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Impact of Surface Film on Electrical Contact Resistance of Silver Impregnated Graphite Contacts

KEYWORDS Silver Impregnated Graphite (SIG), Metal to Carbon relays, tunnel effect, film resistance, EDX.

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ABSTRACT *Silver impregnated Graphite (SIG) contacts are used in Metal to Carbon Relays, which are used in railway signaling on Indian Railways for operating various signaling functions viz. signals / points / track circuits etc. During the course of operation, various films viz. carbide / impurities etc. get developed on these contacts, which influence its contact resistance. EDX analysis confirmed the existence of carbide film on SIG surface, which introduced a tunnel resistance during mating of contacts. Consequently, the electrical current stops flowing and the relays fail. This causes disruption to rail operations and adversely affects the train safety & punctuality. The philosophy of development of surface films on these contacts and their effect on the contact resistance, including the relationship of film resistance with various contact parameters, has been deliberated and suggestions to minimize their effect have been discussed.*

Silver Impregnated Graphite contacts used in metal to carbon relays combine the best properties of conducting silver and refractory graphite carbon. The distinctive features of the silver-carbon material are its hard fusing characteristics, better conduction of heat and electricity, easy brazing etc. The electro – graphite for these SIG contacts is manufactured using the Press-Sinter-Infiltrate (PSI) process of powder metallurgy, which provides the highest density material. Silver impregnation is done to achieve high level of electrical conductivity. The SIG contacts are made from graphite blocks, by several cutting, machining & shaping processes. Impregnation is carried out by soaking the graphite pieces in silver nitrate solution under high vacuum for adequate time and then washing the pieces gently by triple distilled water to remove any sticking silver nitrate from the surface. Then the silver nitrate is reduced into silver through the process of 'firing' and then electroplated on backside for soldering. Finally, three-stage cleaning of SIG contacts is done to remove any water - soluble impurities remaining after electroplating. The final product, as shown in figure 1, shall contain 55% to 60% by weight of silver (without considering the silver plated portion) and the distribution of silver throughout the volume of contact, as seen in micrographs, shall be uniform and free from defects viz. seams, threads, or silver globules [1]. The specific resistance of impregnated graphite shall not exceed 2×10-4 ohms-cm, while the compressive strength of contact shall not be less than 700 kg/cm2 [1]. The hardness of contact shall not be less than 22 VPN. The water-soluble impurities in the finished contacts shall not exceed 0.25% [1].

Fig. 1. Silver Impregnated Graphite Contacts

The Silver Impregnated Graphite contacts are fixed on springs [2] as shown in figure 2.

Fig. 2. SIG Contact fixed on contact spring

SURFACE FILM ON SIG CONTACTS

Even in absolutely clean metallic surfaces, thin films having low conductivity, semiconductor properties or even isolating characteristics develop on the surface [3], as shown in figure 3. These films are formed on the surface of materials due to presence of dirt / debris / impurities on the surface or due to oxidation / sulphation / corrosion etc. There are two types of films - Thin films & Thick Films.

Fig. 3 Metal surfaces covered with films

Thin Films [3] are formed from the chemisorbed oxygen atoms on the metal surfaces. They are up to 20 Angstrom thick and are easily fractured mechanically. They conduct electricity by tunnel effect. Thick Films [3] are actually tarnish films; When clean metal surfaces are exposed to atmosphere, the metal combines with the atmospheric oxygen / sulphur dioxide / carbon dioxide etc. and forms metal oxide / sulphide / carbide films. Their average thickness is 100 Angstrom and are practically insulating. The conductivity through thick films is by fritting. The thickness of the layers and the speed of growth are dependent on the contact material, ambient atmosphere, temperature and time [3]. The films could also be from contamination from atmosphere or manufacturing impurities present on the surface.

