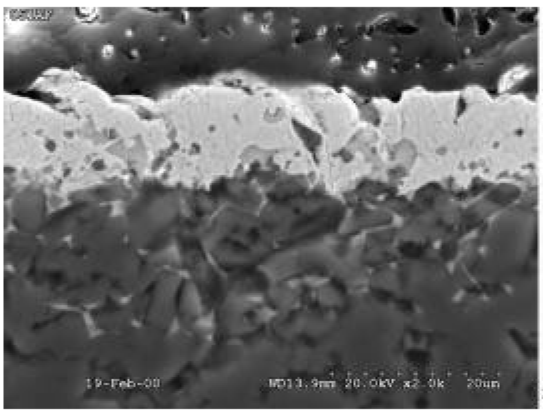
4b)

Figure 4. *SEM photomicrographs of the surface (4a, 1000x) and cross sectional (4b, 2000x) views of the mechanically polished ink.*

The surface SEM photomicrograph (5a) of second ink shows a much smoother surface, and the presence of some dark spots. The cross sections also indicate a less porous structure.



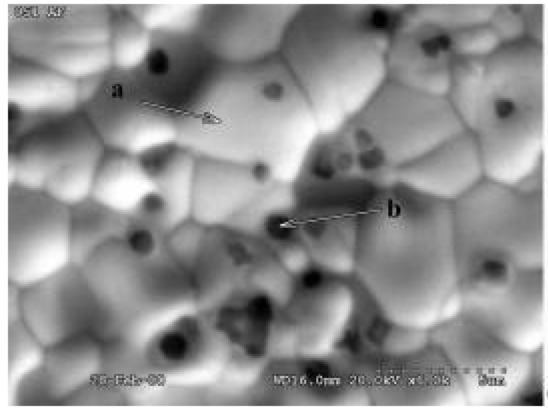
5a)



5b)

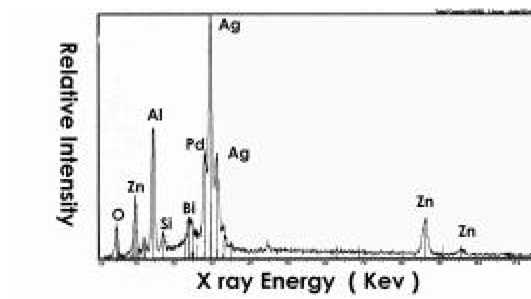
Figure 5. *SEM photomicrographs of the surface (5a, 1000x) and cross sectional (5b, 2000x) views of the as fired, fine frit ink.*

Figure 6a shows a higher magnification view of the surface of the second ink. Figure 6b contains the associated energy dispersive x-ray spectra (EDS) taken from one of the spots. The spots were found to be thin, nearly uniformly distributed, pools of glass. Although both inks show evidence of the glass frit embedded throughout the cross section, only the second ink shows the presence of the small glass pools on the surface of the as fired ink.



6a)

Figure 6a. *High magnification view of the as fired surface from figure 5 showing the presence of small glass pools.*



6b)

Figure 6b) *X-ray spectrum from one of the glass pools in figure 6a.The Pd and Ag peaks are thought from the base conductor formulation and not part of the surface glass.*

Figures 7-9 show SEM photomicrographs and selected EDS x-ray spectra for the various sliding metal contact surfaces at different stages of life. The sliding contacts that were mated to an as-fired surface show evidence of abrasive wear with the exposed surface chemistry consistent with the Paliney 6. The level of wear against the coarse ink was very inconsistent. Figures 7a-c show examples of the inconsistent wear response observed for this ink system. Figure 7a shows evidence of a light burnish after 5.3 million cycles, and figure 7b shows complete finger removal after only 4.0 million cycles. Figure 7c shows the early stages of wear (250,000 cycles) with evidence of both abrasion and adhesive transfer.

