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THE INFLUENCE OF CORROSION INHIBITOR AND SURFACE ABRASION ON THE FAILURE OF ALUMINUM-WIRED TWIST-ON CONNECTIONS

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ABSTRACT

Aluminum wire splices made using constrained-spring twist-on connectors, without corrosion inhibitor, have been found to be failure-prone. Corrosion and poor initial conductor-to-conductor contact were determined to be major factors in the failure process. In this investigation, installation involving the use of inhibitor and aluminum surface abrasion are tested as possible ways of preventing the failures. The tests show that installation using inhibitor and aluminum surface abrasion results in low initial connection resistance and stable operation during two years of testing within rated conditions, a substantial improvement in performance. The initial resistance and long-term performance are compared for several combinations of the installation variables involving inhibitor and abrasion. Limitations of the inhibitor, potential problems from its use, and the need for standards for inhibitors for this application are discussed. (Key Words: Aluminum Wiring; Twist-on Connectors; Connectors; Splicing Connectors; Corrosion; Corrosion Inhibitor; Oxide Inhibitor.)

INTRODUCTION

Twist-on connectors are used for splicing the smaller sizes of branch circuit wire in buildings. Applications include circuit conductor splices and the connection of circuit wire to built-in appliances and lighting fixtures. The most common twist-on connector type consists of a conical spiral spring inserted in a molded plastic insulating shell. The inside of the plastic shell conforms to the shape of the spring, preventing it from expanding as the connector is tightened onto the conductor ends.

Twist-on connectors of this type are inexpensive, easily installed, and versatile with respect to the number and sizes of conductors accommodated. They are the most commonly-used splicing connectors for residential branch circuit wiring in the United States and Canada. According to package markings, most brands of these "constrained spring" twist-on connectors are rated for use with copper wire, aluminum wire, and combinations of the two.

The field performance of these connectors in applications involving aluminum and aluminum-copper combinations has not been satisfactory. A significant number of field failures is reported, with consequences ranging from nuisance to fire ignition.[1,2,3,4] Laboratory tests have shown that aluminum-wired twist-on connectors of this type are failure-prone even though installed according to the manufacturers' instructions and used within rated electrical and environmental conditions.[5,6] The failures involve overheating at the connections, destroying the insulation of the conductors and the connectors. In some cases, sections of the connector springs become red hot.

This paper presents initial experimental findings on aluminum-wired twist-on connections installed with the use of corrosion inhibitor, both with and without conductor surface abrasion. Since the previous work had identified corrosion and poor conductor-to-conductor contact as major factors in the failure of these connections, it is logical to test these means of improving connection reliability and safety.

BACKGROUND

The previous tests have shown that most of the current in aluminum-wired twist-on connections made without inhibitor or abrasion passes from conductor to conductor through sections of the connector spring.[5] Deterioration of both the conductor-to-conductor and the conductor-to-spring contacts occurs with time by several failure mechanisms. Sensitivity to atmospheric humidity was demonstrated by exposure to high-humidity environment, which resulted in rapid increases in connection resistance even with no current flowing.[6] The resistance increase is due to corrosion, which occurs at both the conductor-to-conductor (Al-Al or Al-Cu) and at the conductor-to-spring contacts.

Application instructions for the aluminum wire note that the installation instructions provided with the connectors must be followed.[7,8] Typically, the connector installation instructions call for stripping a given length of insulation from the wires, placing their ends together, pushing the connector on over the wires, and screwing it on by hand (no tool required). The instructions do not call for pretwisting of the wires, the use of inhibitor, or abrasion of the aluminum conductor.

Early experience with aluminum contact surfaces and terminations indicated that the use of inhibitor was a mandatory precaution against failure.[9,10] More recently, it has been claimed that inhibitor is not required for the residential branch circuit sizes of aluminum conductor terminations because the "current density is not high".[11]

The term "inhibitor" is used to describe the various materials sold for use on aluminum wire, cable, and busbar connections as "joint compound", "anti-oxidant", "connection aid", "oxide inhibitor", or other descriptions. The inhibitors are generally greases. Some contain particles whose purpose is to penetrate the aluminum surface under the mechanical pressure at assembly. The principal function of the inhibitor is to act as a barrier against ingress of oxygen and water (or water vapor). As such, they are corrosion inhibitors.

Instructions for the use of inhibitors often call for abrasion of the aluminum surface under a coating of the inhibitor. The purpose of the abrasion is to increase the amount of metallic contact at the interface by removal of the surface films. When the abrasion is accomplished under a coating of inhibitor, the fresh metallic aluminum surface areas will not reoxidize as quickly as they would if exposed to air.

