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A Reasoned Approach to Solving Solderability Problems With Tin-Coated and Nickel-Coated Stranded Conductors in High Performance Wire and Cable Applications

NEMA

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A REASONED APPROACH TO SOLVING SOLDERABILITY PROBLEMS WITH TIN-COATED AND NICKEL-COATED STRANDED CONDUCTORS IN HIGH PERFORMANCE WIRE AND CABLE APPLICATIONS

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Table of Contents

Page

Foreword ii

Section 1 GENERAL
1.1 Scope 1-1
1.2 Referenced Standards 1-1
1.3 Other Referenced Publications 1-2

Section 2 A REASONED APPROACH TO SOLVING SOLDERABILITY PROBLEMS WITH TIN-COATED AND NICKEL-COATED STRANDED CONDUCTORS IN HIGH PERFORMANCE WIRE AND CABLE APPLICATIONS
2.1 Introduction 2-1
2.2 Discussion 2-1
2.2.1 Basics of Solderability 2-1
2.2.2 Conductor Coatings 2-2
2.2.3 The Effect of Processing History and Storage on Solderability 2-3
2.2.4 Solderability Test Methods and Performance Standards 2-3
2.2.5 Solder Fluxes 2-4
2.3 Conclusions 2-5
2.4 Recommendations 2-5

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Foreword

This standards publication has been approved as authorized engineering information.

This standard publication was prepared by the NEMA High Performance Wire & Cable Technical Committee, with input from insulating material suppliers, conductor manufacturers, wire and cable processors, solder flux manufacturers, and users of high performance wires and cables.

This publication and other NEMA standards for high performance wire and cable are periodically reviewed by the NEMA High Performance Wire & Cable Section for revisions considered necessary to keep them current with technological changes. Proposed revision should be submitted to:

Vice President Engineering
NEMA
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Section 1
GENERAL

1.1 SCOPE

This standards publication contains a review of solderability problems with tin-coated and nickel-coated stranded conductors, existing solderability standards, and a discussion of the root causes of these problems. This bulletin further contains recommendations which may supply solutions for specific applications. It is hoped that the review of this bulletin will provide the reader with a better understanding of the complexity of soldering tin-coated and nickel-coated stranded conductors in contrast to silver-coated conductors for high reliability applications.

1.2 REFERENCED STANDARDS

This standard used the references below in the development of this standard. Copies are available from the indicated sources.

DODSSP
Standardization document order desk
700 Robbins Ave, Bldg 4D
Philadelphia PA 19111-5094

MIL-STD-202	*Test Methods for Electronic and Electrical Component Parts* Method 208 — *Solderability*
MIL-STD-2000	*Standard Requirements for Soldered Electrical and Electronic assembly*
MIL-W-22759	*Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy*
MIL-F-14265	*Flux, Solder, Liquid (Rosin-based)*

ANSI
American National Standards Institute
11 W. 42nd St.
New York, NY 10036

ANSI/J-STD 002	*Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires*

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

ASTM B 33	*Tin Coated Copper Conductors for Electronic Applications*
ASTM B 298	*Silver Coated Copper Conductors for Electronic Applications*
ASTM B 355	*Nickel Coated Copper Conductors for Electronic Applications*
ASTM B 678	*Test Method for Soldering Metallic-Coated Products*

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Society of Automotive Engineers
400 Commonwealth Drive
Warrendale, PA 15096-0001

AS4373 *Test Methods for Aerosapce Insulated Electric Wire*
AS4461 *Assembly and Soldering Criteria for High Quality/High Reliability Soldered Wire and Cable Termination in Aerospace Vehicles*

British Standards Institute
2 Park Street
London W1A 2BS

BS 2G 230 *General Requirements for Aircraft Electrical Cables (second series)*

1.3 OTHER REFERENCED PUBLICATIONS

Solderability Testing of Military Specification Insulated Stranded Wire, TR-2467 January 13, 1992, Rex Beach, Naval Air Warfare Center, Aircraft Division, Indianapolis, IN

Solderability Considerations for MIL-STD-202 Method 208, NEMA meeting May 18, 1993 David Scheiner, Kester Solder Division Litton Industries, Des Plaines, Illinois

Eliminating Final Cleaning in Military Connectors, Interconnection Technology April 1993, James H. Moffitt. Naval Air Warfare Center-Aircraft Division, Indianapolis, IN

Heat Aging Evaluation of Common Coated Copper Conductors, 19th IWC Symposium December 1970, McCune, T.B.; Burn, J.H.; Busch, G.A.; Larson, D.J.

Effect of Thermal Aging on the Flexibility and Conductivity of Plated and Unplated Copper Conductors, 28th IWC Symposium November 1979, Inagaki, T.