To study the film formation phenomenon on the surface of SIG contacts, surface analysis was done by Scanning Electron Microscopy (SEM) [4] and the chemical constituents of this film were ascertained using Energy Dispersive X-ray Spectroscopy (EDX)[7]. For this, used SIG samples (from two different metal to carbon relays, which were declared failed in the field due to High Contact Resistance), were analyzed by Scanning Electron Microscope [Model: JEOL JSM 6380 LA]. For comparison purpose, SEM & EDX of fresh unused SIG samples were also done. The results of SEM & EDX analysis [5] were as shown in figure 4, 5 and 6.

Volume : 3 | Issue : 5 | May 2013 | ISSN - 2249-555X

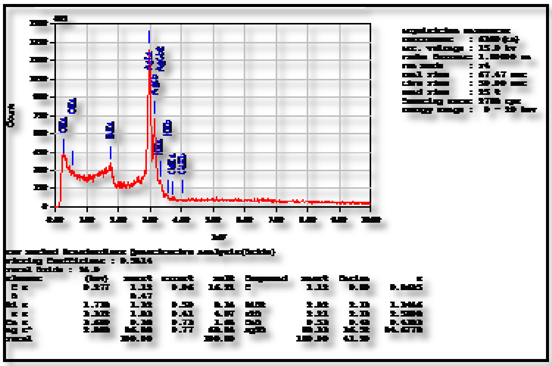

Fig. 4 Fresh (Unused) SIG Contact

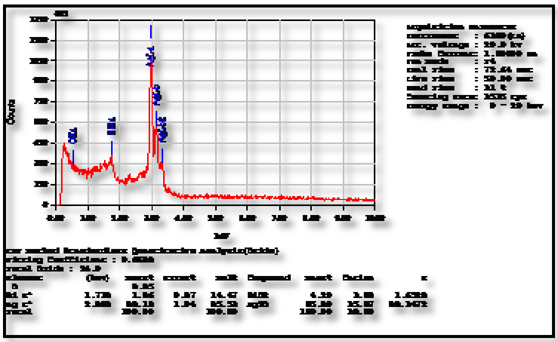

Fig. 5 Failed SIG Contact from Relay No. 1998

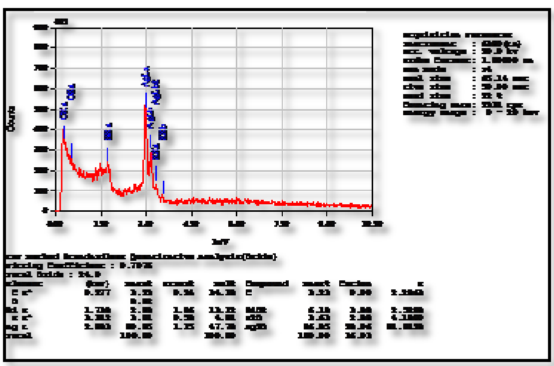

Fig. 6 Failed SIG Contact from Relay No. 2006

The SEM micrographs of failed SIG contacts clearly depicted depletion of silver and presence of free carbon granules on the surface. On comparison, the same was not seen in fresh (unused) SIG contacts.

From the EDX analysis of SIG contacts, it was seen that the carbon mass in fresh SIG sample was 1.12%, while in failed samples it was 3.28 % / 3.23%. This implied that the carbon content had increased in failed samples (during usage) and clearly depicted the formation of carbide film on the failed SIG contact surface. Besides, other chemical impurities had also increased (viz. silicon from 1.32 % to 2.98 %; Silicon dioxide from 2.82 % to 6.19 %; Potassium from 1.83 % to 3.10% and Potassium oxide from 2.21 % to 3.63 %), indicating the presence of impurities on the contact surface. An interesting point in context was that the silver content had decreased from 86.88 % in fresh samples to 83.29 % / 80.95 % in failed samples. This suggested that the silver element had eroded from the surface during operation.