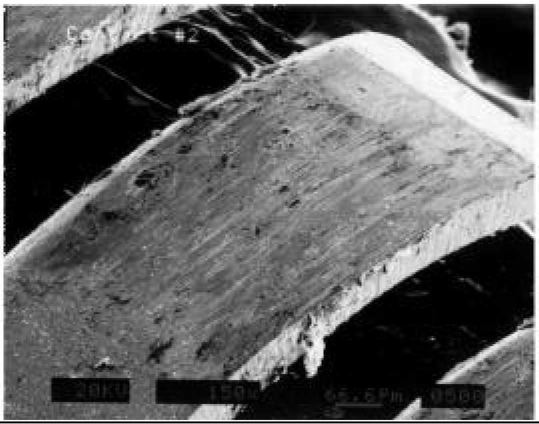


Figure 7a. *Surface SEM photomicrograph of a sliding contact after 5.3 million cycles mated against the as fired, coarse frit ink.*

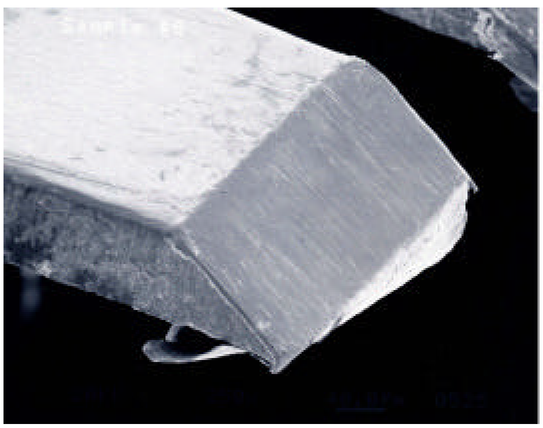
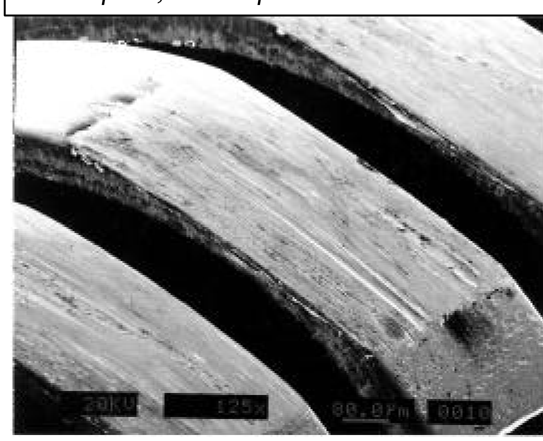


Figure 7b. *Surface SEM photomicrograph of a sliding contact from a second sample after only 4.0 million cycles mated against the as fired, coarse frit ink.*

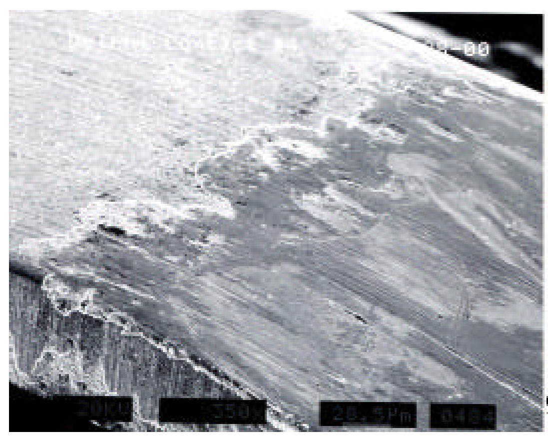


7c)

Figure 7c. *SEM photomicrograph of contact wear after 250,000 cycles riding on the as fired, coarse frit glass.*

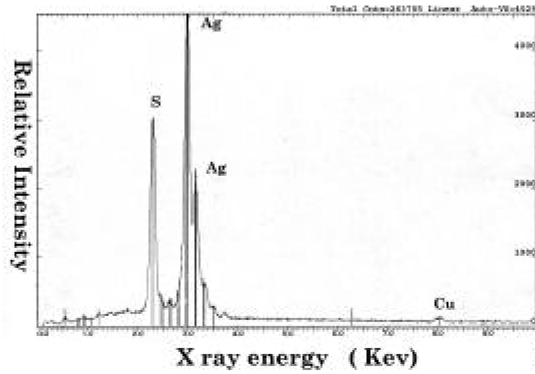
Figure 8. *Surface SEM photomicrograph of a sliding contact after 4.0 million cycles mated against the fine frit ink.*

under the same test conditions. As seen in figure 8, the contact mated to the fine frit ink also showed evidence of abrasive wear, but at a much lower and more consistent level. As seen in figure 9, however, the contact mated to the mechanically smoothed surface shows evidence of adhesive transfer. The x-ray spectrum shows the transferred layer is silver rich with a significant sulfur peak.



