Transfer of Metal between Light-Duty Electrical Contacts

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A study has been made of the metal transfer which occurs between gold-plated reed relay contacts when these are used to make and break a resistive circuit carrying 100 mA DC at 50 V. A scanning electron microscope was used for the investigation of surface topography and enabled the features of the pips and of the craters to be examined in great detail. For the electrical conditions considered, metal transfer was found to be due to a molten bridge mechanism rather than to electric arc processes.

1. Introduction

Reed contact units have recently been introduced into telephone switching systems [1]. Their design and manufacture have been described by Williams and Bishop [2]. Briefly, a reed contact unit consists of two flat 50:50 nickel/iron alloy cantilever "reeds" sealed one into each end of a glass tube such that their free ends, the contact areas of which have been electroplated with gold, overlap and are separated by a small gap. When a coil surrounding the contact unit is energised, the electromagnetic field induces opposite magnetic polarities in the free ends of the reeds which cause the gap to close against the action of the elastic restoring force due to reed deflection. Metal-to-metal contact is thus established between the reeds. Because these components must provide long and reliable service, rigorous quality control is exercised during their manufacture and each completed contact unit is subjected to exhaustive laboratory testing. In addition, however, quite large numbers of contact units, selected at random from each production batch, are presented for prolonged service evaluation (accelerated life-testing) by repeatedly switching one of a number of specified electrical loads several times a second, in an endeavour to obtain an indication of the likely performance of the batch as a whole. For this reason, the Telecommunications Group of The Plessey Company Limited has constructed extensive life-test facilities [3] capable of monitoring, simultaneously, at a rate of 20 switchings per second, each individual switching operation of several hundred reed contact units. Detailed records of the performance of each contact unit, if necessary over as many as several million switching operations, are readily compiled.

The establishment of such comprehensive test facilities has led to the availability of large numbers of reed contact units of known life history, and this has presented an opportunity for the detailed study of contact erosion and metal transfer in such devices. The most severe life-test requirement for telecommunications purposes probably is that which involves the switching of a resistive circuit carrying 100 mA DC at 50 V. Certainly, a pip in the contact area of the cathode reed and a corresponding crater in the contact area of the anode reed are clearly visible after 10^6 such switching operations. Reed contact units typical of normal production, which had been subjected to this test, were chosen for the investigation described here, and for comparative purposes a small number of contact units which had exhibited below-average life-test characteristics were also included.

2. Experimental Technique

The topographical features of the eroded reed contact surfaces were examined using the Stereoscan scanning electron microscope, manufactured by the Cambridge Instrument Company Limited*. A detailed description of a scanning electron microscope, its working principles and its mode of operation, has been given by Oatley, Nixon, and Pease [4], and preliminary assessments of potential applications of the technique have been provided by Asbury and Baker [5], and by Minkoff [6]. The outstanding features of the microscope are its high resolution, 200 Å under optimum conditions, and its very great depth of focus, 300 times that of an optical microscope. The instrument therefore permits the examination of surfaces whose roughness, relief, or geometry would render extremely difficult or impossible their observation by more conventional techniques. Although the instrument may be used to provide stereoscopic photographic pairs, it was not necessary to utilise this facility in the present investigation.

The glass envelopes of the contact units containing the reeds selected for study were broken open using a sharp glass cutter and the reeds removed. Extreme care was exercised during this process not only to prevent glass debris from entering the contact region but also to ensure that no physical contact occurred between the two contact surfaces; this eliminated the possibility of mechanical damage. The reeds were mounted, contact face uppermost, on to small thin discs of aluminium using a proprietary cold-setting electrically-conducting glue. They were then examined using conventional optical microscopic techniques and certain of the more interesting eroded contact areas were selected for study by scanning electron microscopy. Prior to insertion in the scanning electron microscope, the specimens chosen were thoroughly cleaned; degreasing and rinsing was carried out in an ultrasonic tank, and drying was carried out in a dust-filtered atmosphere.

3. Results

A selection of the scanning electron micrographs recorded during the investigation is presented in figs. 1 to 11 inclusive. In all instances, the contact surfaces consisted of a 5 to 6 μm thick plated layer of hard gold† on a nickel/iron base.