Hence, the surface analysis of SIG contacts, confirmed the formation of film on the SIG contact surface. This film is most probably made up of carbon and is formed through a complex process. The continuous opening / closing of contacts during the course of operation of relay causes arcing between the silver and SIG contacts. This increases the temperature of contacts' surfaces. Besides, the SIG contact is softer in comparison to the silver contact, and the continuous hammering action of the hard silver contact on the softer SIG contact dislodges some graphite material from the surface of SIG contact. As has been seen from EDX, some chemical impurities are also present on the SIG contact surface. Besides, other impurities viz. atmospheric dust, silicon sediments, oil or grease may also be present on the SIG surface. Other contaminants can be the result of outgassing of the plastic materials within the relay or generated by catalytic effect, through decomposition of organic vapors under the influence of arc. This dust / debris / impurities, under high temperature and arcing, fuses together and forms a complex carbon film on the SIG contact surface. The thickness of the film and the speed of growth are dependent on the graphite material properties, ambient atmosphere, temperature and time.

IMPACT OF SURFACE FILM ON SIG CONTACTS

When current flows through two metallic surfaces, which are mating under a finite pressure, the localized phenomenon that affects the passage of current is explained by Contact Theory [6]. The electrical current, while passing through the metallic interface, has to encounter two particular phenomena:

- Asperities or constrictions on the mating surfaces, which reduces the effective area available for passage of current.
- Dirt / chemical films on the respective surfaces of the metals, which further obstruct the current path.

Thus, as shown in figure 7, the current through contacting surfaces is restricted to continuity breaks in the superficial film, since the films are electrically insulating.

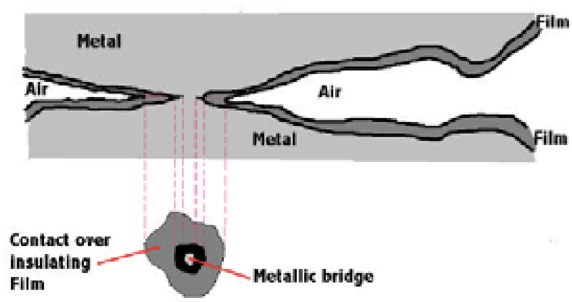

Fig. 7. Contact between surfaces covered with film

Hence, there are essentially three regions within the actual contact area [7]: (i) Full contact region – the current passes through the interface without any transition resistance; (ii) semi – conducting regions – thin film covered areas with resistance values higher than the metal to metal contacts; and (iii) non-conducting regions – areas covered by thick films of oxides, sulfides etc.

This distortion and obstruction in the current flow generates resistance, which is termed as **Electrical Contact Resistance** [6], and is essentially generated from two physically different phenomena. It can be represented by the relationship,

$$R_{\text{contact resistance}} = R_{\text{constriction}} + R_{\text{film}}$$

Where, $R_{\text{constriction}}$ is the **Constriction Resistance** due to surface asperities and R_{film} is **Film Resistance** due to surface films.

The contact resistance depends on the value of current, the pressure acting on the contacting surfaces and their surface

Volume : 3 | Issue : 5 | May 2013 | ISSN - 2249-555X

physiology [6]. The increased resistance not only hampers current flow, but also results in localized Joule heating at the a-spots and causes a considerable rise in the temperature and oxidation growth at the a-Spots, which further aids in film formation. Besides, the localized elevated temperature softens the metal, and combined with the acting pressure, causes plastic deformation resulting in local thermal welding.

In most cases, the constriction resistance is negligible, as with the increment in load, all the asperities disappear and the surfaces mate perfectly. Hence, generally, film resistance is the sole resistance between contacting surfaces. The contact resistance increases due to the film resistance.

When two metallic surfaces, covered by thin insulating film, are in contact, the current flow is through tunnel effect [8]. Only those electrons, which possess sufficient energy to surmount the barrier produced by the insulating film, shall pass over from one surface to another, thus, introducing a tunnel or film resistance. In such scenario, the contact mechanics is dominated by the mechanical properties i.e. the surface roughness of the surfaces and the film resistance dominates the contact resistance. The surface contact produces numerous circular asperity micro-contacts. The contact resistance, decreases with an increase in contact load, fractal dimension and current flow, and decrease in fractal roughness, film thickness and dielectric constant [8]. The presence of the insulating film makes the variation of contact resistance with the contact load more prominent, as the film resistance is mostly non-ohmic. Similarly, increment in applied current makes the variation less pronounced.