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Section 2
A REASONED APPROACH TO SOLVING SOLDERABILITY PROBLEMS WITH TIN-COATED AND NICKEL-COATED STRANDED CONDUCTORS IN HIGH PERFORMANCE WIRE AND CABLE APPLICATIONS

2.1 INTRODUCTION

Although crimp connections are the predominant method employed for terminating stranded conductors in high performance applications, soldered connections are still required and used in certain areas. Traditionally silver-coated copper conductors have been used in these high performance applications and because of its excellent characteristics, solderability has not been a problem. However in recent years, with the increasing use of tin-coated and nickel-coated copper conductors, significant solderability problems have been reported. Focusing primarily on wire quality and conformance as the cause, substantial efforts have been made to review, modify and apply existing solderability requirements to address the problem. Consequently, stringent standards have been applied which were developed for use with terminal lugs and boards and not applicable to small diameter stranded wire constructions. Instead of solving the problem, this has further aggravated the situation by addressing the symptoms rather than the root causes. This report is intended to clarify the fundamental root causes of solderability problems through a review of the metallurgy of conductors, test methods and requirements leading to recommendations and solutions.

2.2 DISCUSSION

The reported problems with tin-coated and nickel-coated copper stranded conductors range from large visible pinholes in the solder coverage to a total dewetting at the solder joints resulting in mechanically weak and unreliable joints and high termination resistance. These problems have been observed both during soldering and pretinning operations. In some cases, visual examination prior to these operations did not reveal a potential for poor solderability. Further, these problems have been found to occur both between and within lots of wire and generally become worse with extended age. Similar solderability problems have also been reported during termination of tin-coated and nickel-coated copper braid shields.

To address this problem, reviews of existing solderability requirements and their application to stranded wire have been initiated. This effort was based on the assumption that the problems were due to manufacturing defects in the tin-coated and nickel-coated copper conductors and, therefore, the incorporation of solderability test requirements to insure product conformance became the primary focus of efforts towards a solution. Some solderability problems can and do occur as a result of improperly manufactured conductors. However, the fundamental root cause of most problems is a result of the basic metallurgical limitations of the conductor systems and the application of inappropriate solderability requirements for the specific conductor coatings employed.

2.2.1 Basics of Solderability

The objective of soldering is to obtain a joint termination which does not electrically or mechanically degrade the interconnect system. For this purpose the solder must wet the conductor and terminal surfaces creating a good metallurgical bond and avoid discontinuities which would increase electrical resistance and lower the mechanical strength.

In a soldering operation the conductor and terminal is heated to a temperature above the melt point of the solder material. The solder is then placed in contact with the surfaces and allowed to melt. A good metallurgical bond is formed when the solder material (tin, tin-lead, silver, silver-tin, etc.) is able to form a thin alloy or compound layer with these surfaces. In their pure state most metal and alloy surfaces can be readily joined in this fashion. However, metals in general have an affinity for oxygen and readily form oxide layers.

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These oxide layers inhibit the formation of a metallurgical bond and require fluxes which contain reducing agents to break down the oxide surfaces and allow soldering.

The degree and tenacity of the oxides vary with the metal or alloy. In the noble metals, such as silver, gold, and platinum, the oxides are extremely thin and are readily soldered without the use of fluxes. For this reason gold and silver coatings are used extensively for terminations in the electronics industry. Note however that gold has some drawbacks in that it may cause embrittlement of the solder connection. Intermetallic compounds, which are discussed later in this document, tend to form the most stable oxides and therefore require the most active fluxes with stronger reducing agents to obtain good solderability.

2.2.2 CONDUCTOR COATINGS

In high performance applications, silver-coated copper stranded conductors manufactured in accordance with ASTM B 298 have traditionally been used. With its high conductivity and resistance to oxidation, the silver-coating not only provides low termination resistance but excellent solderability over extended time. However in recent years stringent solderability requirements have been applied to tin-coated and nickel-coated stranded conductors. Due to the fundamental metallurgical differences in these conductors, similar solderability characteristics cannot be obtained utilizing the same soldering requirements which were appropriate for silver. These differences significantly affect solderability and must be considered in establishing appropriate solderability standards for the different conductor systems.