The micrograph of fig. 1 clearly shows the extent and surface structure of a shallow crater which has formed in the anode reed of a contact unit which has performed 10^6 make and break switchings of a 50 V resistive circuit passing 100 mA. The crater was 0.3 mm long, 0.1 mm wide and approximately 6 μm deep. This contact unit had provided very satisfactory performance and no change at all in its contact resistance had occurred during the 10^6 switching operations. The crater is shown at higher magnification in fig. 2, and fig. 3 is a section of the right-hand edge of the crater at still higher magnification.

Fig. 4 shows the plateau-like mound which has grown on the cathode reed of the same contact unit from which the anode reed of figs. 1 to 3 was taken. The shape and size of the plateau corresponded very closely indeed to that of the crater. The closeness of the match may be better appreciated when it is realised that, for convenience of presentation to the scanning electron microscope, both reed members of a contact unit were aligned side by side, contact ends together. Thus, during operation of the contact unit it was the left-hand wall of the plateau shown in fig. 4 which fitted against the right-hand edge of the crater shown in fig. 2. A section of the left-hand wall of the plateau is shown at higher magnification in fig. 5.

The micrograph of fig. 6 clearly outlines the extent and surface condition of a large deep

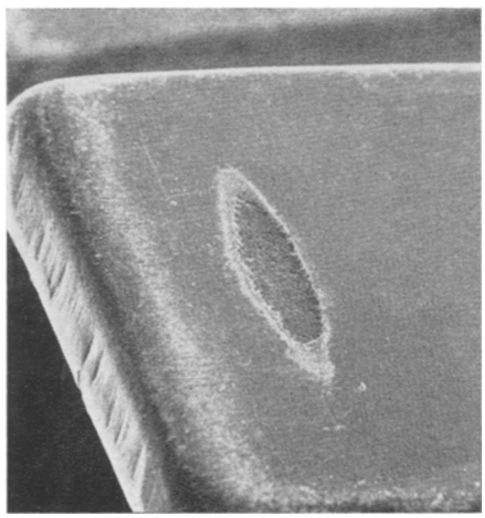

Figure 1 Crater in anode reed after 10^6 switchings of a 100 mA resistive load at 50 V. Reed performance satisfactory (×82).

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†The term "hard gold" is used to describe coatings obtained from proprietary acid gold-plating solutions in which a small quantity of an impurity metal is co-deposited with the gold. This has the effect of increasing the hardness of the deposit by a factor of two or more compared with pure gold deposits

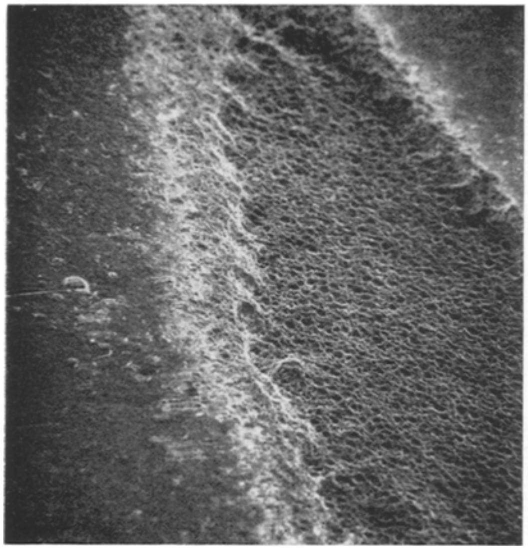

Figure 2 Crater in anode reed at higher magnification (×415).

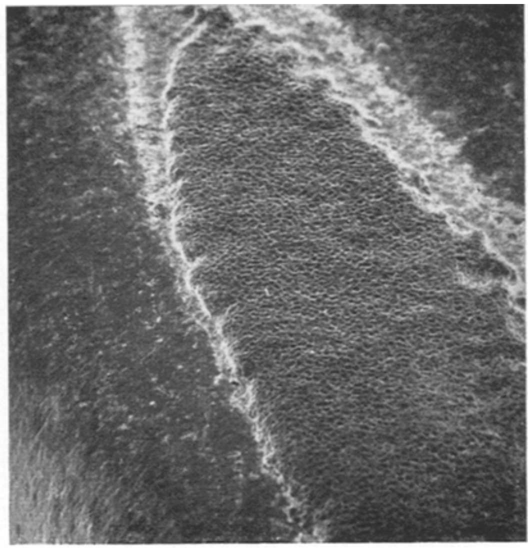

Figure 4 Flat plateau on cathode reed after 10^6 switchings of a 100 mA resistive load at 50 V (×381).

