AWS C3.15M/C3.15:2026
An American National Standard

Standard Methods for Evaluating the Strength of Soldered Joints



American Welding Society®



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Standard Methods for Evaluating the Strength of Soldered Joints

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Prepared by the
American Welding Society (AWS) C3 Committee on Brazing and Soldering

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This standard describes the test methods used to obtain the strength of soldered joints. Monotonic (unidirectional) and cyclic (fatigue) testing are considered in this standard. Sample geometries are described that allow for the application of stresses in tension, shear, bending moment, and peel configurations. Details are provided, which describe specimen preparation methods, soldering procedures, testing parameters, and methods for data analysis.

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Foreword

This foreword is not part this standard but is included for informational purposes only.

The American Welding Society (AWS) C3 Committee on Brazing and Soldering developed and maintains the specification on the mechanical testing of braze joints entitled: "AWS C3.2M/C3.2, *Standard Method for Evaluating the Strength of Brazed Joints*." This document provides guidance towards the standardization of test specimens and methods to allow for an accurate comparison of data obtained at different test facilities.

The requirement for a separate specification that addresses soldered joints arises from the latter having several properties that distinguish them from brazed joints. First, with very few exceptions, soldering filler metals have lower bulk strengths than the base materials used in typical soldered joints. Deformation and fracture take place almost exclusively within the joint clearance. Therefore, soldered joint strength is sensitive to its dimensions—joint clearance and footprint (area). Secondly, tin (Sn)- and indium (In)-based soldering filler metals are strain rate sensitive. As a result, the soldered joint strength is prone to be sensitive to test speed. Third, interface reaction layers, which are typically intermetallic compounds (IMCs), provide the bond between the soldering filler metal and the base material so that, together with the soldering filler metal and base material, determine the soldered joint mechanical strength. Fourth, soldering filler metals are used at relatively high homologous temperatures.[1] Their microstructures and thus, their mechanical properties, can evolve over time even when held at only room temperature.

Traditionally, the mechanical testing of soldered joints has been performed with a particular engineering application in mind. The base materials, filler metal, and in particular, the soldered joint geometry are developed to replicate that application to assure relevance of the data to the intended service. The drawback of this methodology is that soldered joint strengths are obtained from a wide range of test configurations and equipment parameters. Therefore, test data cannot be readily compared between different soldering filler metals, base materials, and joint clearances, to either optimize soldered joint design or provide consistent validation data for computational models.

The purpose of this specification is to provide the needed standardization of soldered joint testing. Monotonic (unidirectional) and cyclic (fatigue) testing are considered in this document. Sample geometries are described that allow for the application of stresses in tension, shear, bending moment, and peel configurations. Details are included in the text, which describe specimen preparation methods, soldering procedures, testing parameters, and methods for data analysis.

Comments and suggestions for the improvement of this standard are welcome and should be sent to the Secretary, AWS C3 Committee on Brazing and Soldering, American Welding Society, 8669 NW 36th Street, Suite #130, Miami, FL 33166.

[1] The homologous temperature, T_h, is defined as the ratio of the absolute temperature of the use condition over the absolute temperature of the solidus point. For example, 63Sn-37Pb soldering filler metal has a solidus temperature of 183 °C (456K). At 25 °C (298K), the T_h is 298K/456K, which equals 0.65. By comparison, a T_h of 0.65 would be equivalent to 814 °C for a nickel-based alloy having a solidus temperature of 1400 °C (1673K), hence, the analogy with the jet engine application.

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Standard Methods for Evaluating the Strength of Soldered Joints

1. General Requirements

1.1 Scope. The purpose of this document is to standardize the methods used to obtain reproducible strength data on soldered joints. Requirements are made with respect to base materials—metal alloy and ceramic; test specimen geometries; soldered joint clearance; test specimen fabrication processes; mechanical testing procedures; as well as data reporting and failure analysis. The standardization of these requirements will allow for the comparison of soldered joint strength data between different testing sources. The objective of this specification is to describe those standard requirements for design, process, reliability, and test engineers and operators.

The user will note that specific base material metal (alloy) and ceramic compositions are specified for the test specimens. This requirement was introduced, once again, with the objective of standardizing the mechanical test data. However, applications may arise whereby the user would deviate from these base material requirements in order to measure the effects on soldered joint mechanical strength caused by the combined effects of temperature cycling and dissimilar coefficients of thermal expansion (CTEs) between base materials or between the base materials and the soldering filler metal. Test documentation should reflect these deviations.