9a)

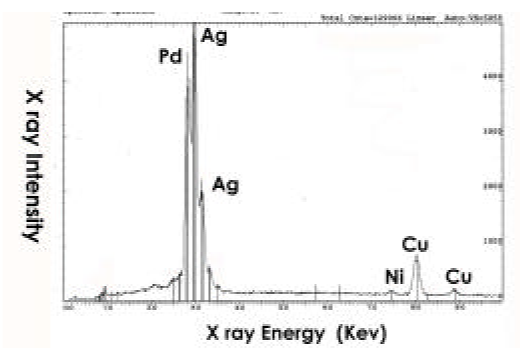
Figure 9. *Surface SEM and associated x-ray spectrum from an adhesively transferred layer found at the contact point mated to the mechanically polished ink.*



9b)

As seen in figure 8, the contact mated to the fine frit ink also showed evidence of abrasive wear, but at a much lower and more consistent level. As seen in figure 9, however, the contact mated to the mechanically smoothed surface shows evidence of adhesive transfer. The x-ray spectrum shows the transferred layer is silver rich with a significant sulfur peak.

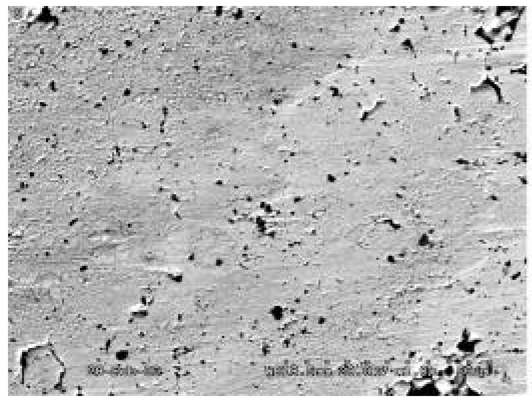
Figure 10 shows the x-ray spectrum from an area of the contact away from the wear spot after 5 million cycles. Only the contact alloy elements are seen, with no sulfur peak present.



10)

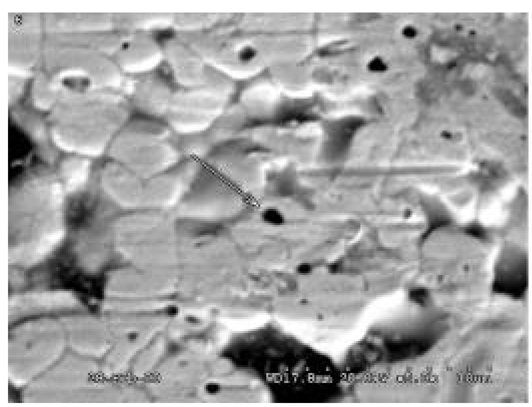
Figure 10 *X-ray spectra from a non-wear area of the sliding contact after 5 million cycles.*

Figure 11 contains surface SEM photomicrographs of the ink surface after different levels of wear. Figure 11 a shows a very flat, burnished appearance typical of the coarse frit ink. This sample was found on one of the segmented spokes after only 250,000 cycles on the as fired, coarse frit ink. In contrast, figure 11b and c show the surface of the fine frit ink after 1,250,000 cycles. In this case, even with five times more cyclic motion, the surface still shows much of the original as fired topography. Additionally, the higher magnification view in figure 11c shows scratches initiating from the surface glass particles. The lack of excessive burnishing suggests the contact actually rides on the surface of the glass particles.



11a)

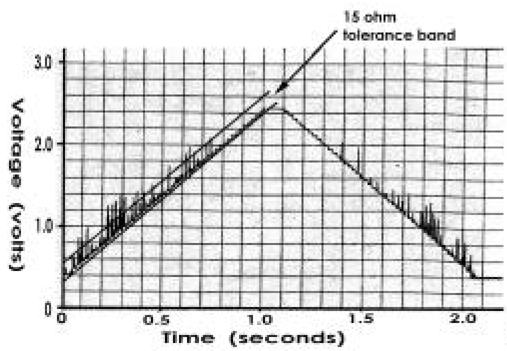
11b)