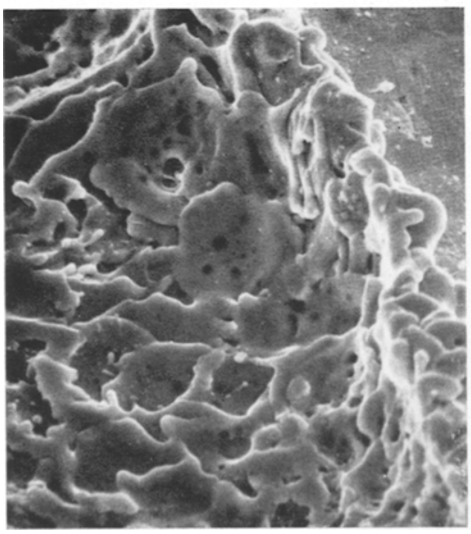

Figure 3 Edge of crater in anode reed (×4235).

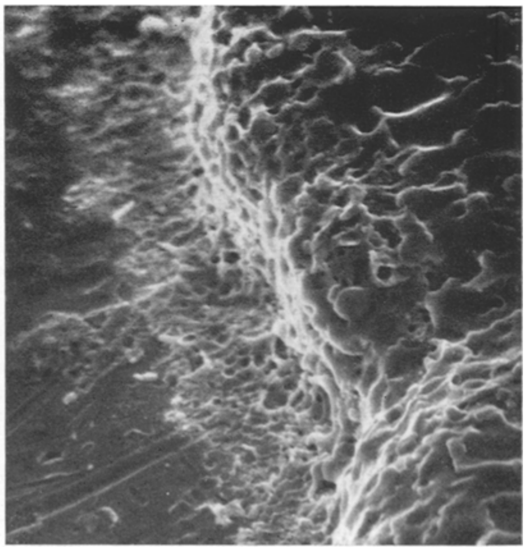

Figure 5 Edge of plateau on cathode reed (×3808).

crater which has formed in the anode reed of a contact unit which has performed 5×10^6 switchings of a 100 mA resistive load at 50 V. This contact unit had proved unsatisfactory in service having failed "stuck-shut" twice during progress of the life-test. The badly eroded area comprises a shallow crater of the type shown in fig. 2, in the middle of which a much deeper crater of about 60 μm diameter has formed. The contact area of the corresponding cathode reed is illustrated in fig. 7, and comprises a tall pip situated towards the centre of a shallow but extensive raised area or plateau of erosion damage. The pip and the surrounding plateau respectively fit the deep crater and the larger shallow crater of fig. 6 and, again allowing for a 180° rotational difference in viewpoint due to the method of presentation (in this instance the near wall of the plateau fitted against the far edge of the shallow crater), the "match" of the two

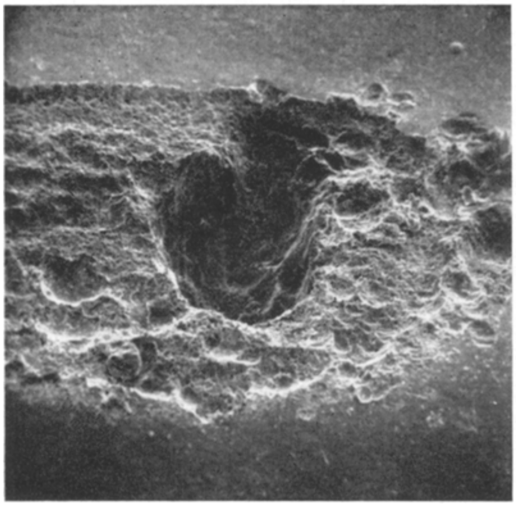

Figure 6 Deep crater in anode reed after 5×10^6 switchings of a 100 mA resistive load at 50 V. Reed performance unsatisfactory (×353).

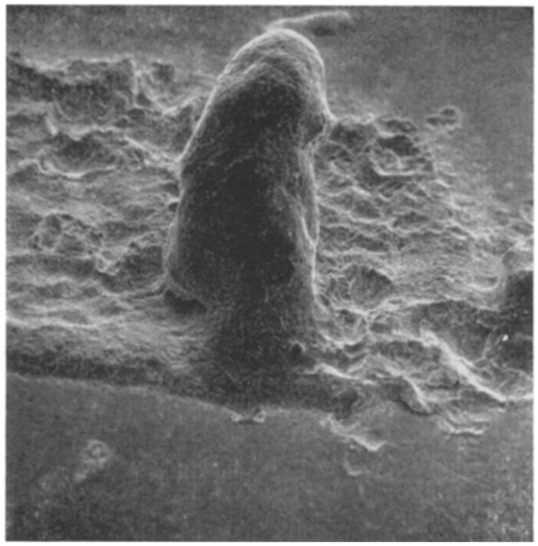

Figure 7 Large pip and low plateau on cathode reed after 5×10^6 switchings of a 100 mA resistive load at 50 V (×371).

