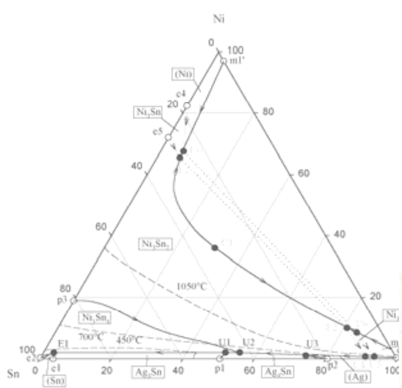
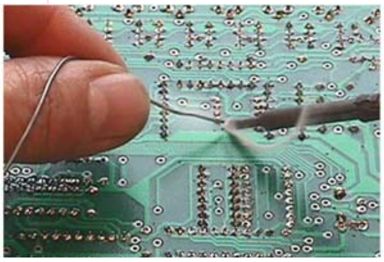
DATABASE
FOR
PROPERTIES
OF
LEAD-FREE SOLDER ALLOYS

Version 1.0





This database is a joint project of ELFNET and COST 531 Action.

**COST 531 ACTION
ON
LEAD-FREE SOLDER ALLOYS**

EURPEAN LEAD-FREE SOLDERING NETWORK

universität wien

soldertec global
your partner in lead-free technology

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Introduction

More than a decade of development has produced a significant amount of published and unpublished technical information on lead-free solder alloy properties - physical, mechanical and thermodynamic. However, these data have not yet been gathered and presented in a form that is convenient for users.

With COST Action 531 already working on a database for thermodynamic properties, there was found demand for a compilation of physical and mechanical properties, too. As this demand was in line with the Issues & Solutions Initiative of ELFNET, this database for physical and mechanical properties of lead-free solder alloys was developed as a joint project between COST Action 531 and ELFNET.

The focus of this new database is on physical and mechanical properties of solders and solder joints of lead-free solders. Comparability of data on solders is complicated by the fact, that only few standards for test methods exist and data were therefore produced by various different methods. In order to be able to judge data presented in this database, descriptions of the corresponding experimental techniques were also included. This database has been accordingly structured, with the first section containing descriptions of experimental techniques and the second one solder alloy properties.

This first version of the database exclusively concentrates on the Sn-Ag-Cu (SAC) alloy family. The SAC family was chosen because of its outstanding technological interest. So far data available in the literature and contributions from COST Action 531 have been included. Any data included in this database were included as provided by their authors.

This database would not have been possible without the help of Dr. Jeremy Pearce (Soldertec Global / ELFNET) and MEng. Usman Saeed (University of Vienna). Their assistance is therefore gratefully acknowledged.

Mag. Clemens Schmetterer, Prof. Adolf Mikula and Prof. Herbert Ipser
Department for Inorganic Chemistry / Materials Chemistry
University of Vienna
February 2006

For further information also visit the ELFNET homepage:
http://www.europeanleadfree.net

and the project website at:
http://www.europeanleadfree.net/POOLED/ARTICLES/BF_DOCART/VIEW.ASP?Q=BF_DOCART_178886

Information on COST Action 531 can be found at:
http://www.univie.ac.at/cost531/

NOTES ON THE DATABASE

o The database contains two main sections, *Experimental Procedures* and *Properties*, respectively. The following numbering system was established to assign the methods to the corresponding properties:

Letter + Number + Title

Letter: A … bulk solder measurements
B … solder joint measurements
C … solderability
D … finished boards

Number: Measurements of the same class (A, B, C or D) are numbered consecutively

Title: Title given to the method

Example: **B2 Push-off Shear Test**

o A lot of research work deals with the comparison of different solder alloy compositions and the Figures available in literature often contain curves for more than one alloy. As it was neither possible nor useful to split these Figures, a separate section on the comparison of solder-alloy properties was included, too. This section can be found after the regular *Properties* section. Please note, that in this section additional information on alloys, which are also featured in the regular *Properties* section, can be found.

USEFUL CONVERSION FACTORS

Mass:
1 lb_m = 0.45359 kg
1 kg = 2.20463 lb_m

Length:
1 in = 2.54 cm = 0.0254 m (exact)
1 ft = 30.48 cm = 0.3048 m (exact)

Density:
1 g/cm^3 = 0.036127 lb_m/in^3 = 62.428 lb_m/ft^3

Force:
1 lb_f = 4.4482 N (newton)
1 kg_f = 9.80665 N
1 dyne = 10^{-5} N

Standard Acceleration of Gravity, g:
g = 32.174 f/s^2 = 9.80665 m/s^2 (not to be confused with "gram", g)

Pressure (or Tensile stress):
1 Pa (pascal) = 1 N / m^2
1 MPa = 1 N / mm^2
1 psi = 6894.76 Pa = 6.89476 kPa
1 kps = 6.89476 MPa

Electrical Conductivity:
1 S (siemens) = 1 Ω^{-1} (reciprocal ohm)

Thermal Conductivity:
1 W/(m·K) = 0.5778 Btu/(ft·hr ·°F)

Energy:
1 cal = 4.187 J (joule)
1 Btu = 1055.056 J = 252 cal = 0.252 kcal (kilocalories)

Specific Heat (Capacity):
1 cal/(g·K) = 1 Btu/(lb_m ·F) = 4.187 J/(kg ·K)

Temperature and Temperature Intervals:
Fahrenheit temperature:
F = 1.8·°C + 32, (°C is Celsius temperature)

Kelvin temperature:
K = °C + 273.15

Temperature Intervals:
1 K (1 Kelvin) = 1 ºC (1 Celsius degree) = 1.8 ºF (1 Fahrenheit)

OTHER DATABASES AND USEFUL LINKS

Database for Solder Properties with Emphasis on New Lead-free Solders:

This database is administered by NIST, but was discontinued in 2002. It is available as an online version and a version for download from:
http://www.boulder.nist.gov/div853/lead%20free/solders.html

NPL database:

This is a smaller online database available at:
http://www.npl.co.uk/ei/iag/leadfree/propertiespbf.html

MPP 5.2 – Models and Methods for Lead-Free Reliability

Measuring and Modelling the Materials Properties Impact on Solder Joint Reliability; NPL - project
http://www.npl.co.uk/ei/research/mpp52.html

Open University – Solder Research Group:
http://materials.open.ac.uk/srg/

National Center for Manufacturing Sciences (NCMS):
www.ncms.org/main.html (general website)

The report of the Lead-Free Solder Project can be ordered at:
www.products.ncms.org/

International Electronics Manufacturing Initiative (NEMI):
www.inemi.org.cms
or
http://www.inemi.org/cms/projects/ese/lf_assembly.html (lead-free assembly project)

GENERAL REFERENCES

The following references are used frequently throughout the document and are therefore listed below:

[NCMS]	*Lead free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998*
[calc]	*calculated according to the COST 531 Thermodynamic Database (A. Dinsdale, A. Watson, A. Kroupa, J.Vrestal)*
[NIST]	*see: NIST Database for Solder Properties with Emphasis on Lead-Free Solders, Table 1.17*
[90Mas]	*T.B. Massalski, 'Binary Phase Diagrams', 2nd ed. (ASM International, Materials Park, 44073, OH, USA, 1990)*

Experimental Procedures

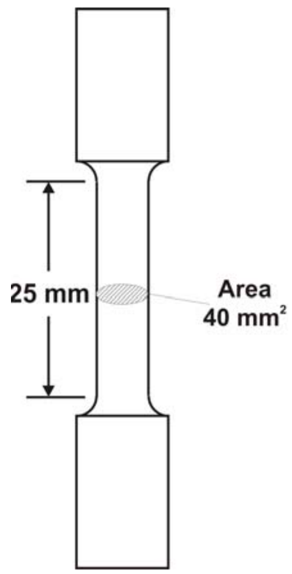
A1 Tensile Strength and Creep Resistance

(Bulk Solders)

Institution / Author: **International Tin Research Institute, ITRI**
Unit 3 Curo Park, Frogmore, St Albans, Hertfordshire, AL2 2DD, UK
Tel:+44 (0)1727 875544
Fax:+44 (0)1727 871341
Email: info@tintechnology.com
Web:www.lead-free.org

Reference: ITRI Publication No.656; Solder Alloy Data – Mechanical Properties of Solders and soldered Joints

Description: Tensile strength and creep resistance of bulk solder alloys were investigated using the specimen design shown in the figure below. Solder alloys were cast into 12.7 mm diameter rods. The pouring temperature was 50 °C above liquidus, and the mould temperature 10 °C above liquidus, for each alloy. The filled moulds were water-cooled from the base to induce uniaxial solidification and minimum piping within the casting. The rods were then machined into tensile test specimens to the dimensions shown.



All of the solder alloys that were prepared conformed to the limits for maximum impurity levels as specified in B.S.219: 1977 and other major national specifications on soft solder compositions.

Tensile strength
was measured using a variable crosshead speed, universal testing machine. Testing was performed at a uniform rate of extension until failure, while continuously recording the stress. The maximum force recorded during the test divided by the initial cross-sectional area of the parallel section gave the reported strength values.

Creep resistance

of the solder alloys was determined by stress-to-rupture tests on specimens by direct loading, with a known weight applied to the end of the specimens and recording the time to failure for a range of initial stress values. Both tensile and stress-to-rupture tests were carried out at room temperature and at elevated temperature (100 °C).

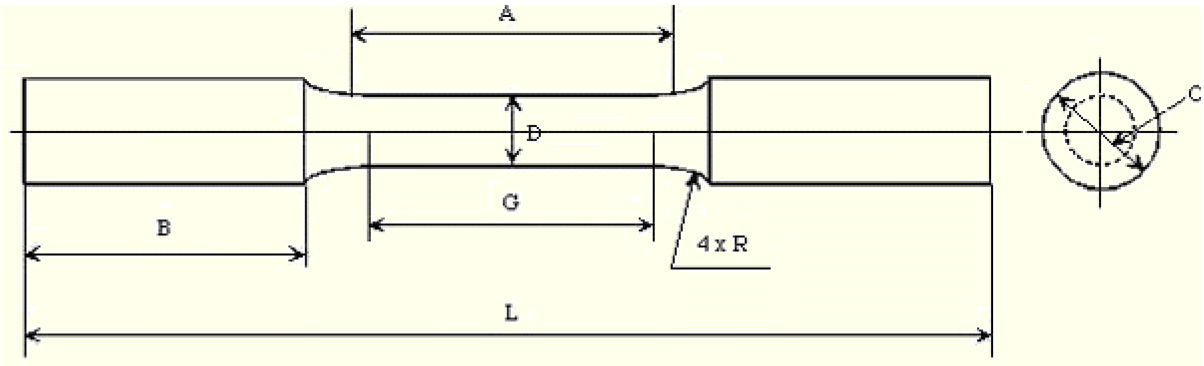
A2 Tensile Testing – NCMS

(Bulk Solders)

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Reference: Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998

Description: Tensile testing was employed to determine properties including elastic modulus, 0.2%-offset yield strength, ultimate tensile strength, uniform elongation, total elongation, strength coefficient and work hardening exponent.
First, uniaxial tensile testing was conducted to determine tensile properties of lead-free candidate solders. Some specimens were chosen and cast using an aluminum or titanium cast mould. They were then annealed for 16 hours at two thirds the melting temperature of the alloy to remove residual stresses from the casting. The figure below shows the geometry of the specimens used.



Nominal diameter **(0150)**
G = gage length **(1.250±0.005)**
D = diameter **(0.150±0.005)**
R = radius of fillet **(3/16)**
A = length of reduced section, min. **(0.25)**
B = length of end section, approximate **(0.75)**
C = diameter **(0.25)**
L = over-all length, approximate **(0.05)**

(units in inches)

The testing was done on an Instron tensile machine and an MTS 810 servo-hydraulic materials testing machine. The cross-head speed (or the actuator speed in the case of the servo-hydraulic machine) was set at 0.02 inch/minute, and the testing was conducted in the ambient environment.
An extensometer was used to collect strain data up to 20%, the limit of the device, before it was taken off the specimen. The test then continued until the load dropped below 5 pounds.