2.2.2.1 Tin-Coated Copper Stranded Conductors

Tin-coated copper stranded conductors currently being employed in high performance applications are manufactured in accordance with ASTM B33. Unlike silver-coated copper, tin-coated copper oxidizes readily with the reaction proceeding quickly under normal storage conditions (50 – 100°F) and less than 90% RH. Visual examination of the surface can reveal the degree of oxidation present. Prior to significant oxidation (bright metallic to light gray), the tin coating can generally be soldered using a rosin (type R) flux. However, within 6 months to one year depending upon storage conditions, a mildly activated rosin (type RMA) flux is required to obtain acceptable solder joints. In the later stages of oxidation (gray to dark gray) a fully activated rosin (type RA) flux becomes necessary to remove the oxidation. Note however, that type RA flux is not recommended for use on stranded wires, rather, one of the more active (but easier to clean) water soluble fluxes (WSF) should be considered. A complete description of the aforementioned fluxes can be found in MIL-F-14256. The degree of oxidation becomes a significant consideration because the wire being soldered and installed is frequently over one year old due to the many levels of manufacturing , distribution , and storage.

In addition to oxide formation, tin-coated copper is also susceptible to intermetallic diffusion reactions which significantly affect solderability. These reactions documented and published in the proceedings of the 1970 IWCS (International Wire & Cable Symposium – *Heat Aging Evaluation of Common Coated Copper Conductors*, McCune, T.B. et. al.), have been found to result in the formation of two intermetallic compounds.

The first (Cu_3Sn), is a high temperature phase which forms at about 105°C while the second (Cu_6Sn_5), is a low temperature phase which occurs at room temperature. These compounds are extremely brittle and not only present conductor breakage problems but severely inhibit solderability. Since these compounds result from diffusion reactions, the extent of formation will be a function of time and temperature. Of particular concern is the low temperature compound which will form under normal storage conditions resulting in a degradation of solderability with time. This phenomenon together with oxide formation is the root cause of the degradation of solderability in tin-coated copper stranded conductors and necessitates the use of activated fluxes to obtain reliable solderability.

The use of 4 to 5 times the normal tin coating thickness used in some component applications to extend the solderable life have been suggested. Although this is a possible solution for component solid lead wires,

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substantially thicker coatings for stranded conductors are not desirable. This is due to the increase in electrical resistance and possible occurrence of strand bonding which significantly reduces the flexibility and flex life. Further, the formation of intermetallic compounds and surface oxidation are not eliminated by the use of thicker coatings.

2.2.2.2 Nickel-Coated Copper Stranded Conductors

The nickel-coated copper stranded conductors currently used for high performance applications are manufactured in accordance with ASTM B355. Although historically limited to high temperature applications such as fire zone wiring and environmentally harsh areas, use in traditional hookup applications has grown due to its excellent corrosion resistant properties. Nickel-coating is extremely resistant to environmental corrosion due to the stable oxide which quickly forms on the surface as a protective barrier. This barrier, however, makes it extremely difficult to activate the surface resulting in poor solderability characteristics. Consistent soldered termination generally can only be achieved with a fully activated rosin or alternative flux and usually require higher soldering temperatures.

Solderability of nickel-coated copper conductors have not been required in most specifications. However, as these conductors become increasingly used in mainstream high performance applications, solderability issues are beginning to be raised. Solderability issues such as shelf life have been observed.

2.2.3 The Effect of Processing History and Storage on Solderability

Since both the rate of oxidation and intermetallic formation are temperature and time dependent reactions, the thermal processing and storage history can have a significant effect on solderability. Depending on the type of primary insulation and subsequent operations such as jacketing, striping and/or printing, the conductors can be exposed to heat in excess of the conductors' continuous use temperature rating. Individually, these operations may only result in exposure for short time periods. However, the effects on the conductor are cumulative and in the case of complex cable constructions incorporating many process steps, the total time can be significant.

Although the elevated heat exposure as a result of the process history will increase both oxide and intermetallic formation, the primary detrimental effect on solderability is the formation of intermetallics. This is due to the fact that after primary insulation the availability of oxygen to the conductor becomes limited. The intermetallic reactions, however, are only diffusion dependent and will continue. This is another reason why tin-coated conductors, which readily form intermetallic compounds, can exhibit poorer solderability when compared to silver coated conductors.

Wire in storage is subject to the same time and temperature effects as mentioned above. In addition, uncontrolled environmental conditions, such as high humidity, airborne contaminates, and outdoor exposure can further degrade solderability.

2.2.4 Solderability Test Methods and Performance Standards

2.2.4.1 MIL-STD-202, Method 208 – Solderability

MIL-STD-202, Method 208 is the primary test method employed for the solderability of all terminations in the U.S. as well as in some foreign countries. This method, originally developed for terminals, lugs, and component leads, is essentially a dip and look method with a visual acceptance criteria of 95% minimum coverage under 10X magnification.

The method has been modified to include insulated stranded conductors. It requires a one (1) hour steam aging prior to testing to simulate shelf life and allows only the use of a type R flux. Solid conductors will require an eight (8) hour steam aging. There are three basic problems with this method:

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1) The test procedure does not provide for material property differences between the different conductor coatings currently used.