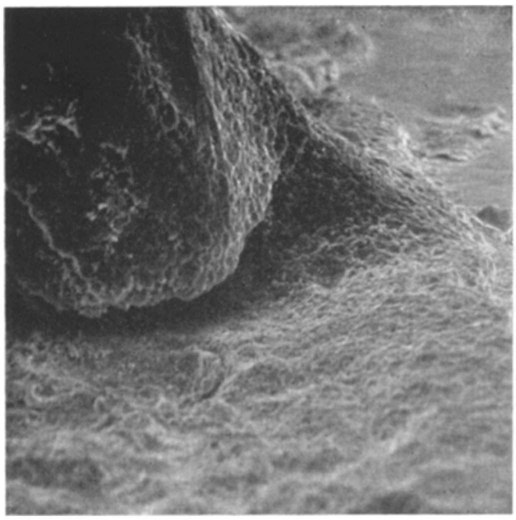

Figure 8 Plateau on cathode reed before removal of the large pip (×992).

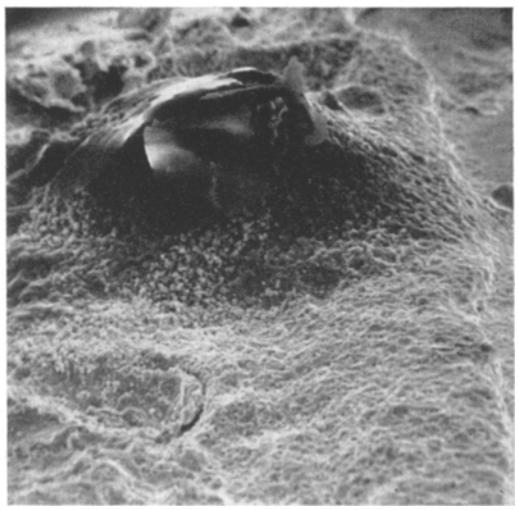

Figure 9 Plateau on cathode reed after removal of the large pip (×992).

surfaces is very good. The undercut appearance of the large pip at the left-hand side of its base suggested that it was not attached to the plateau over the entire apparent area of its base, but only over a much smaller area. In order to verify this, the reed was placed under an optical microscope and the pip was removed by striking its upper portion with a fine needle point. Re-examination of the reed by scanning electron microscopy showed that the pip had indeed only been attached to the underlying plateau over a very small area. This is clearly illustrated in figs. 8 and 9, taken at the same magnification and, as shown by the fine detail surrounding the base of the pip, from the same viewpoint. Fig. 8 shows the undercut base of the large pip in the region where it appeared to be attached to the low erosion plateau (a 90° anti-clockwise rotation of the specimen has been made with respect to fig. 7), and fig. 9 shows the same plateau region after removal of the pip. A few smooth strips of sheared metal cover the area where the pip was once attached.

Smooth patches are visible on the sides of the large pip (fig. 8), which roughly correspond in position to smooth patches observed on the crater walls, providing evidence that mechanical rubbing has occurred between the walls of the pip and those of the crater. This rubbing has increased the friction between the pip and the crater, possibly also contributing to the observed sticking of the contacts.

Evidence that satisfactory operation of a reed contact unit can continue, even after erosion has penetrated through the gold plating of the anode reed into the nickel/iron alloy beneath, is provided by the micrograph of fig. 10. The large flat plateau had formed on the cathode reed of a contact unit which has satisfactorily performed 8×10^6 switchings of a 100 mA resistive load at 50 V. It exhibits two distinct erosion areas;