A3 Tensile Testing – J. Zhao

(Bulk Solders)

Institution / Author: J. Zhao et al.
Dalian University of Technology
116023 Dalian
Republic of China

Reference: J. Zhao, Y. Mutoh, Y. Miyashita and S.L. Mannan; J. Electr. Mater., Vol. 31, 8 (2002) p.879

Description:

Tensile tests were carried out using round specimens with a diameter of 7mm and a gauge length of 20 mm. Young's modulus was measured at a strain rate, where the initial slope of the stress-strain curve was no longer a function of the strain rate. Measurements were performed at strain rates of 0.04 sec^{-1} and 0.004 sec^{-1}. The values for Young's modulus were derived from the data at a strain rate of 0.04 sec^{-1}.

A4 Tensile Testing – K.S.Kim

(Bulk Solders)

Institution / Author: K.S. Kim et al.
Department of Adaptive Machine Systems
Osaka University
Yamadaoka 1-1, Suita, Osaka 565-0871, Japan
Tel.: +81 6 6879 8520
Fax.: +81 6 6879 8522
Email: kskimm12@sanken.osaka-u.ac.jp

Reference: K. S. Kim, S. H. Huh, K. Suganuma, Mater. Sci. Eng. A, 333 (2002), 106 – 114

Description:
Solder alloys prepared to the desired compositions were remelted at 300 °C for 1 hour and cast into a steel mould having a dumbbell shape for tensile specimens. They were cooled at three different speeds, 0.012 °C s^{-1} (slowly cooled, s.c.), 0.43 °C s^{-1} (mildly cooled, m.c.), and 8.3 °C s^{-1} (rapidly cooled, r.c.). The cooling speeds were measured as the average values from 230 to 180 °C. r.c. is equivalent to the cooling speed for soldering in practical conditions in industry and m.c. simulates soldering of some large components or printed wiring boards with a lot of heat capacity.
The dimensions of the gage section of the tensile test specimens were 2.0 mm thick x 4.5 mm wide x 24 mm long. Tensile specimens were polished with 3 µm Al_2O_3 powder and heat-treated at 100 °C for 30 minutes to remove residual defects. Tensile tests were carried out at room temperature at strain rates from 10^{-5} to 10^{-1} s^{-1} for the R.C. specimens, and from 10^{-4} to 10^{-2} s^{-1} for the S.C. specimens.

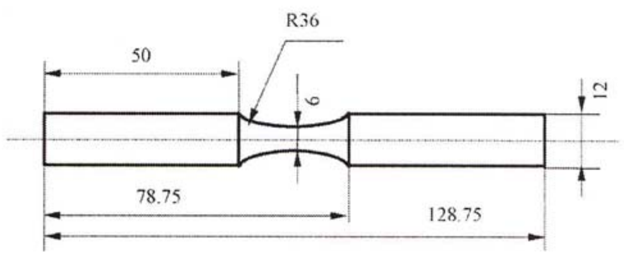
A5 Low Cycle Fatigue Testing of Bulk Solders

(Bulk Solders)

Institution / Author: C. Anderson et al.
Swedish Microsystem Integration Technology (SMIT) Center
Division of Electronics Productions
Chalmers University of Technology
c/o IVF, Argongatan 30, SE 431 53 Mölndal
Sweden

Reference: C. Anderson, Z. Lai, J. Liu, H. Jiang and Y. Yu; Mater. Sci. and Eng. A, 394 (2005) p.20-17

Description:
Alloys were prepared by vacuum-melting. Cast dogbone-shaped specimens with round cross-sections were used for the fatigue tests. The specimens were hand-ground and polished down to 1 µm diamond-finish (see Figure below).



The fatigue tests were performed under total-strain control, with strain ranges of 1, 2, 4 and 10 %. A triangular wave-form with a strain rate of 0.3 % s^{-1} was used. All the tests were carried out at room temperature and a 50 % load reduction was used as the criterion for failure. On an average, five to six samples were tested under the same conditions.

A6 Tensile Testing – Auburn University Method

(Bulk Solders)

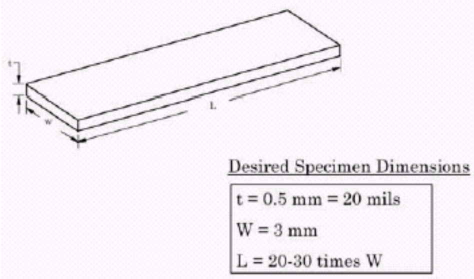
Institution / Author: Q. Wang et al.
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
Qing Wang, William F. Gail, R. Wayne Johnson
johnson@eng.auburn.edu

Mark Strickland NASA/MSFC, Jim Blanche NASA/MSFC/Allied Aerospace

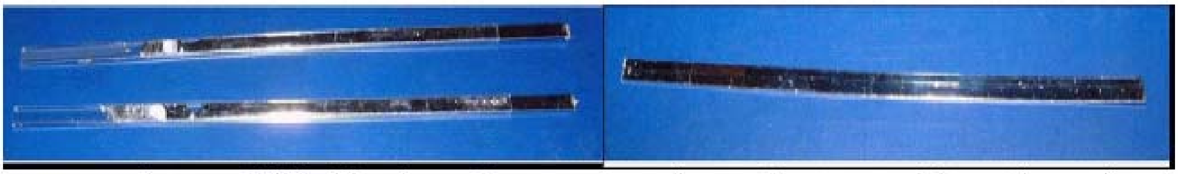
Reference: Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder'
In cooperation with: Mark Strickland NASA/MSFC, Jim Blanche NASA/MSFC/Allied Aerospace
June 24, 2005

Link: http://nepp.nasa.gov/DocUploads/B04F2DB5-001E-4F16-9B0190ABB573BD95/Pb%20Free%20Solder%20Report%20Draft%20R3%2D71305%2Epdf

Description:
For sample preparation commercial Sn-shot (purity 99.99 + %, 3 mm), Ag-shot (99.9 + %, 1-5 mm) and Cu-shot (99.5 + %, 0.5 – 0.8 mm) were mixed according to the specified composition ratios, and then combined with small quantities of flux (Kester Tacky Flux TSF-6522).
An special specimen preparation process has been developed using rectangular cross-section small glass tubes and a controlled vacuum system. The solder is melted in a quartz crucible (length = 120 mm, diameter = 19 mm) with a heating coil. A thermocouple and temperature control module were used to monitor and control the melting process temperature. After the temperature of the molten solder had maintained the desired temperature for five minutes the rectangular cross section glass tube connected to the controlled vacuum system was inserted into the molten solder and the molten solder was pulled into the glass tube. This tube was then immersed in oil or cold water immediately after filling. Once the sample had cooled to room temperature, the specimen was extracted. The Figures below show the dimensions of the specimens and the specimens themselves.
Compared with the dog-bone or casting specimens usually used, the thickness of the Auburn uni-axial specimen described here is close to the one of real CSP (0.25 - 0.5 mm) and BGA (0.5 mm) solder joints. This new specimen replicates the solder joint thermal history of typical electronic packages and also separates the specimen from the effects of other variables.

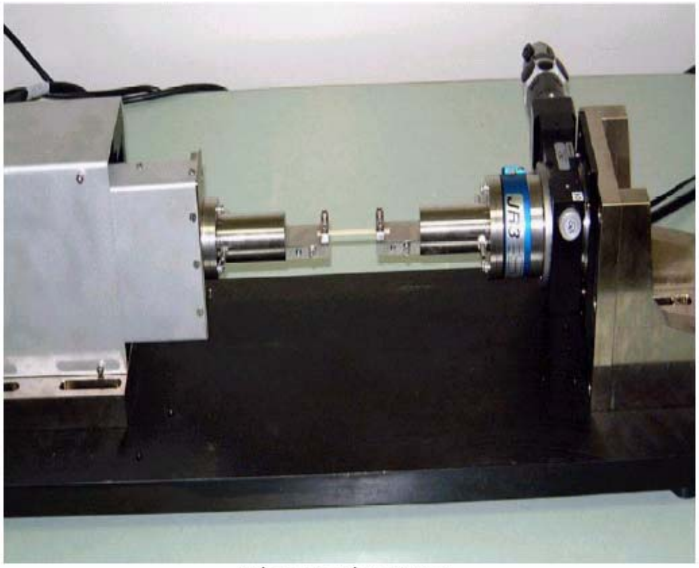


Auburn Uniaxial Specimen [22]



Specimen solidified in glass tube　　Specimen after removal from glass tube

Tensile tests were performed using the MT-200 tension/torsion thermo-mechanical test system made by Wisdom Technology Inc. shown below.



Micro Tension Tester

This system provides an axial displacement resolution of 0.1 µm and a rotation resolution of 0.001°. The testing machine utilizes displacement control. Load and displacement data were recorded and used to determine the true stress / true strain curve. True stress and true strain were calculated from the engineering stress and strain based on the conventional constant volume assumption.
At least five specimens were tested for each alloy composition at each set of conditions.

A7 Creep Test – Auburn University Method

(Bulk Solders)

Institution / Author: Q. Wang et al.

Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
Qing Wang, William F. Gail, R. Wayne Johnson
johnson@eng.auburn.edu

Mark Strickland NASA/MSFC, Jim Blanche NASA/MSFC/Allied Aerospace

Reference: Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder'
In cooperation with: Mark Strickland NASA/MSFC, Jim Blanche NASA/MSFC/Allied Aerospace
June 24, 2005

Link: http://nepp.nasa.gov/DocUploads/B04F2DB5-001E-4F16-9B0190ABB573BD95/Pb%20Free%20Solder%20Report%20Draft%20R3%2D71305%2Epdf

Description:
Samples were prepared according to the method already described in Section A6 Tensile Testing – Auburn University Method.
Creep tests were performed using an MT-200 tension / torsion thermo-mechanical test system for selected alloy compositions (Sn-4Ag-1.5Cu, Sn-4Sg-0.5Cu, Sn-2Ag-1.5Cu, Sn-2Ag-0.5Cu, Sn-3.5Ag-0.8Cu) for three conditions: as-cast; aged for 100 hours at 125 °C; and aged for 250 hours at 125 °C. The compositions of Sn-4Ag-1.5Cu, Sn-4Sg-0.5Cu, Sn-2Ag-1.5Cu, and Sn-2Ag-0.5Cu represent the four corners of the alloy range previously characterized for tensile properties, while the Sn-3.5Ag-0.8Cu alloy represents a mid-point and is close to the eutectic composition of the SnAgCu ternary alloy. Tests were conducted at three different temperatures (22 °C, 100 °C and 150 °C) at a range of constant stress levels (5 – 45 MPa). The applied stress was selected to be below the yield stress. A thermal chamber was used for creep tests at different temperatures. The temperature of the specimen was monitored and controlled by a thermocouple placed close to the center of the specimen. Each test was continued until the minimum true strain rate was identified. As expected, the creep specimens failed earlier at high applied stress and had a long quasi-steady-state at low applied stress.
In the study, each experiment was run twice to verify the test data reliability. At each aging condition (e.g. aging 100 h at 125 °C), there were at least 9 creep strain vs time curves generated from the experimental set up combination (3 temperature levels x 3 stress levels). Generally, high stress levels were selected for low temperatures, and low stress levels for high temperatures. Occasionally there were some scatter in the data for high stress levels because of tiny scratches at the surface of the specimens. There were a total of 135 creep strain rate vs stress data sets (5 alloy compositions, each with 3 aging conditions (as-cast, 100 h and 250 h at 125 °C aging), and each aging condition with 9 creep strain vs. time curves), which were conducted in order to evaluate the creep behaviour of the Sn-Ag-Cu alloy system.