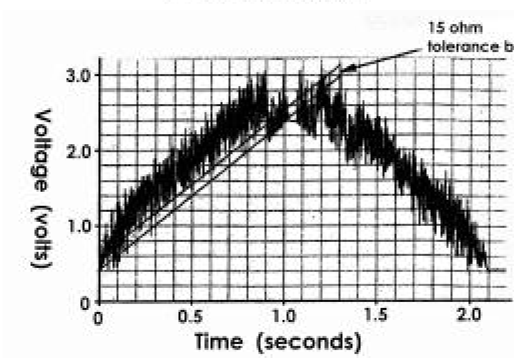
11c)

Figure 11. *SEM photomicrographs of the two as fired ink surfaces after different levels of cyclic wear.*
a) Coarse frit ink after 250,000 cycles
b and c) Fine frit ink after 1,250,000 cycles

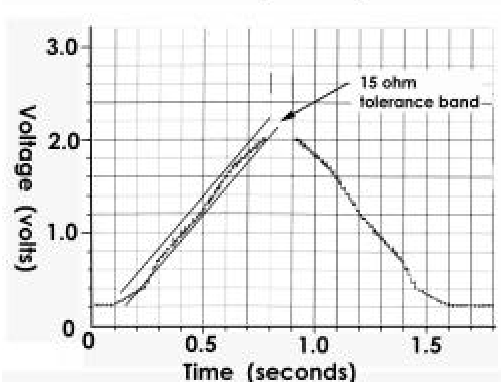
Figures 12 show the electrical output of from each of the substrates tested. As shown in figure 12a, some of the samples with the as fired, coarse grained frit failed after slightly over 1 million cycles by exceeding the 15 ohm threshold. As noted earlier, others with this same frit showed premature failure due to wear. As seen in figure 12b, the mechanically polished units failed due to excessive noise after only 250,000 cycles. However, the fine grained frit shows acceptable noise and wear up to beyond 3.5 million cycles. For the fine frit ink, once the noise spikes appear, they tend to remain at a fixed location on the ink for a short time, and then disappear to be replaced with noise at other locations.



12a)



12b)



12c)

Figure 12. *Electrical output of fuel level sensors from each of the three inks*
a) coarse frit 1,250,000 cycles
b)polished surface 250,000 cycles
c) fine frit 3,600,000 cycles

5. Discussion

The objective of this work was to provide a better understanding of the potential wear mechanisms for thick film conductive inks in a rotary, potentiometer style, fuel level sensor. In most sliding contact applications, there is a trade off between noise and wear.[2] Higher gram loads tend to provide lower noise levels, but can often lead to higher wear levels. This is especially true in systems where abrasive wear is prevalent. However, based strictly on the hardness values for the contact and the resultant Pd-Ag composition of the ink, abrasive wear of the contact was not anticipated. Table 1 contains a listing of the anticipated mechanical properties for the contact and ink materials.[1]

Table I
UTS of the Ink Formulations
And Contact alloy

Alloy	Temper	UTS	
		(N/mm^2)	(psi)
3::1 ink	Annealed	115.5	16,768
Paliney 6	Age Hardened	1,206.1	175,000

Clearly, the annealed Pd-Ag conductor material should not be hard enough to abrasively cut the contact surface. However, for both as fired inks, abrasive wear of the contact is quite evident. However, for the mechanically polished ink, the wear mode is changed to adhesive transfer of the ink to the contact. This type of adhesive transfer has been documented by Antler[3] and others[4, 5] and is typical of wear for radiused contacts sliding against wrought, or plated, precious metal surfaces. Unfortunately, in the sulfur containing environment of an automotive fuel tank, the adhesively transferred surface tends to be very reactive. The resultant film is found to be Ag and S rich and is likely a silver sulfide. The surface layer is a mechanical mixture of sulfides, transferred ink, and newly exposed wear surface. Under sliding conditions typical of a potentiometer, the resulting contact would likely produce areas of erratic resistance, consistent with figure 12b.

In contrast, the abrasive wear, seen in figures 7b and 8, acts to keep the contact surface clean of films. Therefore, it appears that one approach to ensuring a low noise contact system is to allow mild abrasive wear to clean the contacts. With this approach, the level of wear is likely to determine the cyclic lifetime of the sensor. However, if not controlled properly, the wear can become excessive and lead to premature mechanical failure (see figure 7b).