2) The visual acceptance criteria is extremely subjective leading to contradictory interpretation of results.

3) The steam aging test procedure and equipment are not adequate to provide consistent results and has not been demonstrated to be quantitatively correlated to shelf life on stranded conductors.

MIL-STD-202 Method 208 allows only one test procedure for all types of conductors tested. With tin-coated and nickel-coated copper conductors, normal surface oxidation and/or intermetallic compound formation can result in test failures of properly manufactured products. The standard should recognize these differences and specify different types of fluxes and test conditions (time in flux and solder baths, solder temperature, etc.) for the different types of coated conductors tested. Further, this solderability test method frequently does not correlate to the actual soldering practices employed in end-use applications. These practices are often developed from experience with the specific conductor material being used. MIL-STD-202 Method 208 should be modified to reflect actual end-use soldering practices.

The visual acceptance criteria used in MIL-STD-202 Method 208 is inherently subjective. Although drawings and photographs are provided as reference standards, it is extremely difficult for the test examiner to differentiate between 90% coverage which fails and 95% which passes. In addition, visual inspection may not detect internal voids due to bridging of the solder which may lead to termination failures.

The steam aging test was incorporated into MIL-STD-202 Method 208 to provide assurance that the tested products would still be solderable after some period of time. Unfortunately the testing to date has not been able to demonstrate a conclusive correlation between the steam aging time and shelf life. Further, the variables inherent in the current covered beaker test procedure has resulted in repeatability problems.

2.2.4.2 Other Methods

2.2.4.2.1 BS 2G 230, General Requirements for Aircraft Electrical Cables

BS 2G 230 is widely referenced in European specifications and contains methods to measure solderability. The wetting balance method provides a measuring technique for solderability of solid conductors but may not be reproducible for stranded conductors. The globular method appears to be more widely referenced for measuring solderabity of stranded conductors. Additional work needs to be done in order to verify the utility of this latter method.

2.2.4.2.2 ANSI/J-STD-002 Solderability Test for Component Leads, Terminations, Lugs, Terminals and Wires

This document contains the MIL-STD-202 Method 208 as well as the wetting balance and globular method described above. This document states that there are no "established accept/reject criteria" for the wetting balance and the globular methods.

2.2.5 Solder Fluxes

A number of new soldering fluxes have been developed in the past five years to assist in solving soldering problems. It is suggested that consultations with flux manufacturers will provide assistance to the reader. This standard does not address the merits of the individual fluxes.

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2.3 CONCLUSIONS

a) Each type of conductor coating has different properties which can significantly affect solderability:

1) Silver coated copper conductors exhibit excellent solderability over time due to their excellent thermal stability and resistance to a detrimental oxidation.

2) Tin-coated copper conductors exhibit variable solderability due to oxidation. In addition, the formation of intermetallic compounds can contribute to poor solderablity.

3) Nickel-coated copper conductors are usually the most difficult to solder. Activated fluxes and higher soldering temperatures are generally required to achieve acceptable solderability.

b) Solderability requirements as currently set forth in MIL-STD-202 Method 208 cannot be met consistently over time for properly manufactured tin coated and nickel coated copper stranded conductors.

c) The visual acceptance criteria incorporated in MIL-STD-202 Method 208 is subjective and has produced misleading results. A quantitative method that is accurate and reproducible is still needed.

d) The steam aging test as specified in MIL-STD-202 Method 208 exhibits poor repeatability and may not provide a conclusive correlation with shelf life.

e) The newly developed alternate fluxes hold promise to overcome inherent solderability problems with tin-coated and nickel-coated copper conductors.

f) Users should recognize that tin coated and nickel coated wire undergo a continuous degradation in solderability over time.

2.4 RECOMMENDATIONS

a) The fundamental material properties of each conductor coating as well as the intended application requirements should be reflected in any solderability standard and/or test method. This should include variables such as fluxes, soldering temperature, and aging requirements as well as the quality of the solder connection required for the specific applications.

b) Alternative fluxes which have been specifically developed for different coated conductors should be incorporated into the solderability standards.

c) Any alternative solderability test method which yields a quantitative measurement should be fully investigated in order to verify reproducibility.

d) Steam aging may provide a means to evaluate shelf life of conductors. Current test equipment and procedures should be modified utilizing equipment which can produce precise and repeatable results. A test program utilizing such equipment should be initiated to determine shelf life correlation and establish realistic steam aging procedures and requirements.

e) Wire should be used as soon as possible in order to reduce the effects of storage on solderability.

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(Standardization Policies and Procedures, p. 1)

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(Standardization Policies and Procedures, p. 6)

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(Standardization Policies and Procedures, pp. 5)

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(Standardization Policies and Procedures, pp. 5)

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