A8 Tensile Testing – J. Madeni

(Bulk Solders)

Institution / Author: J. Madeni and S. Liu
Center for Welding, Joining and Coatings Research
George S. Ansell Department of Metallurgical & Materials Engineering
Colorado School of Mines
Golden, Colorado 80401, USA

T. Siewert
Materials Reliability Division, NIST
Boulder, Colorado 80305, USA

Link: http://www.boulder.nist.gov/div853/Publication%20files/NIST_ASM_Pb_free_casting.pdf

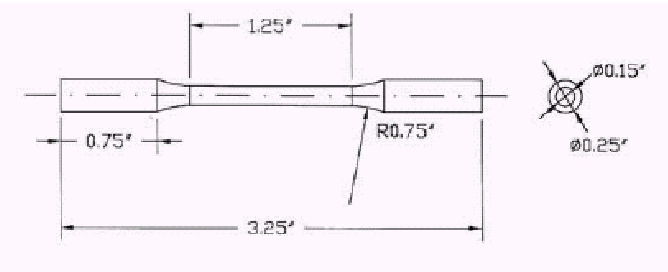
Description:

The bulk specimens were cast inside a cylindrical mould made of titanium, which was preheated to 150 °C above the melting points of the alloys. The mould was 5 inches tall (12.7 cm) with an internal radius of 1/4 inches (0.635 cm) and an external radius of 7/32 inches (0.556 cm). The resulting wall thickness of 0.03 inches (0.0762 cm) was thin enough compared to the internal volume of the mould to promote an efficient heat extraction during quenching.

The solder alloys were melted and maintained 100 °C above their respective melting point for 20 minutes in an argon atmosphere. A first set of specimens was quenched into water. The measured water temperature was 14 °C. All of these steps were in accordance with recommendations from the National Center for Manufacturing Sciences (NCMS – see: Lead-Free Solder Project CD-Rom, NCMS, June 1998).

For comparison, the other set of specimens was naturally air-cooled at ambient temperature (22 °C).

The tensile test specimens were produced from the bulk specimens after machining with the dimensions and geometry according to the drawing to the right. Once machined to their final dimensions, a polishing silicon carbide paper of 800 grit was used to reduce the surface roughness.



Geometric and dimensional configuration of the tensile test specimens.

Prior to the tensile tests, the specimens were annealed at two thirds of their respective melting temperature, for 16 hours. This moderate heat treatment relieved the stresses that were caused by the machining. As for the quenching procedure, tensile specimen preparation again followed the NCMS recommendations.

The tensile tests were conducted using a computer-controlled MTS system, equipped with one-inch extensometers. All the tensile tests were conducted with a cross-head speed of 0.01 in/min.

A9 Tensile and Fatigue Testing

(Bulk Solders)

Institution / Author: Chaosuan Kanchanomai et al.
Department of Mechanical Engineering
Nagaoka University of Technology
Nagaoka 940-2188
Japan

Reference: C. Kanchanomai, Y. Miyashita and Y. Mutoh; J. Electr. Mater., 31 (5) (2002) p.456-465

Description:
Solder alloys were supplied in as-solidified form.
Round specimens with a diameter of 7 mm and gage length of 20 mm were used for monotonic tensile testing. A strain rate of 0.04 mm s^{-1} was used for the tensile tests at 20 °C.
From bulk solder materials, fatigue specimens were machined on an NC lathe machine (see Figure below for dimensions).

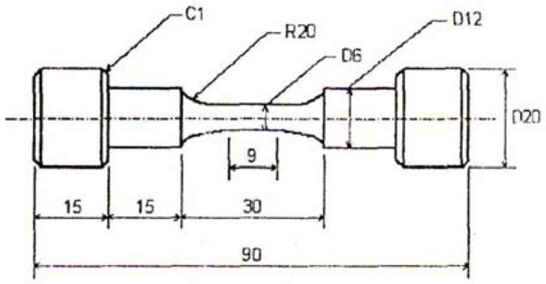


Fig. 2. Low-cycle fatigue specimen geometry (dimensions in mm).

The configuration of the specimen, which was designed according to the ASTM recommendation (ASTM Standards, ASTM E606: Standard Practice for Strain-Controlled Fatigue Testing; Philadelphia: ASTM, 1998; Vol. 03.01., p.525-539) has a diameter of 12 mm at the two ends, a center diameter of 6 mm, and a gage length of 9 mm with a radius of curvature of 20 mm to prevent any stress concentration due to sharp corners. In order to remove the deformation layer due to machining, the gage part of the specimen was electrolytically polished and left to fully age at room temperature for more than 30 days. Electrolytic etching was performed at room temperature with 8 DC voltage for 3 minutes in a solution of ethanol (80%) 800 mL, distilled water 140 mL, and perchloric acid (60%) 60 mL. The total strain-controlled fatigue tests were performed by using a servohydraulic fatigue machine with 2 kN load cell under 55 % relative humidity and a constant temperature of 20 °C. A triangular waveform with 0.1 Hz frequency and R = -1 strain ratio was used for the fatigue tests. The cycle loading was started from the tensile tests. The fatigue failure was defined as 24 % reduction of maximum tensile load.
In order to avoid the local deformation and stress concentration at the contact point induced by the conventional displacement-measurement system, a digital image measurement system was used in the present strain-controlled fatigue test.
With a 50 mm CCD camera lens and 200 mm working distance (between specimen and lens), the field of observation was approximately 10 mm in the longitudinal direction of the specimen, covering the entire gage length. The smallest displacement that the system can detect is 8 µm.

A10 Tensile Testing

(Bulk Solders)

Institution / Author: D.Q. Yu et al.
Department of Materials Engineering
Dalian University of Technology
Dalian 116024
PR China

Reference: D.Q. YU, J. Zhao and L. Wang; J. All. Comp., 376 (2004) p.170-175

Description:
Solder alloys were prepared from pure metals. They were melted in a vacuum furnace at 500 °C for several hours. The melt was chill-cast as an ingot in a Cu mould. The cooling rate of about 15 °C s^{-1} is close to the real cooling rate during reflow soldering.
Tensile tests were carried out on a CSS testing machine at a strain rate of 1.5 x 10^{-2} (no units mentioned! – *ed.*) at 298 K in order to get data on fracture elongation and tensile strength. Before testing, the samples were aged at 373 K for 5 hours.

A11 Thermal Cycling Testing

(Bulk Solders)

Institution / Author: Y.-H. Pao et al.
Research Laboratory
Ford Motor Company
Dearborn
MI48121-2053

Reference: Y.-H. Pao, S. Badgley, R. Govila and E. Jih, Mat. Res. Soc. Symp. Proc. Vol. 323, p. 128 (MRS 1994)

Description:
The double beam specimen consists of two beams, one Al_2O_3 and the other Al 2024-T4, bonded together at the end with solder joints. The specimen is 42 mm long and 5 mm deep. The thickness of the Al 2024-T4 and the Al_2O_3 beams are 3 and 1.2 mm, respectively. The solder joint at each end is 2 mm wide and 5 mm deep, and the thickness is 0.381 mm. Prior to making the joint, the areas to be soldered were sputtered with a thin layer of chromium (~200 nm) to increase the adhesion to the alumina and a 3 µm thick Cu layer. These areas were then fluxed and pretinned with the same solder used in the test.
Four high temperature strain gages were mounted on the aluminium beam, two on the inside surface and two on the outside surface, to measure the curvature and forces in the beam, from which the average shear stress and strain in the solder can be determined. In addition, a temperature sensor was bonded on the aluminium for the control of the temperature cycle.
To produce the solder joint, the Al_2O_3 and Al 2024-T4 beams were clamped together with two spacers (0.381 mm in diameter) inserted in between to form the gap for the solder joint to be made. One end of the specimen was first dipped into a molten solder bath for 5 – 7 seconds, removed and allowed to cool at room temperature. The solder bath was kept approximately 50 °C above the melting point of the solder. The same process was then repeated to form the solder joint at the other end. After the joint was made, the deformation of the specimen due to residual stresses in the solder joint was measured using a profilometer. The specimen was stored for a few days for stress relaxation and microstructure stabilization. The method used to determine the steady state creep properties of the solder assuming the behaviour to follow Norton's law has been delineated in *Y.-H. Pao, R. Govila and S. Badgley, Proceedings of the Joint ASME/JSME Conference on Electronic Packaging, Advances in Electronic Packaging (1992), Milpitas, California, p.291-299* and *Y.-H. Pao, R. Govila, S. Badgley and E. Jih, ASME Transactions, J. Electronic Packaging, 115 (1) (1993).*

A12 Tensile and Creep Properties Testing

(Bulk Solders)

Institution / Author:

Qiang Xiao
Department of Mechanical Engineering
University of Wyoming
Laramie
WY 82071

Luu Nguyen and William D. Armstrong
National Semiconductor Corporation
Santa Clara
CA 95052

Reference: Q. Xiao, Luu Nguyen, W. D. Armstrong, Electronic Component and Technology Conference

Description:

Test samples were cast by melt flowing the solders into a heated stainless steel mold followed by water quenching. Specimens were made to have a rectangular cross section of 12.7 x 1.58 mm and with a gauge length of 25.4 mm.

Each alloy was aged to a set of conditions. The aging temperatures were room temperature and 180 °C. The aging times ranged from as cast up to 35 days. Tensile tests were performed on a MTS 858 Mini Bionix II testing machine under displacement control. True stress and true strain were calculated from engineering stress and strain by the conventional constant volume assumption. The strain rate used was 1.78 x 10^{-3} l/sec.

Creep tests were performed on the same MTS machine under force control. Each sample was aged four hours at 120 °C in an air furnace before creep tesing. The temperature of the specimens was monitored by a thermocouple placed at the center of the gauge length. Temperatures remained constant within ±0.2 °C during the course of testing. The tests were carried out at 80, 115 and 150 °C.

B1 Shear strength and Fatigue Tests by the Ring and Plug Joint method

Institution / Author: **International Tin Research Institute, ITRI**
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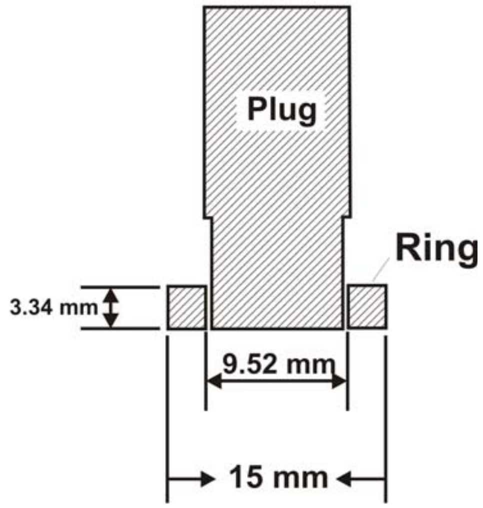
Reference: ITRI Publication No.656; Solder Alloy Data – Mechanical Properties of Solders and soldered Joints

Comments by the operator: The ring and plug joint is a solder joint configuration which allows to simulate the most commonly encountered stress situation, is producible under easily controlled conditions and gives reproducible test values.

This form of joint presents the least practical difficulties and can be made in an easily reproducible manner with minimum sensitivity to fabricating conditions. Using components of small dimensions the mass of the assembled joint is sufficiently low to ensure that the rate of heating during soldering approximates to that, which is encountered in normal soldering practice.

In order to control the uniformity of the joint gap, spacer wires were incorporated in the joint gap prior to soldering. The presence of these non-wetting spacing wires did not have a significant effect on joint strength.