1.1.1 Printed Circuit Board Soldered Joints. This specification does not address the mechanical testing of soldered joints used on printed circuit boards (PCBs). The omission of this topic does not imply that the mechanical properties of PCB soldered interconnections are of lesser importance in soldering technology. Rather, addressing this specific category of soldered joints would require a separate set of requirements to address the sheer breadth of materials and design configurations that are used on PCBs. Such an effort was beyond the scope of this document. Nevertheless, the test procedures and analysis techniques, which are discussed in the following paragraphs, could be applied to the development of mechanical tests for PCB soldered joints.

1.1.2. Computational Modeling. Lastly, the level of rigor underlying the requirements in this specification will result in property data with sufficient fidelity to validate computational model predictions.

1.1.3. Control Documents. Control documents shall have the following order of authority from highest to lowest: instructions from the Organization Having Quality Responsibility (OHQR), assembly drawings, contract or purchase order contents, and this specification. The OHQR shall have the authority to make any modifications to the requirements in this document or other control document(s) and the responsibility to communicate those modifications to the relevant engineer(s), operator(s), or both. Any and all modifications to control documents shall be fully documented by the OHQR.

1.2 Units of Measurement. This standard makes use of both the International System of Units (SI) and U.S. Customary Units. The latter are shown within brackets ([ ]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system must be used independently.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard; some safety and health information is provided, but such issues are not fully addressed herein.

Safety and Health information is available from the following sources:

American Welding Society:

(1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

(2) AWS Safety and Health Fact Sheets

(3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

(1) Safety Data Sheets supplied by the materials manufacturers

(2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments or revisions of the publications may not apply since the relevant requirements may have changed.

American Welding Society (AWS) standards:

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*

AWS C3.2M/C3.2*, Standard Method for Evaluating the Strength of Brazed Joints*

AWS C3.3, *Recommended Practices for the Design, Manufacture, and Examination of Critical Brazed Components*

AWS C3.12M/C3.12, *Specification for Furnace Soldering*

ASTM International (ASTM) standards:

ASTM B488, *Standard Specification for Electrodeposited Coatings of Gold for Engineering Uses*

ASTM B689, *Standard Specification for Electroplated Engineering Nickel Coatings*

ASTM B700, *Standard Specification for Electrodeposited Coatings of Silver for Engineering Use*

ASTM B733, *Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal*

ASTM B734, *Standard Specification for Electrodeposited Copper for Engineering Uses*

ASTM C1161, *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature*

ASTM E8/E8M, *Standard Test Methods for Tension Testing of Metallic Materials*

ASTM E399, *Standard Test Method for Linear-Elastic Plane-Starin Fracture Toughness of Metallic Materials*

ASTM E2368, *Standard Practice for Strain Controlled Thermomechanical Fatigue Testing*

ASTM F19, *Standard Test Method for Tension and Vacuum Testing Metallized Ceramic Seals*

IPC International (IPC) standards:

IPC 4552B, *Specification for Electroless Nickel/Immersion Gold (ENIG) Plating for Printed Circuit Boards*

IPC 4556, *Specification for Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG) Plating for Printed Circuit Boards*

IPC 9701A, *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*

IPC-J-STD-004, *Requirements for Soldering Fluxes.*

SAE International standard:

SAE AMS 2750, *Pyrometry*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions,* provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

adhesion layer. Thin film or thick film layer deposited on a ceramic or glass base material surface to support adhesion between the latter and a thin film solderable or protective layer. The thin film adhesion layer can be deposited by physical vapor deposition, chemical vapor deposition, or a plating process.

aperture mask (shadow mask). Metal sheet having a pattern of openings or apertures through which is deposited thick film paste, soldering filler metal paste or, in the case of physical deposition processes, the passing through of evaporated or sputtered metal atoms to deposit on the base material surface with a desired pattern.

bulk (gold) embrittlement. The loss of ductility by tin (Sn)-based soldering filler metals when the concentration of a solute metal (e.g., Au, Ag, or Pd) exceeds the solubility limit upon solidification, resulting in the precipitation of a sufficient concentration of brittle intermetallic compound particles (e.g., Au-Sn, Ag-Sn, or Pd-Sn, respectively) so as to reduce the ductility of the soldering filler metal.

coefficient of thermal expansion (CTE) mismatch. Difference in CTE values between the base materials or between the base material(s) and soldering filler metal comprising the soldered joint. The CTE mismatch is categorized as global when it results from base materials of different CTE values and local when it results from different CTE values between the base material(s) and the soldering filler metal.