As noted earlier, the Ag-Pd conductor is much softer than the Paliney 6 contact. Therefore, it is reasonable to assume that the abrasive wear is caused by any exposed glass particle. The level of wear would be related to the height of the particles above the ink surface.

As seen in the cross sectional views, all the inks used in this study have large glass particles below the surface. However, the coarse frit glass also has a very rough topography coupled with a very porous structure. As seen in figure 7c, at the very early stages of wear it appears that both adhesive transfer and abrasive wear can be active. We believe that the long term wear response is actually determined at this early stage. As the contact initially slides over the surface, it begins to burnish the soft Ag-Pd conductor and flatten the topography into a nearly featureless track (see figure 11b). If no glass particles are exposed during the initial burnishing rotations, then one can expect adhesive transfer across the interface with limited mechanical wear of the contact (similar to the mechanically polished condition). This adhesive layer can also lead to sulfide film formation and the resultant noise.

If on the other hand, the burnishing begins to expose large glass particles just below the as fired surface, then abrasive wear will dominate and premature contact wear can be expected. If only small glass particles are exposed, then it should be possible to get the ideal condition of light mechanical abrasion to remove the surface film, but provide a long contact life.

Unfortunately, with the coarse frit ink, the tendency toward either condition appears to be somewhat random, with a bias toward the abrasive contact wear mode. The rough topography and excessive porosity further complicate the situation. Since filling in the deep pores is going to take a lot of metal movement, it will increase the time required to reach the flat stable wear track that symbolizes the end of the burnishing process. The requirement for increased metal movement increases the odds for exposure of large, subsurface glass particles and higher abrasive wear rates.

In contrast, the fine frit ink was found to have a much smoother topography with much less porosity. Under these conditions, it would be easy to get the burnished track established. However, this is likely to lead to strictly adhesive transfer of the ink material, and the resultant high noise typified by figure 12b. However, the fine frit ink also has the small pools of glass on its surface. The small disk like shape of the glass pools provides the low level abrasion needed to keep the contact surface clean. The fact that the particles resulted from molten glass pools with a slow furnace cool ensures that a smooth flat surface will be facing the sliding contact. This smooth surface should provide good mechanical polishing with minimal material removal from the contact.

Even under this scenario, there is likely to be some adhesive transfer, and because of the surface glass, this material will be continuously abraded away as fine debris. Most of the debris should be carried away by the gasoline. However, some is likely to be pressed into the surface valleys on the ink.

Since this is similar to the adhesively transferred layer seen in figure 9, it is also reasonable to assume that this compacted layer will contain a high proportion of sulfide films. Eventually the layer will build up to the point where it begins to interact with the contact and could cause noise. Additionally, as shown in figure 11c, there reaches a point where the shear force generated by the sliding contact causes the small surface glass pools to break away from the ink. As the number of pools is reduced, the surface of the fine frit glass begins to approach the burnished surface of the coarse frit ink. Once this state is reached, the failure mode could again be by either wear or noise. However, because of the initial controlled wear caused by the small surface glass particles, the fine frit ink provides a much longer useful lifetime.

6. Conclusions

The primary objective of this work was to identify the factors controlling contact wear and signal noise in a potentiometric fuel level sensor. Based on the observations made in this paper, it appears that contact wear is controlled by the glass particle distribution within the ink. Noise appears to be caused primarily by silver sulfide films resulting from freshly exposed wear surfaces on the ink.

If the glass particle size and distribution is not well controlled, the performance of the sensor is likely to be erratic and failures from both premature wear and excess noise are likely. The apparently erratic performance is likely magnified by increases in surface roughness and ink porosity.

However, it has also been shown that a controlled abrasion approach can produce consistent lifetimes in excess of 4 million cycles. The approach uses small, flat surface pools of glass to provide a mechanical polishing of the sliding contact. In the absence of adhesively transferred layers from the ink, the Paliney 6 contacts are resistant to sulfide formation and act to wipe clean the wear surfaces on the ink. In term, the glass pools provide a light mechanical polishing and prevent any transfer buildup on the sliding contact. This combined effect provided the means for achieving long cyclic lifetimes.

With this improved understanding of the wear and noise mechanisms, additional work is planned to further extend the life of the sensor.

Acknowledgments

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