Description: The components of each joint were degreased in organic solvent and chemically etched for 10 seconds in either 50% HNO_3 for copper joints or a 'bright dip' solution (130 H_2SO_4 : 25 HNO_3 : 1 HCl : 144 H_2O – volume ratio given) for brass. After washing, rinsing and drying the joint components were fluxed using a 10% solution of HCl (S.G. 1·16) in glycerol. The joints were then assembled, spacer wires added in order to control the joint gap and the whole assembly was then dipped in solder at a temperature of 50 °C above the liquidus of the solder alloy. After the soldered joints had cooled they were machined to the required dimensions, including the removal of the solder fillets. It has been shown that the joint manufacturing technique described enables the production of joints free from voids and flux entrapment within the solder.



Shear Test:

The majority of testing was performed on the ring and plug joints shown in the figure above, with a soldered joint area of 100 mm^2. Tensile testing of the joints was carried out using a universal testing machine to impose tensional shear stress on the solder. This gave shear strength values for each alloy over a range of testing speeds from 0.05 to 50 mm min^{-1}. Strength is expressed as the maximum load measured during extension to failure divided by the original joint area (nominally 100 mm^2).

Fatigue Tests

These were carried out using the universal tensile testing machine. Cyclic compression / tension was imposed on the joint between pre-set stress levels at a constant testing speed and the number of cycles to failure was recorded. Most testing was performed at a strain rate (crosshead speed) of 0.2 mm min^{-1} with a mean stress of zero.

All test were carried out at 20 °C and at elevated temperature (100 °C).

B2 Push-off Shear Test

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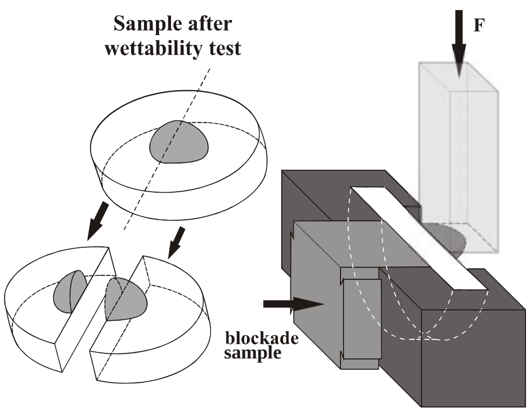
Reference: N. Sobczak, J. Sobczak, R. Nowak, A. Kudyba, P. Darlak; J. Mater. Sci. 40 (2005), p.2547-2551

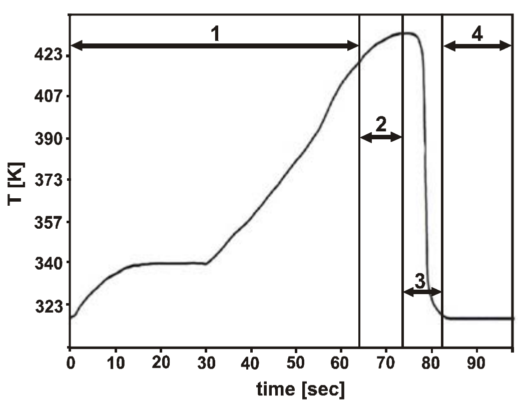
Description:

The materials used were Cu substrates and several Sn-alloys. Directly before wettability tests, the Cu substrates were polished up to an average roughness of a few nano-meters while the Sn-alloy samples were cleaned mechanically and next both Cu substrate and Sn-alloy samples were cleaned ultrasonically in acetone.

For the push-off shear tests samples from the C1 wettability tests were used.

Solidified sessile drop samples were adopted as model Sn-alloy/Cu joints for bond strength measurements using improved push-off shear test, schematically shown in the Figure below left. The drop/substrate samples were carefully cross-sectioned at the mid-plane of the contact circle perpendicular to the substrate surface and polished. The first half of each sample was used for shear test while the second half of the same sample was thermally cycled (1000 cycles according to temperature profile shown in the Figure below right), and afterwards sheared in the same way as the first halves of each sample.
In the improved push-off shear test, the sample is placed in a holder of special design and loaded in an INSTRON 1115 machine. A load was applied to the flat end of the bisected couple at a constant rate of 1 $mm.min^{-1}$ and the load versus displacement data were digitally recorded until failure under shear occurred. Assuming uniform distribution of shear stress along the line during the push-off test, the shear strength was calculated by dividing the maximum load with lateral interface area estimated from geometry of the drop/substrate contact under ×10 magnification.





B3 Creep Testing of Solder Joints

Institution / Author: H.G. Song et al.
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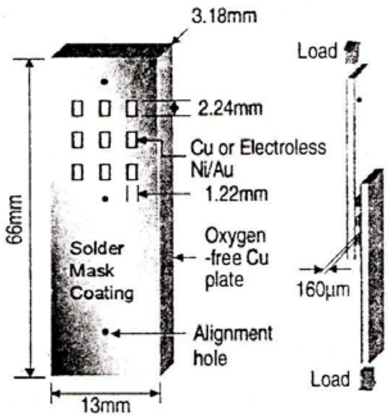
Reference: H.G. Song, J.W. Morris and F. Hua, JOM, 54(6) (2002) p.30-33

Description:

Solder Alloys were prepared by melting 20 g ingots from pure (99.999% in metallic base) elemental starting materials. After melting, the alloys were homogenized for 55 hours at 180 °C, and then cold-rolled into foils of about 155 µm thickness. Creep tests were done on nine-pad single shear creep specimens shown in the Figure to the right. The joints were made between dissimilar substrates (as is common in industrial practice); the pad metallization on one side was copper while that on the other side was about 4 µm electroless nickel coated with about 0.13 µm immersion gold. The shear specimens were reflowed in nitrogen with a peak temperature of 235 °C. Samples were cooled at the rate of 2.7 °C/s, followed by aging at 160 °C for 4 hours.



Creep tests were done in a dead-load machine with the temperature controlled by an oil bath. The shear stress was measured as load divided by the solder-substrate contact area (total area of the wetted pads). The shear strain (simple shear) is the relative displacement of the sample plates divided by solder joint thickness. Creep tests were conducted until steady-state was reached and passed, and the reported creep rates were the steady-state creep rates. Samples were tested at three different temperatures: 60 °C, 95 °C and 130 °C, and at five different load levels at each temperature.

B4 Ring and Plug Shear Strength Measurements

Institution / Author: J.C. Foley et al.
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Ames,
IA 50011

Reference: J.C. Foley, A.Gickler F.H. Leprevost, D. Brown; J. Electr. Mater., Vol. 29, No. 10 (2000) p.1258

Description:
Solder alloys were manufactured by Johnson Manufacturing with their standard industrial alloy practice. The rings and plugs were machined to the dimensions illustrated in Fig.1. The joint gap of 175 µm was chosen after several tests by Johnson Manufacturing showed that this gap was less likely to produce microporosity of the lead-free alloys. The machined ring and plugs were cleaned using an acid etch (ITRI formula) and rinsed thoroughly with deionised water, then with alcohol. A perform of solder was made for each ring and plug sample. Flux (Johnson #1) was applied by dipping all parts in a beaker containing flux. The assembled ring and plug were moved to a hot plate where additional flux was added with a brush as needed. The samples were heated to a maximum temperature of 350 °C at about 1 °C / s to ensure that a solid joint was made. After soldering the samples were placed on a heat sink to cool to room temperature at about 1.5 °C / s. It should be noted that spacing wires were not used in this work, because of the problems they appeared to induce in the sample joint integrity. Moreover, the relatively high soldering temperature appeared to be necessary to obtain a completely solid joint. Although the lack of spacing wires did produce some joints with varying thickness, the results obtained were relatively constant.

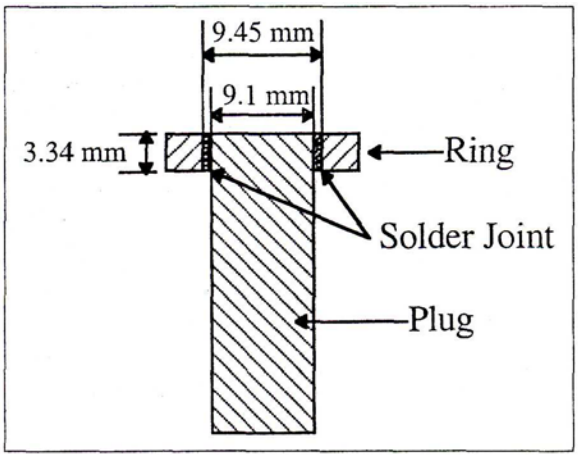

Fig. 1. Diagram of the ring and plug sample configuration used in this study.

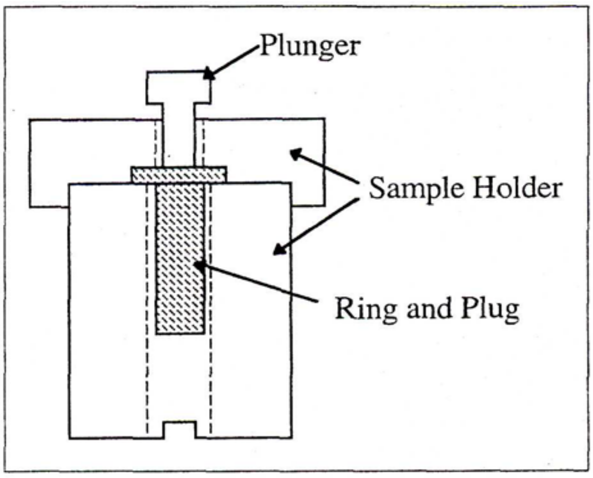

Fig. 2. Diagram of the ring and plug holder used in this work.

The samples were tested using the test fixture pictured in Fig. 2. The test fixture ensured a consistent set up was achieved during each test. In addition, the test fixture reduced the risk of having off axis loading occur. Samples were tested at room temperature and 125 °C at a displacement rate of 0.1 mm / min.

B5 Shear Force Tests

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Jangan-gu, Suwon 440-746
South Korea

Reference: J.W. Kim, S.-B. Jung; Mater. Sci. Eng. A, 371 (2004) p.267-276

Description: Solder balls of BGA solders having a diameter of 500 µm were used in this study. The substrate was a bismaleimide triazine (BT) laminate with subsurface solder bond pads whose nominal size and shape were defined through a circular opening of 460 µm diameter. The pads comprised electroplated Au over Ni over an underlying Cu pad in thickness of 0.5 and 7.0 µm, respectively. The solder balls were bonded to the substrate in a reflow process employing RMA flux in an IR four zone reflow machine (RF-430-N2, Japan Pulse Laboratory Ltd. Co.) with a maximum temperature of 255 °C for 60 seconds.
Shear force tests were conducted using a global bond tester (Dage-4000s, Richardson Electronics Ltd.) in various shear speeds with a fixed shear ram height of 50 µm, minimum shear probe height recommended by JEDEC standard. Shear test conditions of this work are given in the table below.

Table 1
Examined shear speeds with a fixed shear ram height of 50 µm

Shear ram height (µm)	Shear speed (µm/s)							
50	10	50	100	200	300	400	500	700

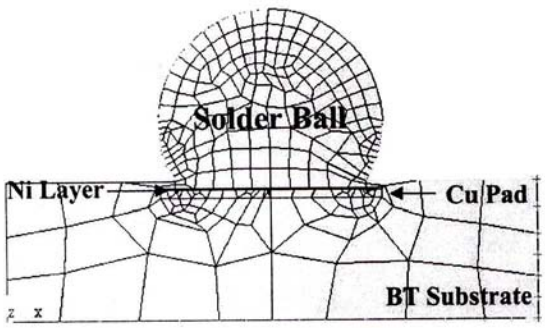

Fig. 1. Cross-sectional view of a reflowed Sn–3.5Ag–0.75Cu solder joints (a) and finite element model for ball shear test (b).