computed tomography (CT). Use of multidirectional, x-ray images compiled from a rotating source and detector so that, when compiled by computer software, provides a three-dimensional rendition of the object. The software can decipher two-dimensional slices from the x-ray data to target a particular plane in the object. The term, industrial CT, is frequently used to distinguish its use for industrial inspection as opposed to medical CT that is used in healthcare.

control document. Includes a contract, purchase agreement, consensus specification, or drawing, which identifies the requirements of the soldered joint.

creep rupture. Failure of a structure (soldered joint) caused by the time-dependent deformation of the base material(s) or soldering filler metal resulting from an applied stress or residual stress.

destructive physical analysis (DPA). The process of determining the acceptability of a material or a component that renders the material or component unusable in the future.

dewetting. The action of a molten soldering filler metal to initially wet and spread on the faying surface, but then retract, leaving molten solder filler metal in the form of mounds between which are discontinuous films that then undergo solidification.

diagnostic mechanical test. A time-independent deformation (stress-strain) test, which is performed at room temperature and subsequent to a monotonic or cyclic mechanical test, so as to reveal the fracture surfaces resulting from the latter tests.

fiber stress. Tensile or compressive stresses through the cross-section of a beam subjected to a bending moment.

galvanic corrosion. Corrosion process that occurs in one of two or more dissimilar metals that are in contact with one another in the presence of an electrolyte.

gold embrittlement. See bulk embrittlement or interface embrittlement but being specific to dissolved gold (Au).

hermeticity. Property of the joint to provide a non-permeable barrier so as to establish a hermetically sealed container.

high-cycle fatigue (HCF). Cyclic deformation is described as having a sufficiently high frequency or small strain amplitude so that the cycles to failure, N_f, exceed 10^4.

homologous temperature. Ratio of the service temperature to the solidus temperature of the soldering filler metal or base material when both are expressed in degrees Kelvin.

hot-solder dipping. The application of soldering filler metal coating, which serves as a protective layer, by immersing the base material into a bath of the molten soldering filler metal. (The legacy terminology is "tinning," which is not preferred because the molten soldering filler metal need not be pure Sn.)

hysteresis loop. Load-displacement graph (or stress-strain graph if the equipment is capable of the in-situ calculation) that is generated during isothermal fatigue testing.

interface embrittlement. Form of soldered joint embrittlement caused by the formation of an intermetallic compound layer at the soldering filler metal/base material or soldering filler metal/solderable layer interface. The intermetallic compound layer may form directly as a result of the above interface reactants or when a component of the soldering filler metal or dissolved protective layer solid-state diffuses to the interface to react with the base material.

intermetallic compound (IMC). Material of covalent bonding that is high strength, but as such, relatively brittle. The IMC can be a phase in the soldering filler metal or be a reaction product layer along the interface between the soldering filler metal and the base material.

isothermal fatigue. A form of cyclic (fatigue) deformation, high-cycle or low-cycle, that results from varying loads applied to the material at a constant temperature.

interlayer. A strip of material having the same footprint as the soldered joint, which is placed within the soldering filler metal to mitigate the residual stresses that develop between dissimilar base materials.

Kirkendall voids. Voids that form in the region of solid-state diffusion activity (e.g., interfaces) where the diffusion rates of two atom species moving in opposite directions is sufficiently different that the mass balance is maintained by the diffusion of vacancies that accumulate into voids at that region, but in the faster diffuser material.

liquid metal embrittlement. The embrittlement of a solid base material when placed in contact with a liquid metal.

load drop. Reduction in the load-bearing capacity of a soldered joint that results from the accumulation of cyclic (fatigue) deformation and cracking. Load drop is usually represented as a percentage of the load originally sustained by the soldered joint prior to cyclic deformation.

low-cycle fatigue (LCF). Cyclic deformation described as having a sufficiently low frequency or large strain amplitude so that the cycles to failure, N_f, were less than 10^4. The regime of low-cycle fatigue includes thermal mechanical fatigue (TMF).

mini-wave. Miniaturized wave soldering machine whereby the soldering filler metal wave has the form of a small fountain, typically 2 cm–3 cm in width in order to localize the soldering process.

non-wetting. A condition of a soldered joint in which the molten soldering filler metal does not form a metallurgical bond with the base material.