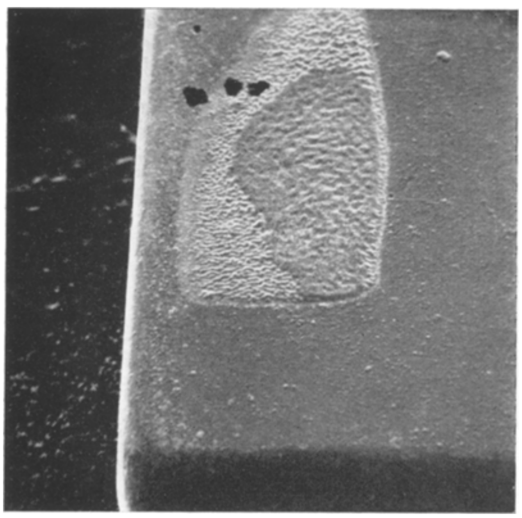

Figure 10 Plateau on cathode reed after 8×10^6 switchings of a 100 mA resistive load at 50 V, showing transfer of nickel and iron in addition to gold ($\times 96$).

differences exist both in topography and in tonal density. Variations in tone occur between elements due to their different abilities to reflect primary electrons and to emit secondary electrons. This variation thus indicates that metals of different atomic numbers comprise the two areas. Electron microprobe analysis of the erosion damage indicated that the lighter erosion area comprised pure gold and that the darker erosion area comprised nickel, iron and gold. Analysis of the corresponding anode reed indicated that erosion had only recently penetrated through the gold-plating of the anode reed to reveal the nickel/iron base and that transfer of nickel and iron to the cathode had just commenced. Consequently, a thin layer only of nickel and iron had built up on the raised gold erosion plateau on the cathode reed which had still not fully covered the plateau.

In contrast to the previous micrographs, fig. 11 shows the topography of a small (50 μm diameter) smooth-topped mound situated in a larger (150 μm diameter) shallow crater in the anode reed of a contact unit which has performed 10^5 switchings of an inductive load of 300 mA at 50 V. The circuit inductance was 400 μH. Extensive arcing had occurred during the break operations.

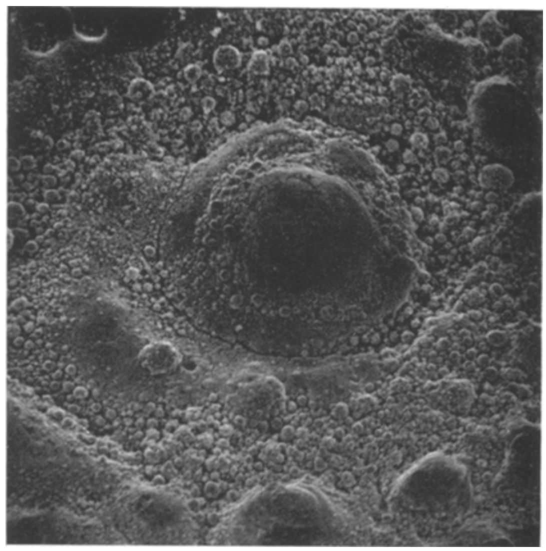

Figure 11 Small mound and surrounding crater in anode reed after 10^5 switchings of an inductive load of 300 mA at 50 V ($\times 700$).

4. Discussion

The micrograph of fig. 3 shows that the original gold-plated surface of this anode reed only a micron or so away from the crater edge has been entirely unaffected by the erosion process. The end of the crater is abrupt, and is characterised by a steep wall topped by a two-micron-wide built-up lip around the edge. Similarly, the micrograph of fig. 4 shows that the wall of the corresponding plateau on the cathode reed is very steep, and the plated surface just a few microns from the wall has once more been unaffected by erosion. These facts, together with the very close fit which exists between the plateau and the crater, tend to suggest that bridge transfer as opposed to arc transfer is the predominating erosion mechanism, since arc processes would tend to spread the transferred material and thus produce a more gradual slope for the pip wall [7]. The plateau is built up of layer upon layer of overlapping platelets of once-molten metal, the top layer being clearly visible in the micrograph. The structure of the base of the crater is similar to the surface structure of the plateau, and these overlapping-platelet-like structures tend to confirm the hypothesis that transfer is due to bridge mechanisms. At some time, each platelet has been in a molten state, and it would appear that these once-molten regions in turn constituted part of the metal bridges which were drawn out and initially spanned the gap between the reeds at the commencement of the break operation. Probably each platelet represents one break of the circuit. The platelets average 3 μm in diameter, and assuming that some spread of the molten metal occurred during its collapse after bridge rupture, the diameter of the molten metal bridges was probably nearer to 2 μm, indicating, if a single bridge carries all the current, a current density of 3×10^6 A/cm^2 at break. In certain instances it is possible that more than one bridge was formed at break, resulting correspondingly in the formation of several new platelets. Inevitably, some platelets must overlap those already there. One peculiar feature of the platelets is the presence within each of several minute holes. Also visible are a number of very small (less than 0.25 μm diameter) solidified globules of molten metal adhering to the surfaces of the platelets. It is likely that these globules are formed when a bridge explodes during rupture, and that they fall while still molten into neighbouring platelets and consequently adhere where they strike. The escape of gas, entrapped from the atmosphere of the reed contact unit at some stage during the formation or collapse of the bridge, could have been responsible for the small blow holes.