B6 Low-Cycle Fatigue Testing of Solder Joints

Institution / Author: C. Anderson et al.
Swedish Microsystem Integration Technology (SMIT) Center
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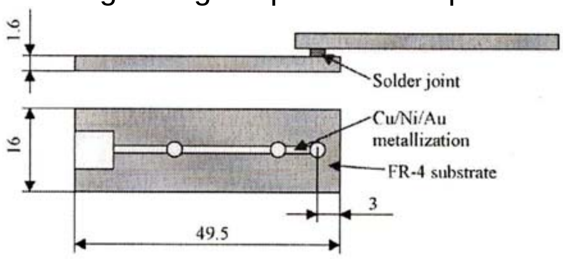
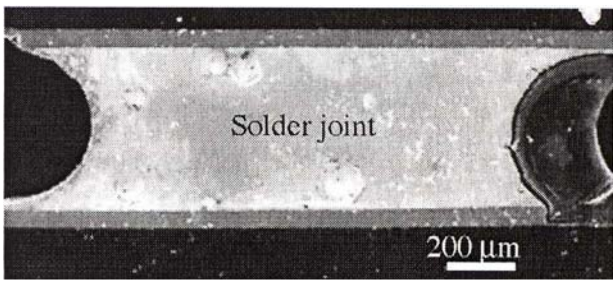
Reference: C. Anderson, Z. Lai, J. Liu, H. Jiang and Y. Yu; Mater. Sci. Eng. A, 394 (2005) p.20-17

Description:
Solder Joints were tested using a single lap-shear sample shown in the Figure below.



The joint was formed by reflow soldering and sandwiched between two FR-4 boards with the following dimensions: width 16 mm, length 45 mm, thickness 1.6 mm. The pads on the FR-4 boards were circular with a diameter of 2 mm and metallized with Cu/Ni/Au. The manufacturing process of the solder joints followed a traditional SMT process. The solder paste was applied by means of a manual stencil printer, resulting in an accurate solder volume for each joint. Reflow soldering was done in an IR/convection reflow oven with six different temperature zones, resulting in tailored and optimised temperature profiles. The temperature profile had a maximum of 240 °C and a duration of 8 minutes. Cooling was done in air until room temperature was reached. The final height of the solder joints was controlled using a spacer with a height of one FR-4 board plus the solder joint height of 2 mm. This spacer was placed between the upper FR-4 board and a support plate during the entire reflow soldering and cooling steps. The final joints displayed an hourglass shape and averaged 0.4 mm (± 0.05 mm) in height and 1.5 mm (± 0.1 mm) in diameter in the narrowest part of the joint (se the Figure on the right).



Low-cycle fatigue tests were carried out using an Instron 4458 Microtester at room temperature. The tests were performed under displacement control. Displacement amplitudes of 30, 40, 50 and 60 µm respectively were used resulting in strain ranges (measured in the solder joints) of 1.4, 3, 4 and 7.5 %. The test frequency was kept constant at 0.2 Hz for all tests. This resulted in different strain rates applied. The strain rate effect, however, is expected to be of less importance compared to the strain range. The failure of the solder joint was defined as a 50 % load reduction.

B7 Tensile and Shear Testing of Solder Joints

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Reference: K.S. Kim, S.H. Huh, K. Suganuma; J. All. and Comp., 352 (2003) p.226-236

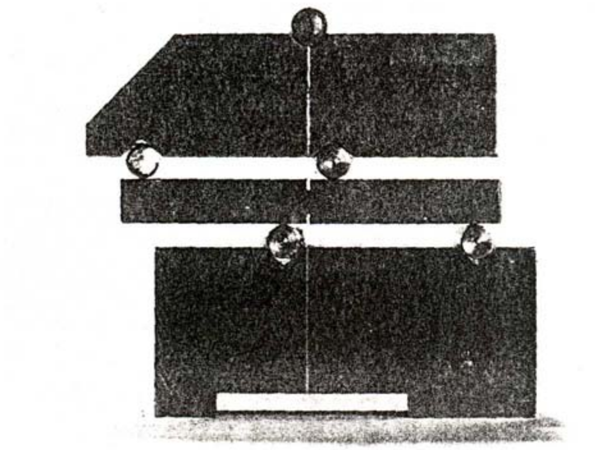
Description:
Solder alloys (Sn 3.0Ag 0.5Cu, Sn 3.5Ag 0.7Cu and Sn 3.9Ag 0.6Cu) in the forms of pastes and balls were supplied by Senju Metal.
Joint strength was evaluated by tensile test and shear test. The Cu-solder-Cu joints for the tensile test were prepared with two Cu cubes (15mm) and a 250 µm thick solder sheet. Two Cu cubes were soldered together with a Sn-Ag-Cu solder sheet at 260 °C for 30 s in air with the aid of RA-type flux. The soldered joints were cut into bars of 3x1x30 mm pieces for tensile test. High temperature stability of the soldered structures was also examined. All joined samples were aged for 100, 500 and 1000 hours at 125 and 150 °C in air.
The specimens were polished to optical flatness using 3 µm Al_2O_3 powders. Tensile tests were carried out at room temperature at a strain rate of $3.5x10^{-4}$/s. Shear test of the solder ball (760 µm diameters) on Cu pads (600 µm in diameter) on FR4 circuit board was carried out at room temperature. The shear speed was 500 µm/s by a Dage Bondtester 4000. The Sn 3.0Ag 0.5Cu and Sn 3.9Ag 0.6Cu solder pastes were printed on the Cu land pads of the FR4 boards to a thickness of 150 µm and were reflowed with the solder balls. More than ten specimens were evaluated for each set of conditions.

B8 Asymmetrical Four Point Bend [AFPB] Shear Test

Institution / Author: Ö. Ünal et al.
Iowa State University
Ames Laboratory
Ames
IA 50010

Reference: Ö. Ünal, I.E. Anderson, J.L. Harringa, R.L. Terpstra, B.A. Cook and J.C. Foley; J. Electr. Mater., Vol. 30 (9) (2001) p.1206-1213

Description:
The experimental setup can be seen in the Figure below.



AFPB shear fixture

The Figure shows the AFPB test fixture with a solder joint specimen. Although the AFPB fixture utilizes four loading pins, it is different from the conventional four-point test method due to the asymmetry of loading pins with respect to the loading axis. Notice in the picture, that the outer pins generate a counter clockwise rotation while the inner pins create a clockwise rotation. These counteracting force couples lead to a near 'pure shear' stress state in the middle of the specimen. This fixture was designed based on experience with a number of test materials, including solder joints.

C1 Wettability Test

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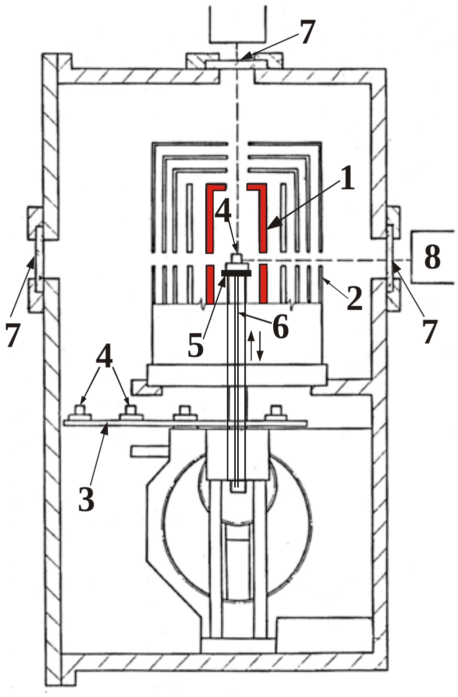
Tel: 48-12-2618526
e-mail: natalie@iod.krakow.pl

Reference: N. Sobczak, J. Sobczak, R. Nowak, A. Kudyba, P. Darlak; J. Mater. Sci., 40 (2005), p.2547-2551

Description:

The materials used were Cu substrates and several Sn-alloys. Directly before wettability tests, the Cu substrates were polished up to an average roughness of a few nanometers while the Sn-alloy samples were cleaned mechanically and next both Cu substrate and Sn-alloy samples were cleaned ultrasonically in acetone.

Wettability of Sn-alloy/Cu substrate couples was studied by a sessile drop method at 503K for 5 min under vacuum of 2-3x10^{-6} Pa. Design of apparatus used (see below) allowed to control the time of drop/substrate contact because the Sn alloy/Cu substrate couples before and after testing were stored on the loading table in the cold part of the vacuum chamber. One couple was introduced inside the molybdenum furnace when experimental conditions (vacuum and temperature) were reached. The time of drop/substrate contact was measured from the moment of visually estimated melting of the Sn alloy. After wettability test for 5 min, the couple was again removed into the cold part. Under conditions used the rates of heating and cooling of the couples were about 20 K/min.



1 - Mo heater
2 - Mo screens
3 - rotating loading table

4 - couples
5 - experimental table with up and down movement
6 - thermocouple
7 - windows
8 - camera

C2 Wettability Test

Institution / Author: D.Q. Yu et al.
Department of Materials Engineering
Dalian University of Technology
Dalian 116024
PR China

Reference: D.Q. YU, J. Zhao and L. Wang; J. All. Comp., 376 (2004) p.170-175

Description:
Solder alloys were prepared from pure metals. They were melted in a vacuum furnace at 500 °C for several hours. The melt was chill-cast as an ingot in a Cu mould. The cooling rate of about 15 °C/s is close to the real cooling rate during reflow soldering.
The wetting behaviour was evaluated using the meniscometer / wetting balance technique by Memisco ST50. The Cu-plate used was 0.1 mm thick and 10 mm wide. After polishing the Cu coupons were degreased in a 50 % water solution of HCl, then cleaned in ethanol and dried. The immersion depth and time were 3 mm and 10 s. The soldering temperature was 250 °C and RMA flux was used to investigate the wetting properties.

D1 Life of Drop Test

Institution / Author: Kwang-Lung Lin
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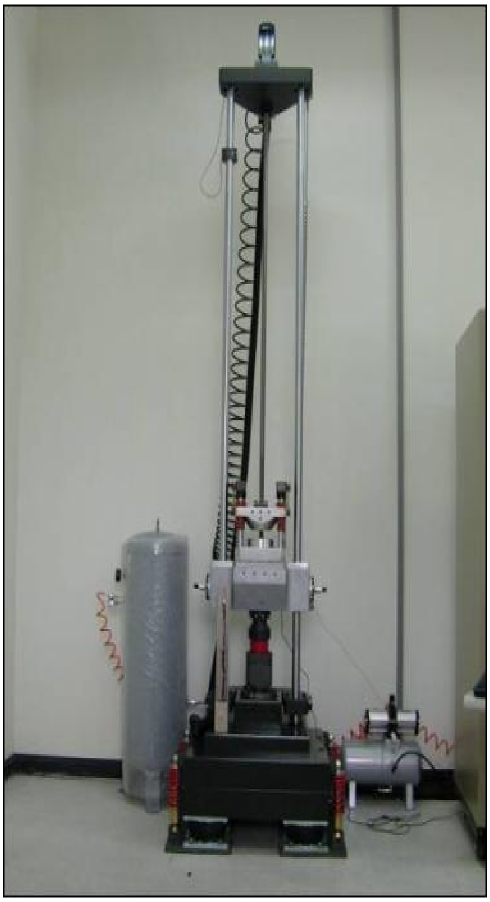
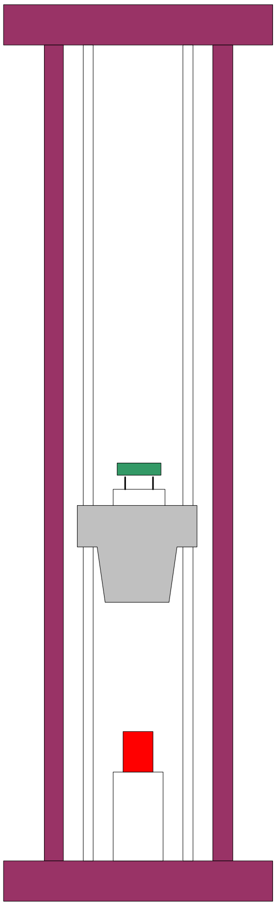
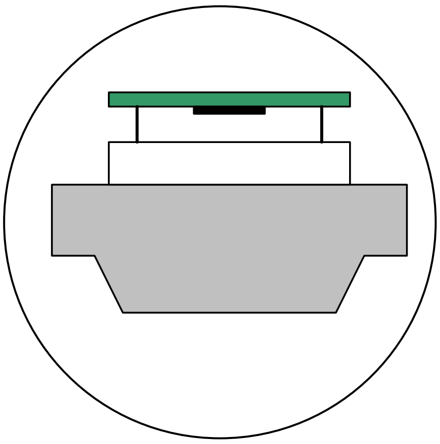
Email: matkllin@mail.ncku.edu.tw

Reference: JEDEC JESD22-B110 Subassembly Mechanical Shock

Description: The BGA test substrates were fixed on the test board. The drop test was conducted at a dropping height of 112 cm with a gravity acceleration of 1500 G. The solder balls are of 0.3 mm in diameter. The reflow profile of the Sn-3Ag-0.5Cu has a peak temperature of 255~265^{o}C.
The experimental setup can be seen in the Figures below.