For a single micro-contact of area a_i (in cm^2) covered by a thin insulating film of thickness **t** (in Å), dielectric constant **K**, and the energy height above the Fermi level ϕ_0 (in Volt), the tunnel or film resistance $\mathbf{R_{ti}}$ (in Ohm) is given by the formula [9],

$$R_{ti} = \frac{\Delta S \exp\left(1.025 \Delta S j_L^{1/2}\right)}{3.16 \times 10^{10} j_L^{1/2}} \frac{1}{a_i} \qquad (1)$$

Where,

$$j_L = j_0 \left(\frac{5.75}{K \Delta S}\right) \ln\left[\frac{S_2 (t - S_1)}{S_1 (t - S_2)}\right] \qquad (2)$$

And $\Delta S = S_2 - S_1$ (3)

Where S_1 and S_2 are given by,

$S_1 = 6/(K \phi_0)$ and $S_2 = t - 6/(K \phi_0)$ (4)

The thickness of carbide film on SIG contact is not known as it is very difficult to measure the same. Hence, the film resistance has been calculated for varying thickness of film in the range 6 Å to 50 Å, by using equations 1 - 4. The dielectric constant K for carbide film is in the range of 5.8 – 7.0 and for this exercise the average value of 6.4 has been used. The barrier height ϕ_o has been assumed as 0.5 V as the voltage drop across a closed silver – SIG contact of metal to carbon relays is approx. 0.4 V, while the contact area is taken as 174.35 sq. cm. for a silver contact of radius 19 R.

The film resistance for varying thicknesses of carbide film is shown in the graph of figure 8.

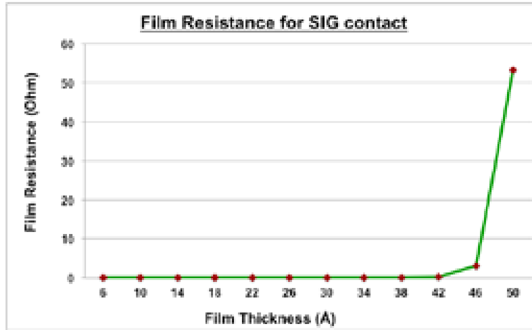

Fig. 8. Film Resistance of carbide film on SIG contact

As can be seen from the above graph, the film resistance is negligible (in nano / micro ohms) for very thin films but it becomes quite substantial when the film thickness becomes substantial, viz. more than 50 Å. Beyond this, the film resistance increases exponentially. This confirms that film resistance is the dominant component in the overall contact resistance of silver – SIG contact pair.

As the wear increases with number of operations of relay, the film thickness increases and along with it the film resistance and inter alia, the contact resistance increases. During the operational life of relay, the contact load, current flow through contact pair and the dielectric constant of SIG contacts remain reasonably constant, and thus do not play a vital role in increment of contact resistance. However, after some number of operations, the wear of SIG contact increases. This not only causes the contact surface to become increasingly rougher, but also aids in formation of carbide film on the surface due to deposition of loose carbon particles and debris / dust. As the number of operations progresses, the wear keeps on increasing and the film thickness also increases. Both these phenomena significantly enhance the film resistance and consequently, the contact resistance increases to extremely high values, which obstructs the current flow completely.

Increment in contact resistance during usage causes the metal to carbon relays to fail. An analysis of signaling equipment failures during last four years (2007 – 08 to 2010 - 11) on Indian Railways revealed that the failures of metal to carbon relays amounted to approx. 7% of the total signaling equipment failures. This failure rate was quite substantial and totally unacceptable. FMEA [10] of metal to carbon relays established that the High Contact Resistance was the major cause of failures (highest RPN - 576). Thus, it was very clear that the failures caused by High contact resistance were the most potential risk.