To the extent that the abrasion is successful in cleaning the surface of the aluminum of corrosion film it should solve the problem of poor initial conductor-to-conductor contact. Long-term stability would then be enhanced by the additional number and larger sizes of the metallic conductive spots, together with the retardation of corrosion as a result of the use of the inhibitor.

EXPERIMENTAL METHOD

Connections Tested

The connections tested are two-wire splices of solid #12 AWG aluminum wire. The twist-on connectors are those identified as type "Z_1" in the previous tests.[5] According to the package markings, the connectors are rated for use with aluminum wire in both Canada and the United States. The conductors used are EC ("Electrical conductor") grade aluminum from a home in Toronto, Canada, and alloy aluminum conductor purchased from an electrical distributor in the United States. (These conductors were identified as types "Al #4" and "Al #3", respectively, in the previous tests.[6])

Connections are made in series-connected groups, consisting of 152 mm (6 in) lengths of conductor spliced together with the twist-on connectors. In addition to the insulation stripped from the conductor ends for the splices, a short length of conductor insulation is removed at a specific point along each section of wire to permit measurement of the potential drop of individual connection segments. All of the connections in a group are made in the same way, with the same conductor. The specific combinations of installation method and conductor for the various groups are shown later, with the experimental results.

All connections indicated as "hand" installed were tightened until there was a significant amount of twisting together of the conductors outside of the connectors. Connections indicated as "torque-wrench" installed were tightened to 0.46 Nm (4 in-lb) torque.

Two types of inhibitor were used. The inhibitor indicated as type "A" is a grease with suspended zinc particles, while the type "B" inhibitor does not contain metallic particles. The application of the inhibitors was accomplished by coating the conductors and also filling the connector spring cavity.

Conductor abrasion, when used, was accomplished after coating the bare conductor with inhibitor. The abrasive used was #240 silicon carbide paper. The coating of inhibitor was maintained during the abrasion operation.

Applied Electrical Conditions

The connections subjected to long-term testing are in a circuit powered by a conventional 115 Vac source, with resistive load. Current flows in the circuit for periods not exceeding one hour. Off periods are one-half hour minimum, and several days maximum. (The test system is energized only during normal working hours.) The applied current is 13.5 A, and the average duty cycle (portion of time that current is applied) is 13%.

Environmental Conditions

The environment for the long-term tests represents conditions within a junction or receptacle box in a residential perimeter wall. The temperature varies on a seasonal and daily basis, and has ranged from 6 C to 40 C. The relative humidity generally ranges between 40% and 60% during the year, with occasional higher values according to outside ambient conditions.

EXPERIMENTAL RESULTS

Two-Year Tests

Two groups of aluminum-wired twist-on connections made with inhibitor have been tested for two years. The connectors were installed by hand, and the use of the inhibitor and conductor abrasion (on one of the two groups) are the only significant differences in installation method compared with the twist-on connection groups previously reported.[5,6] The two-year test results are shown in Table 1. For comparison, a connection group made without inhibitor or abrasion and a copper-wired group are also shown.

The connections made with inhibitor and conductor abrasion have low average potential drop (connection plus conductor segment) and tight distribution. The potential drop is essentially dominated by the bulk resistance of the conductor. The measured potential drop of a reference conductor is used to estimate the connection resistance.[5] The average connection resistance for this group is found to be 0.07×10^{-3} ohm. The connections are stable, as the potential drop results are essentially unchanged in two years of testing within normal service conditions.

Connections made with inhibitor (type "A") but without abrasion of the aluminum conductor have higher initial potential drop and somewhat wider distribution. After two years, there is some increase noted in the average potential drop, and the distribution has broadened. The average initial connection resistance for this group is found to be 0.16×10^{-3} ohm, and after two years it is 0.28×10^{-3} ohm.

CONDUCTORS	NO. OF CONNEC-TIONS	INHI-BITOR	ABRA-SION	FAILURES initial/ 2-year	POTENTIAL DROP, mV @ 13.5 A initial/2-year			
					MEAN	STD. DEV.	MIN.	MAX.
Al-Al (EC)	20	yes	yes	0 / 0	17.6/17.6	0.84/0.81	16.4/16.3	19.5/19.2
" "	"	"	no	0 / 0	18.9/19.9	0.95/1.21	17.1/18.4	21.9/23.6
" (alloy)*	40	no	"	1 /10	23.9/25.6	2.90/4.07	18.0/17.4	30.0/36.3
Cu-Cu (#14)**	20	"	"	0 / 0	18.7/19.0	0.69/0.62	18.0/17.8	21.0/20.3

note: failures not included in potential drop data.