Properties of Pure Metals

Sn

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	Sn_{100} (weight per cent)
	Sn_{100} (atom per cent)
Melting temperature:	231.93 °C [90Man]
	231.2 °C [94Mil]
	231.97 [90Mas]
Phase transformation $\alpha \leftrightarrows \beta$ temperature :	13.05 °C [Thermo]
Density:	7.29 Mg m^{-3} [25Gue]
Volume Change on Freezing:	2.7 % contraction [52Tat]
Coefficient of linear thermal expansion:	23.5 x 10^{-6} K^{-1} [76Smi]
Young's Modulus:	41.6 GN m^{-2} [39Cut]
Hardness:	3.9 HB (10 kg / 5 mm / 180S) [38Hom]
Specific heat capacity at 25 °C:	226 J g^{-1} K^{-1} [76Smi]
Latent heat of fusion:	59.5 kJ Kg^{-1} [50Kub]
Thermal Conductivity:	73.2 W m^{-1} K^{-1} [76Smi]
Electrical Conductivity:	15.6 % IACS [79Met]
Electrical Resistivity:	12.6 $\mu\Omega$ cm [76Smi]
Viscosity:	0.01382 N s m^{-2} at 351 °C [70Thr]
	0.01148 N s m^{-2} at 493 °C [70Thr]
Surface tension:	548 mN m^{-1} at 260 °C [71Whi]
	529 mN m^{-1} at 500 °C [71Whi]
Poisson's Ratio:	0.33 [79Met]

References:

[25Gue] *P. G. J. Gueterbock and G. N. Nicklin, J. Soc. Chem. Ind., 1925,* **44**, *370T.*
[38Hom] *C. E. Homer and H. Plummer, J. Inst. Metals, 1938,* **64**, *p. 169*
[39Cut] *J. W. Cuthbertson, J. Inst. Metals, 1939,* **64**, *p. 209*
[50Kub] *O. Kubaschewski, Z. Physikal. Chem., 1950,* **54**, *p. 275*
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[94Mil] *Chad M. Miller, Iver E. Anderson and Jack F. Smith, 'A Viable Tin-Lead Solder Substitute: Sn-Ag-Cu', J. Electronic Matls.* **23** *(7), 595-601 (1994)*

[Thermo] *COST 531 Thermodynamic Database (A. Dinsdale, A. Watson, A. Kroupa, J.Vrestal)*

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**

Institution / Author:

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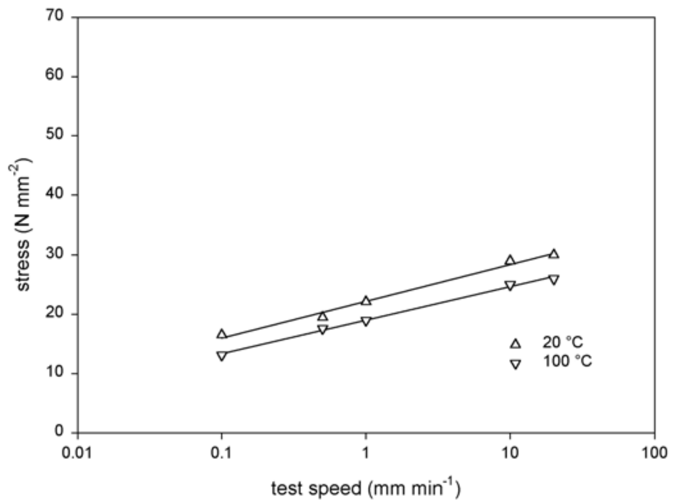
Measurement technique: **B1 Shear Strength by the Copper Ring and Plug Joint Method**

Reference: *ITRI Publication No.656; Solder Alloy Data – Mechanical Properties of Solders and soldered Joints*

Temperature [°C]	Test Speed [mm min^{-1}]	Stress [N mm^{-2}]
20	20	30
20	10	29
20	1	22.1
20	0.5	19.5
20	0.1	16.5
100	20	26
100	10	25
100	1	19
100	0.5	17.6
100	0.1	13.1



Shear strength of copper ring and plug joints soldered with pure Sn and tested at 20 °C and 100 °C

Measured property: **Stress to rupture**

Institution / Author:

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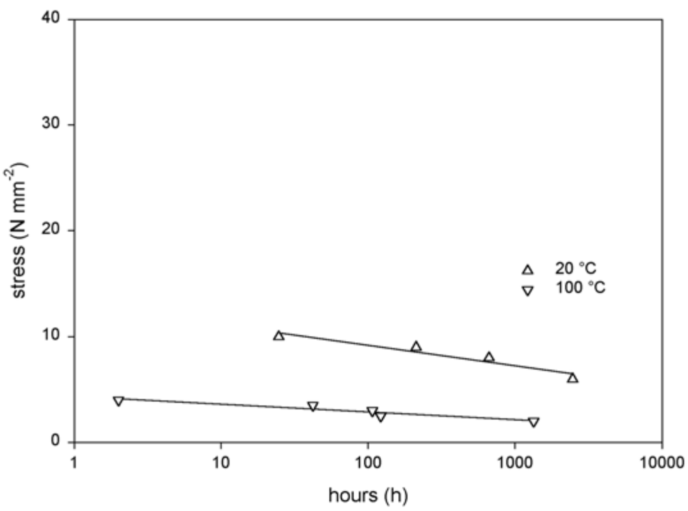
Email: info@tintechnology.com
Web:www.lead-free.org

Measurement technique: **B1 Shear Strangth by the Copper Ring and Plug Joint Method**

Reference: *ITRI Publication No.656; Solder Alloy Data – Mechanical Properties of Solders and soldered Joints*

Temperature [°C]	Stress [N mm^{-2}]	Life [h]
20	6	2470
20	8	666
20	9	212
20	10	24.7
100	2	1339
100	2.5	122
100	3	107
100	3.5	42
100	4	2



Stress vs. time to failure for copper ring and plug joints soldered with pure Sn and tested at 20 °C and 100 °C.

Measured property: **Fatigue Strength**

Institution / Author:

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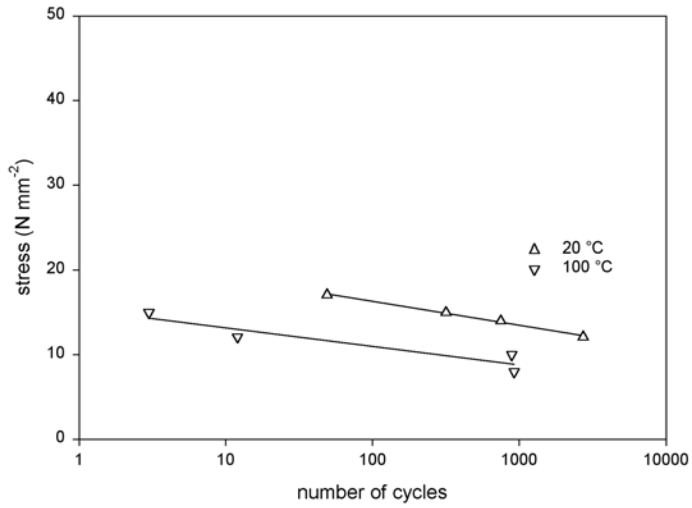
Unit 3 Curo Park, Frogmore, St Albans, Hertfordshire, AL2 2DD, UK
Tel:+44 (0)1727 875544
Fax:+44 (0)1727 871341
Email: info@tintechnology.com
Web:www.lead-free.org

Measurement technique: **B1 Shear Strangth by the Copper Ring and Plug Joint Method**

Reference: *ITRI Publication No.656; Solder Alloy Data – Mechanical Properties of Solders and soldered Joints*

General conditions: Crosshead Speed: 0.2 mm min^{-1}

Temperature [°C]	Maximum Stress [N mm^{-2}]	Life, cycles
20	±12.1	2733
20	±14	747
20	±15	316
20	±17.1	49
100	±8	922
100	±10	889
100	±12.1	12
100	±15	3

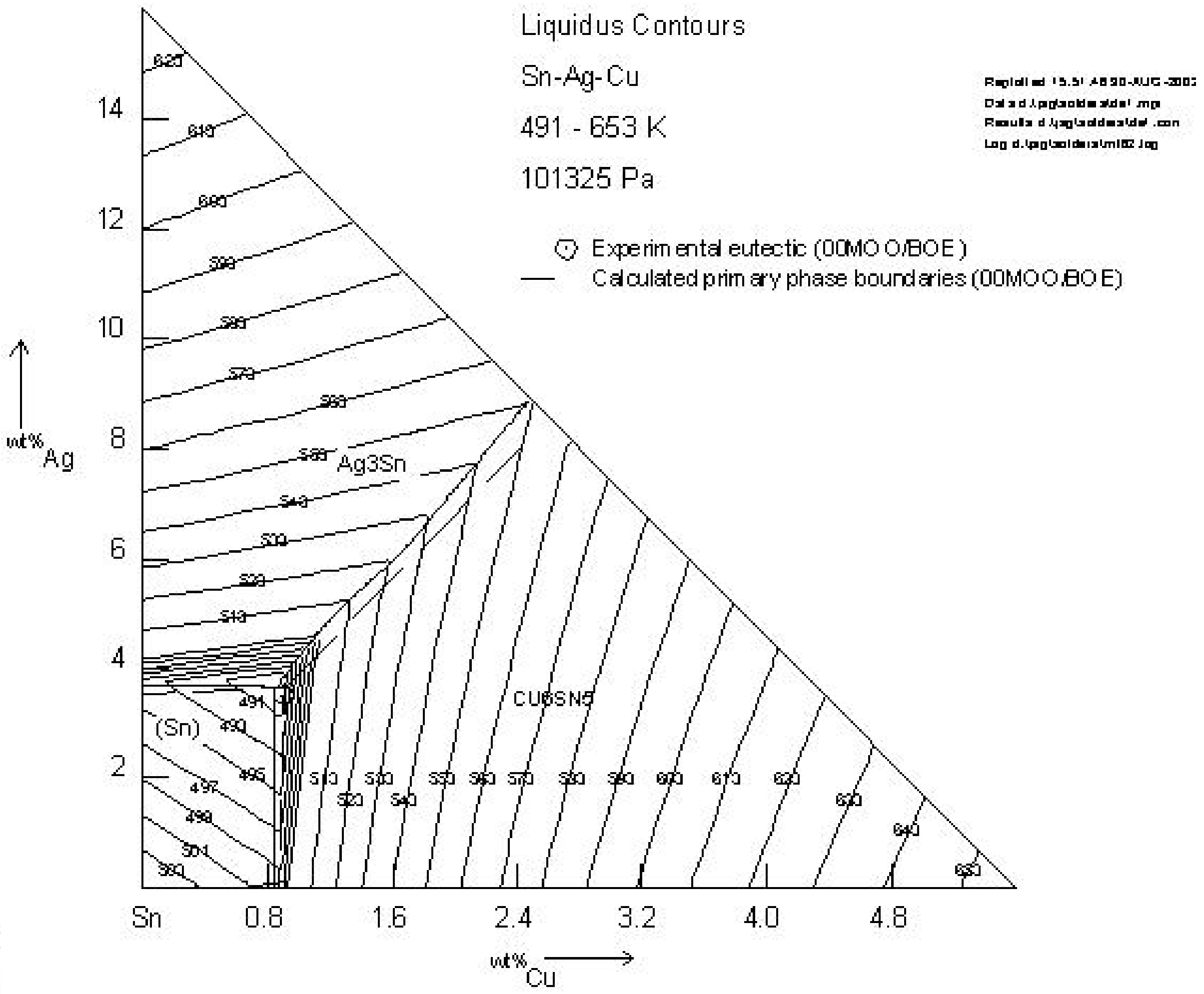


Fatigue strength of copper ring and plug joints soldered with pure Sn and tested at a crosshead speed of 0.2 mm min^{-1} at 20 °C and 100 °C.