Examination of many reeds has shown that in all instances where the performance of a contact unit has been satisfactory, the form of the crater on the anode reed has always been that of a shallow dish, the crater of figs. 1 and 2 being typical, and the mound on the corresponding cathode reed has always been a large slightly-raised plateau, of which that of fig. 4 is typical. Evidence has been obtained from which it would appear that a good reed pair initially provide contact at several points, and that as erosion progresses, these areas grow and eventually coalesce, to form one very large but shallow erosion affected area. Erosion and transfer then continue slowly over the entire area, which may also gradually increase in size. As illustrated by fig. 10, this process continues even after erosion has penetrated through the gold plating of the anode reed into the nickel-iron alloy beneath.

When the performance of a contact unit has been unsatisfactory, the crater in the anode reed has always been very deep, with a correspondingly tall pip on the associated cathode reed. Reed pairs giving poor service either initially provide only one area of contact so that all the erosion and transfer of material occurs solely in this region, or alternatively erosion progresses normally up to the point of coalescence, whereupon at some later stage it becomes concentrated over a much smaller area. In several instances, evidence was found that a deep crater, similar to that of fig. 6, had in fact been initiated in the region of a flaw in the nickel/iron of the anode reed, erosion being concentrated around the flaw and following it deep into the reed. The micrographs of figs. 8 and 9, which clearly show that only a very small neck of material connects the comparatively large pip to the cathode reed, also tend to support this hypothesis. Here the pip initially grew slowly over a wide area. Later, probably owing to some unsoundness in the anode, erosion became concentrated in the region of the neck and the height of the pip then increased rapidly over that small area. Later still, after reaching sound material once more, erosion continued on a broader front and a massive pip was formed which overhung the neck quite considerably.

Two explanations are possible for bridge transfer of material from anode to cathode. Either both contacts have contributed equally to the bridge which has then broken, due to some temperature asymmetry within it, nearer to the anode, or alternatively the anode has become hotter than the cathode during the formation of the bridge and has therefore contributed more material to it, the bridge subsequently breaking at its mid point. Which effect predominates in practice is uncertain since much of the available experimental evidence is contradictory. Consequently, although many theories exist, neither causes of the temperature asymmetry within the bridge, nor reasons why the anode should get hotter than the cathode have been verified experimentally. Comprehensive reviews of the situation have been made by Llewellyn Jones [8] and by Holm [9]. Although the present investigation does not provide an explanation of bridge transfer, the reason for the concentration of erosion which occurs in certain instances appears to be fairly clear. Less heat can be conducted away from a hot spot sited in the vicinity of a flaw in the contact material than from one sited in a sound region of metal. The discontinuity of metal contact which occurs at the interfaces with fissures, voids, and non-metallic inclusions, not only results in a lack of thermal conductivity across them, but also reduces the total heat capacity in that region. Thus when a molten metal bridge forms near to a flaw in one of the contacts, that end of the bridge becomes the hotter, so that not only will the unsound contact contribute more metal to the molten bridge, but also the bridge will eventually break nearer to that end. If the flaw is in the cathode, then transfer due to this process occurs in the opposite direction to the natural transfer, and diminishes the overall erosion; if, however, the flaw is in the anode this transfer reinforces the natural transfer and greatly enhanced erosion takes place.

5. Conclusions

The primary mechanism of transfer experienced by reeds while switching a resistive load of 100 mA DC at 50 V, is one of molten metal bridge erosion, and not one of electric arc erosion. Evidence for this is provided by the abrupt steeply-rising edges to the pips and craters, by the exactness of the fit of erosion-damaged contact-surface pairs upon one another, and by the presence and nature of the numerous small platelets of once-molten metal which entirely cover the eroded region. Further support is provided by the fact that a high speed oscilloscopic study of the transient voltage waveforms, which appear across reed contact units during the switching operations, has failed to reveal evidence of arcing. Enhanced erosion leading to the early formation of tall pips and deep craters can, in certain instances, be attributed to defects in the underlying nickel-iron reed.

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