TABLE 1 - POTENTIAL DROP MEASUREMENTS, INITIAL AND AFTER TWO YEARS

*Comparison group (group "D", Reference 5)

**Comparison group (group "E", Reference 5)

The comparison groups were made in the conventional manner, without inhibitor or abrasion. The copper-wired group was identified as group "E" in the previous work.[5] After two years, there is essentially no change in potential drop of these connections. They are stable.

The aluminum-wired comparison group was identified as group "D" in the previous work.[5] After two years of testing, there are 10 failures (potential drop above 40 mV) out of 40 connections. The surviving connections show increased potential drop and very wide distribution.

Initial Resistance, Torqued Installation

Measurements have been made of the initial performance of groups of aluminum-wired twist-on connections installed with several combinations of treatment. As it was desireable to isolate the effects of the variables of surface preparation, the connectors were uniformly tightened with a torque wrench to 0.46 Nm (4 in-lb). This value of torque has been determined to be the approximate maximum that can be expected to be applied to the connector when hand tightened, as is the common installation practice.[4, 12] The measurement results for these groups are shown in Table 2.

Table 3 allows comparison of the initial resistance for the various installation methods. The groups wired with alloy aluminum show essentially the same results with respect to installation preparation as do those wired with the EC aluminum.

CONDUCTORS	INHIBITOR	ABRASION	INITIAL POTENTIAL DROP, mV @ 13.5 A			
			MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
Al-Al (EC)	type A	yes	16.9	0.49	16.2	17.9
"	"	no	18.0	0.52	17.3	19.2
"	type B	no	19.5	0.54	18.5	20.8
" *	none	no	20.3	1.23	18.0	22.5
Al-Al (alloy)	type A	yes	17.5	0.55	16.7	18.5
"	"	no	18.4	0.39	17.8	19.1
"	type B	no	19.8	0.46	18.9	20.7
" *	none	no	20.3	1.07	18.1	22.9

* 40 connections in group (all others in table are 20 per group)

TABLE 2 - INITIAL ~~RESISTANCE~~ Potential Drop, TORQUE-WRENCH INSTALLATION

INSTALLATION METHOD			AVERAGE INITIAL CONNECTION RESISTANCE mΩ	
TIGHTENING	INHIBITOR	ABRASION	Al-Al (EC)	Al-Al (alloy)
Hand	Type A	Yes	0.067	
"	"	No	0.163	
Torqued	"	Yes	0.041	0.015
"	"	No	0.107	0.070
"	Type B	No	0.211	0.185
"	None	No	0.266	0.196

TABLE 3 - INITIAL RESISTANCE OF ALUMINUM-WIRED TWIST-ON CONNECTIONS

DISCUSSION

Long-Term Results

The combined use of inhibitor and aluminum conductor abrasion results in low initial connection resistance and, within the time frame of the test, stable operation (Table 1). This is in marked contrast to the results obtained on the aluminum-wired connections installed without inhibitor and abrasion. In terms of resistance stability, these connections are equivalent to the copper-wired connections.

Application of the inhibitor with the metallic particles without abrasion does not have the same effect, either in initial resistance or long-term stability. While these connections are superior to those made in the conventional manner (without inhibitor or abrasion), the 75% increase in average connection resistance in two years of normal service conditions is not a favorable indicator of long-term reliability for an aluminum-wired connection.

Initial Connection Resistance

With inhibitor and abrasion, the initial connection resistance for both hand and torque-wrench tightened connections is of the same order of magnitude as previously determined for copper-wired twist-on connections (Table 3). The connection resistance is the combined parallel resistance of two current paths between the wire conductors. One path consists of the conductor-to-conductor contacts, while the other results from the conductor-to-spring contacts plus sections of the connector spring. The resistance of the latter path has been determined to be approximately 0.7×10^{-3} ohm in the newly-made connections.[5] This is a lower limit which is a function of the bulk resistance of the sections of the spring in the current path, and therefore it is not influenced (reduced) by the conductor abrasion. The order-of-magnitude lower resistance of these connections (Table 3) must therefore be due to low conductor-to-conductor resistance resulting from the abrasive disturbance of the surface films on the aluminum conductor.