Properties of Ternary Alloys

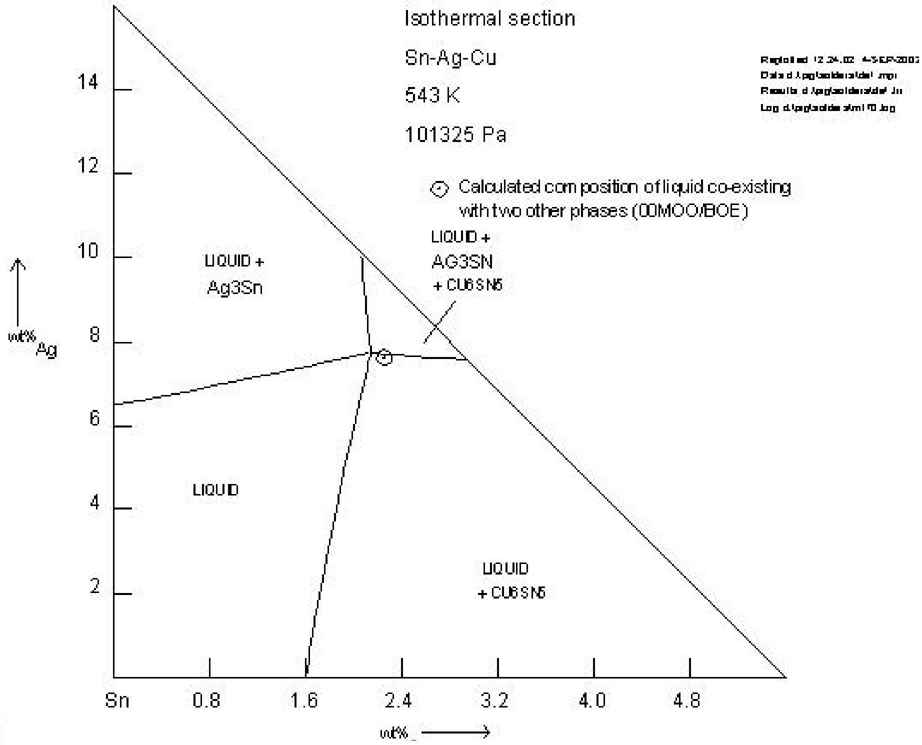
Ag-Cu-Sn Alloys

LIQUIDUS PROJECTION:

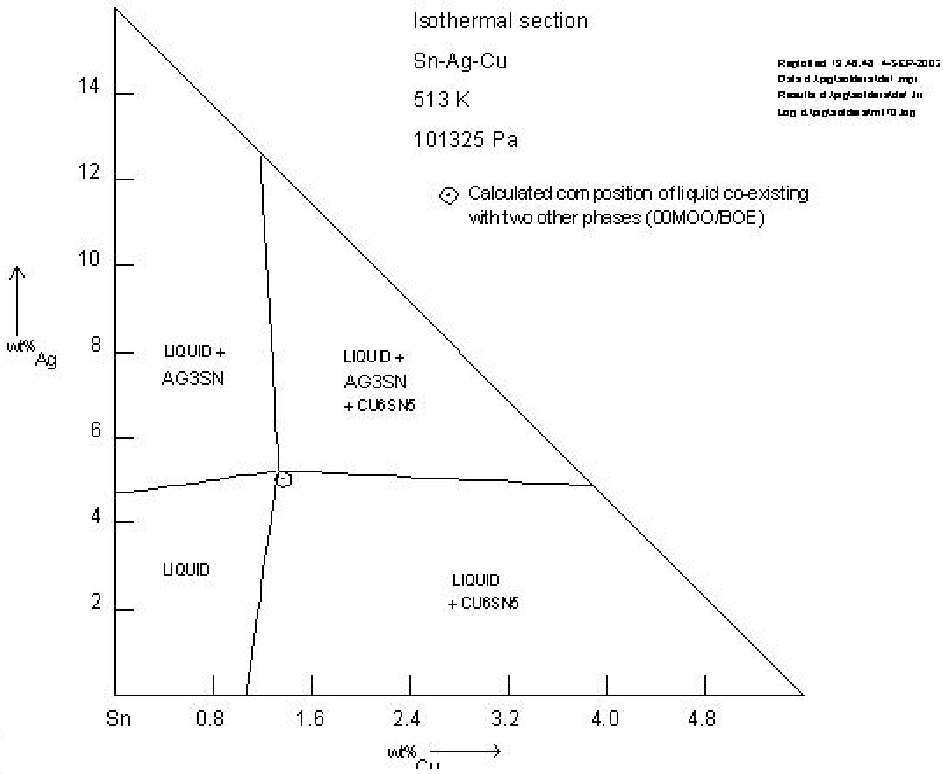


Liquidus Projection of the Ag-Cu-Sn ternary system showing the eutectic point, liquidus isotherms and fields of primary crystallization.

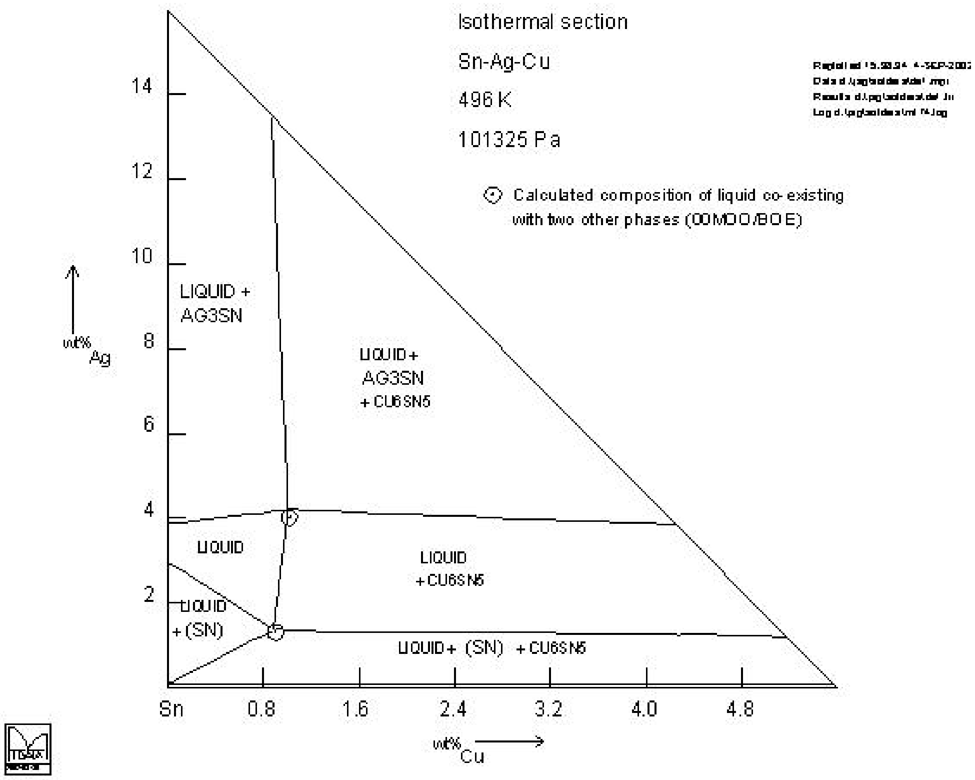
ISOTHERMAL SECTIONS:



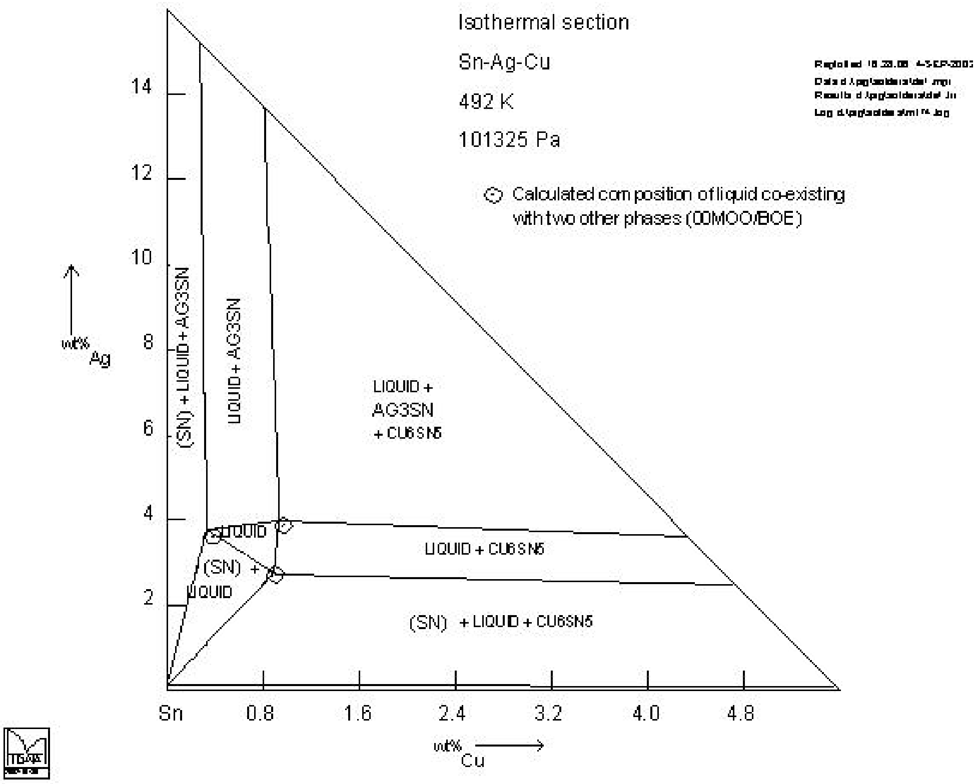
Sn-rich corner of Ag-Cu-Sn system at 270 °C.