Organization Having Quality Responsibility (OHQR). The organization responsible to the end user of the product for the quality of the product and its suitability for the intended use. This organization is usually the manufacturer and marketer of the final product in commercial business and the prime contractor in government procurement. Although such organizations may subcontract soldering and related operations to others, they cannot delegate the ultimate responsibility for the service suitability of the product to these subcontractors.

physical vapor deposition (PVD). The deposition of a metal or alloy thin film using the processes of evaporation or sputtering.

plane strain fracture toughness (K_{Ic}). A measure of the resistance of a material to crack extension under predominantly linear-elastic conditions, that is, when there is little to no plastic deformation at the crack tip.

protective layer. A coating layer deposited on either the base material or a solderable finish to protect their solderability.

referee magnification. The referee magnification power is intended for use only after a defect has been determined but is not completely identifiable at the [standard] inspection power.

return-of-gold (Au). Solid-state diffusion of gold atoms back to the soldering filler metal/base material or solder/solderable layer interface, which were initially dissolved in the soldering filler metal at the time of the soldering process.

The returning Au atoms typically react with the base material or solderable layer atom to form an IMC layer to increase the risk of interface embrittlement.

shadow mask. See aperture mask.

solderable layer. A coating layer deposited on top of the base material to which the soldering filler metal will wet and form a metallurgical bond.

solder fountain. See mini-wave.

surface finish. A metal layer, which is deposited by hot solder dipping, plating, physical vapor deposition, or chemical vapor deposition, having one of the following roles: corrosion protection, solderable layer, protective layer, or cosmetic appearance.

tensile button. Tension strength and vacuum seal test specimen, the geometry of which, is defined by ASTM F19, *Standard Test Method for Tension and Vacuum Testing Metallized Ceramic Seals*.

thermal mechanical fatigue (TMF). A variation of low-cycle fatigue (LCF) in which cyclic deformation is established in the soldered joint by the combination of temperature cycling and a mismatch of coefficients of thermal expansion (CTEs) between different base materials ("global CTE mismatch") or between the base materials and the soldering filler metal ("local CTE mismatch").

thick film layer. A metal or alloy layer that is printed as a paste, dried, and fired to a ceramic or glass surface, which provides electrical signal conveyance as well as a solderable layer for soldered joint formation. The printing process is performed through an aperture mask or a screen.

4. Introduction

4.1 Mechanical Testing—Bulk Soldering Filler Metals. The material properties of the bulk soldering filler metal are critical input data for computational models. ASTM International (ASTM) and the International Standards Organization (ISO) have developed specifications to control specimen geometries and procedures for such testing. As such, bulk materials mechanical testing is not addressed in this document. The reader is referred to those documents for evaluating the mechanical properties of bulk soldering filler metals. The mechanical properties of the soldered joint cannot be directly calculated from the mechanical properties of the bulk soldering filler metal due in large part to the plane strain effect. The calculated soldered joint properties, which are based on the bulk properties of the soldering filler metal, are typically minimum values.

4.2 Mechanical Testing—Soldered Joints

4.2.1 Effects of Surface Finishes. Surface finishes are used to enhance the solderability of the faying surfaces on difficult-to-solder materials such as aluminum alloys, steels, refractory metals, ceramics, and glasses. The use of surface finishes introduces, not only the layer(s) of additional material to the soldered joint, but also interfaces between those materials, all of which, can affect the joint mechanical strength. The layers and interfaces must have excellent adhesion to support the overall mechanical performance of the soldered joint.

Surface finishes are introduced into mechanical test specimens for two reasons. The first reason is that a surface finish is required in the application that is being represented by the mechanical test program. The second reason is that the mechanical test program is evaluating base materials that have difficult-to-solder faying surfaces and thus, require surface finishes to support the solderability performance needed to make the soldered joint.

4.2.1.1 Surface Finish Methodologies. There are three surface finish methodologies:

(1) Protective Layer, Only. The protective layer assures the solderability of the base material that can be, otherwise, degraded by oxidation or contamination. The most common protective layer is gold (Au). Other candidate layers include silver (Ag) and palladium (Pd). Silver tarnishes (AgS) and Pd oxidizes (PdO) over prolonged storage times following deposition, which can lead to a degradation of solderability for the coatings.

The protective layer is dissolved into the molten soldering filler metal during the soldering process. The final metallurgical bond is made between the soldering filler metal and the base material. The dissolved protective layer can potentially alter the melting and solderability properties of the soldering filler metal during the soldering process. The dissolved protective