Without abrasion, the connection resistances are higher. The type "A" inhibitor, with the suspended zinc particles, is not as effective by itself in achieving low conductor-to-conductor contact resistance as it is in combination with the abrasion (Tables 1, 2, and 3). That the suspended particles have some effect is demonstrated by comparing the results obtained with the two types of inhibitor without the conductor abrasion (Tables 2 and 3), although other differences in properties of the two inhibitors may be responsible for this effect.

The groups made with the type "B" inhibitor, without abrasion, have lower initial connection resistance and tighter distribution than the groups made without any inhibitor. This is possibly due to the effect of the inhibitor as a lubricant, since with a lower coefficient of friction the normal force between the conductors is expected to be higher for a given tightening torque.

Comparing the results obtained on the EC aluminum with those obtained on the alloy, the initial resistance relationships as a function of surface preparation are the same for both types. The higher potential drop of the alloy aluminum connections (Table 2), is due to the higher bulk resistance of the section of conductor included in the measurement. Reference conductor measurements indicate the alloy wire resistance (per unit length) to be 3% higher than that of the EC wire, resulting in approximately 0.5 mV higher potential drop in these measurements due to this factor. As seen in Table 3, the alloy aluminum conductor has lower connection resistance compared with the EC conductor. This may be due to the initial surface condition of the wire and/or the fact that the alloy wire is softer.

Effect of Inhibitor

Electrical conductor splices in permanent wiring must be predictably stable under normal use. Within the scope of these tests, the use of inhibitor is seen to have an important beneficial effect on the stability of the aluminum-wired twist-on connections.

It has previously been shown that atmospheric humidity has a strong influence on the failure of the aluminum-wired twist-on connections, indicating that corrosion is involved in the failure process.[6] The beneficial effect of inhibitor probably results from blocking the ingress of atmospheric moisture and oxygen.

Corrosion processes are not the only failure mechanisms involved, however. For instance, microscopic motions at the conductor-to-conductor and conductor-to-spring interfaces can lead to destruction of the metallic contact spots, increasing connection resistance even in the absence of oxygen. This points out the importance of achieving low initial connection resistance.

High initial resistance indicates a fragile contact, with few metallic contact spots at the interfaces, making the connection failure-prone even with the inhibitor. A high failure rate was demonstrated in heat cycle tests of aluminum to copper splices, using inhibitors but without abrasion, with twist-on and barrel (set-screw) connectors.[13]

Therefore, the use of inhibitor alone, without abrasion cannot be considered as a sufficient condition for long-term stability of the aluminum-wired twist-on connections. A sound initial conductor-to-conductor contact is required, and this is seen to be achieved only by the use of aluminum surface abrasion in this type of connection.

Requirements for Inhibitors

While the use of inhibitors can be beneficial, there are also potentially harmful effects. Some inhibitors will deteriorate plastic and rubber insulating materials. The lubricating effects of inhibitors can result in decreased mechanical security of conductors in a splice. Inhibitors can reduce the dielectric withstand capability of insulators, by surface conduction due to residual or flowed inhibitor. Some inhibitors are readily flammable. The choice of an inhibitor is not a simple matter, therefore, but such products today are not subject to performance qualification standards.

The successful long-term performance of an inhibitor depends on many factors. The inhibitor must be stable with respect to its primary function as a barrier to moisture and oxygen. Inhibitors must not dry out or oxidize. They must resist deterioration and flow due to the environmental constituents and temperatures to which they will be exposed in the anticipated service applications. Inhibitors must be chemically compatible with the materials of the connections, both metals and insulators. Qualification standards for inhibitors must be developed which take these and other factors into account. This is not a trivial task, but is necessary if uniformly satisfactory results with aluminum wire are to be achieved with twist-on connectors of the types presently rated for the application.

CONCLUSIONS

The results of these tests show that the combined use of inhibitor and aluminum surface abrasion results in lowest initial resistance of aluminum-wire twist-on connections and that the resulting connections are stable. To a limited extent, this result confirms by another method the previous analysis which identified poor conductor-to-conductor contact and corrosion as major factors in the failures of these connections.

The results point the way to installation methods by which this type of splicing connector might possibly be successfully used with aluminum wire. However, considering the number of types of twist-on connectors, wire combinations, and installation and electrical variables involved, considerable additional testing is required before one could claim that the problem is solved. Also, since the tests so far conducted with the aluminum-wired twist-on connections do not accelerate failures, long-term stability predictions must be determined by more strenuous testing. Finally, in order to achieve predictable results, appropriate standards must be developed for the inhibitors used.

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