Metal to Carbon relays are used in railway signaling systems for configuring various signaling circuits, governing the change in aspect of railway signals from red to yellow to green, as per the requirement of the train operation, and as commanded by the train controller [11]. Since the current for various selections of signaling interlocking passes through these contacts, their conductivity is of utmost importance. Due to High Contact Resistance the current can't pass through these contacts. This disrupts the electrical connection between the contacts, causing the relay to fail [12], eventually resulting in the failure of signaling system. Thus, essentially, the superficial films impact the reliability of relays in negative way.

SOLUTIONS FOR FILM REMOVAL

The development of surface film is an intrinsic property of the SIG contact functioning. Due to high temperature and arcing, the film shall always be formed. In hot and humid areas, the process shall be faster and consequently, recurrently gener-

Volume : 3 | Issue : 5 | May 2013 | ISSN - 2249-555X

ate High Contact Resistance. The resistance of film depends upon the depth of the layer, effective contact area and the specific resistance of the graphite material. In absence of film, the contact resistance remained within reasonable working limits. Hence, in order to prevent development of High Contact Resistance, the surface film should either be prevented from being formed or should be removed / broken every time it forms.

Preventing the formation of surface film is an unmanageable task, for as long as the dust / debris is present on the surface, it shall always fuse under high temperature and arcing to form the film. An easier task is to remove / break the film every time it is formed. This shall provide reliable electrical contact and thus, help in maintaining the contact resistance within reasonable limits, consequently preventing failure of metal to carbon relays. This can be achieved in two ways [13] –

(i) Mechanical methods
The film on SIG contact can be destroyed mechanically during closing of contacts, when the metal surfaces hit against each other several times (bouncing), causing elastic deformation of the effective contact area. Increasing the contact pressure shall also cause micro deformation of the contact surface, thus destroying the insulating film. Besides, allowing the contact surfaces to wipe across each other during movement shall also rupture and remove the non-conductive films on the contact surface.

(ii) Electrical methods
The film can be broken down electrically through fritting i.e. applying a sufficiently high voltage (fritting voltage) across the closed Silver – SIG contact. Due to the applied voltage and very short distance (the thickness of film) between the two potentials an extremely high electric field is generated. The film will break down and a small current (a few nA) is forced through very thin channels in the film. The resulting local high current density heats the conducting channels up quickly, destroying the film and electrically linking the two surfaces.

Alternatively, very high contact current will destroy the film thermally and create a larger effective contact area. Besides, extremely high temperatures of the arcs generated during contact making shall also destroy the contact layers and burn or disintegrate other contaminants or particles in the vicinity of the point of contact.

However, the most effective way is wiping (mechanical cleaning), as fritting is a temporary measure, increasing the contact current is not possible due to design constraints [14], and arcing is not good for the health of SIG contacts. The contact wipe can be introduced by modifying the contact pressure and contact radius of silver contact.

CONCLUSION

The existence of a complex carbide film on SIG contact surface was proven through EDX analysis of contacts. This film introduced a film or tunnel resistance during mating of silver – SIG contacts. The film resistance was directly proportion to the fractal roughness of SIG surface, carbide film thickness and the dielectric constant of carbon. Surface roughness and film thickness increased as the number of operations increased and consequently the film resistance also increased. This adversely impacted the reliability of relays. Introduction of wipe and increasing the contact pressure, by modifying the Silver / SIG contact design parameters shall certainly break up the film every time and consequently, prohibit the development of High Contact Resistance, eventually enhancing the reliability of metal to carbon relays. Improvement in reliability of metal to carbon relays by reducing / eliminating their failure modes shall enhance the performance of Railway Signaling Systems, resulting into better punctuality of trains and additionally, improving the safety performance of railway signaling systems and reducing public grievances.

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