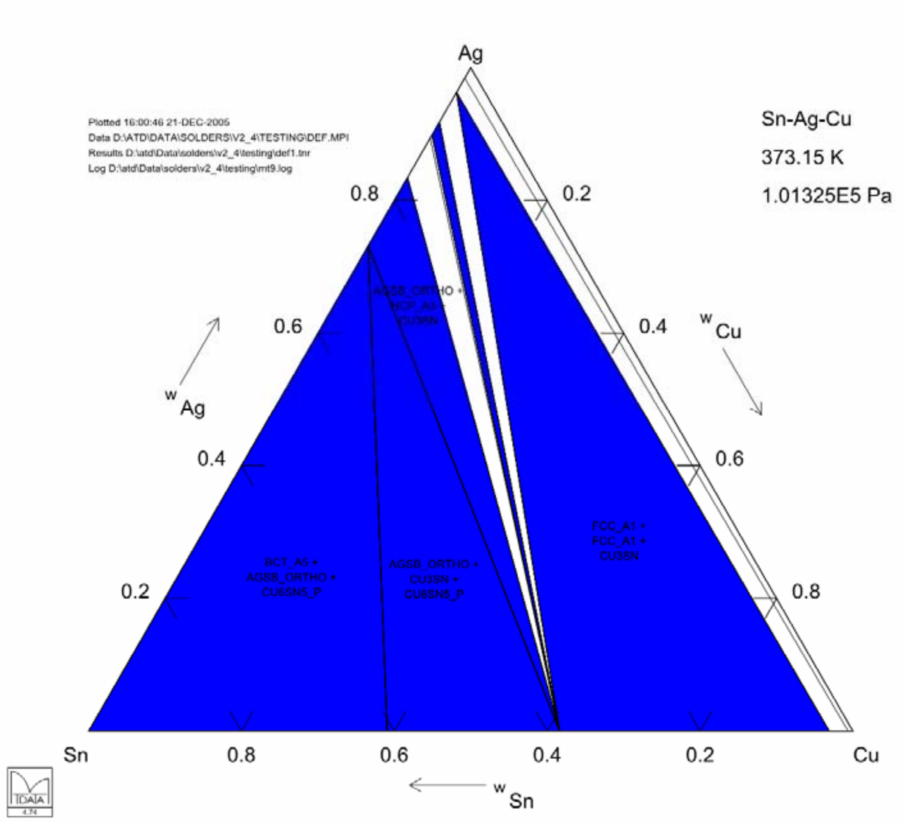
Sn-rich corner of Ag-Cu-Sn system at 240 °C.



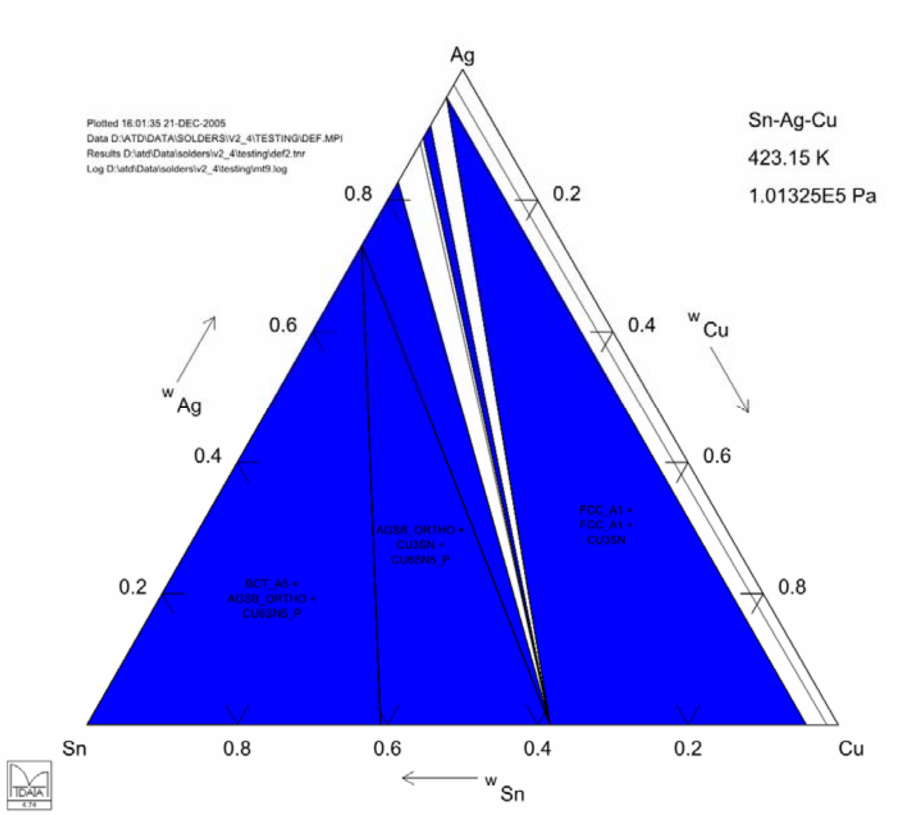
Sn-rich corner of Ag-Cu-Sn system at 223 °C.



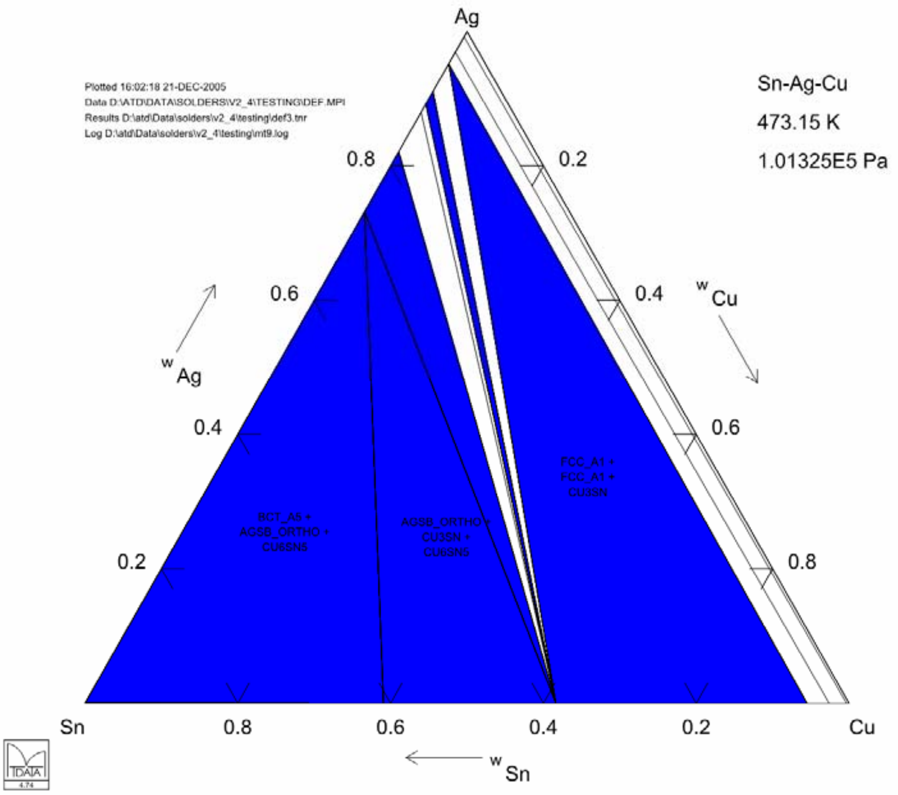
Sn-rich corner of Ag-Cu-Sn system at 219 °C.



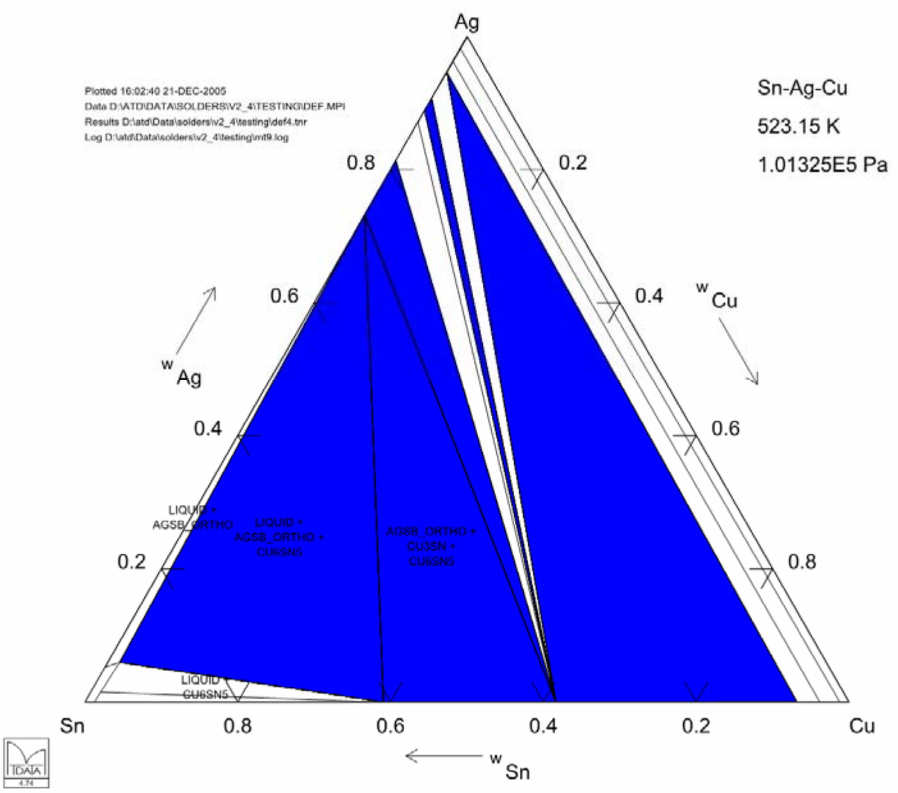
SAC - Isothermal Section at 100 °C



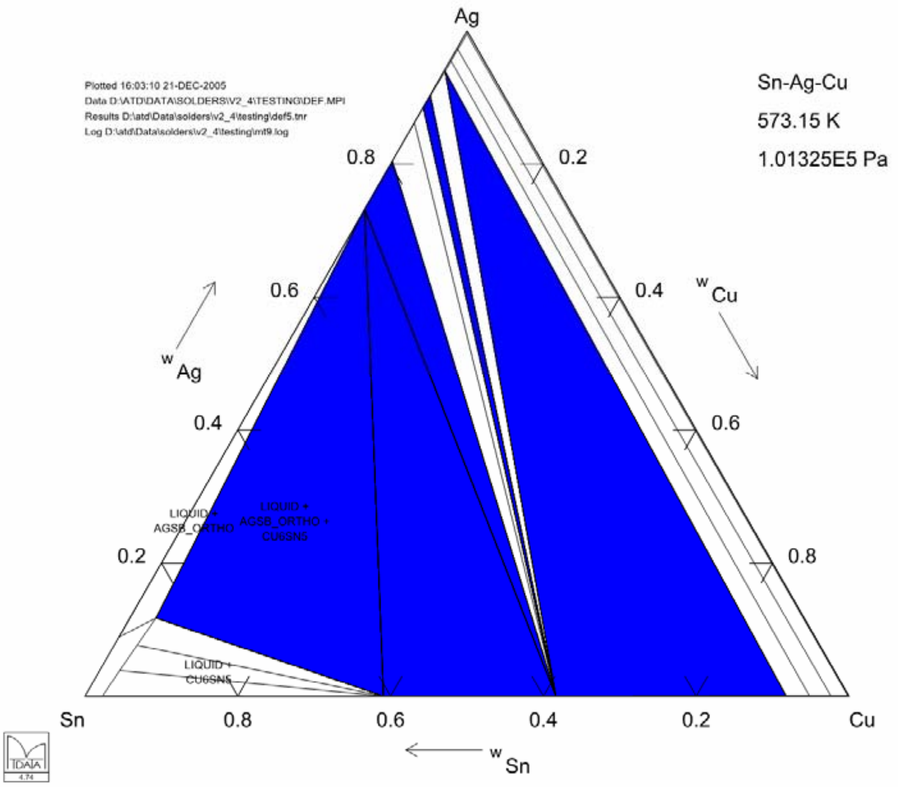
SAC - Isothermal Section at 150 °C



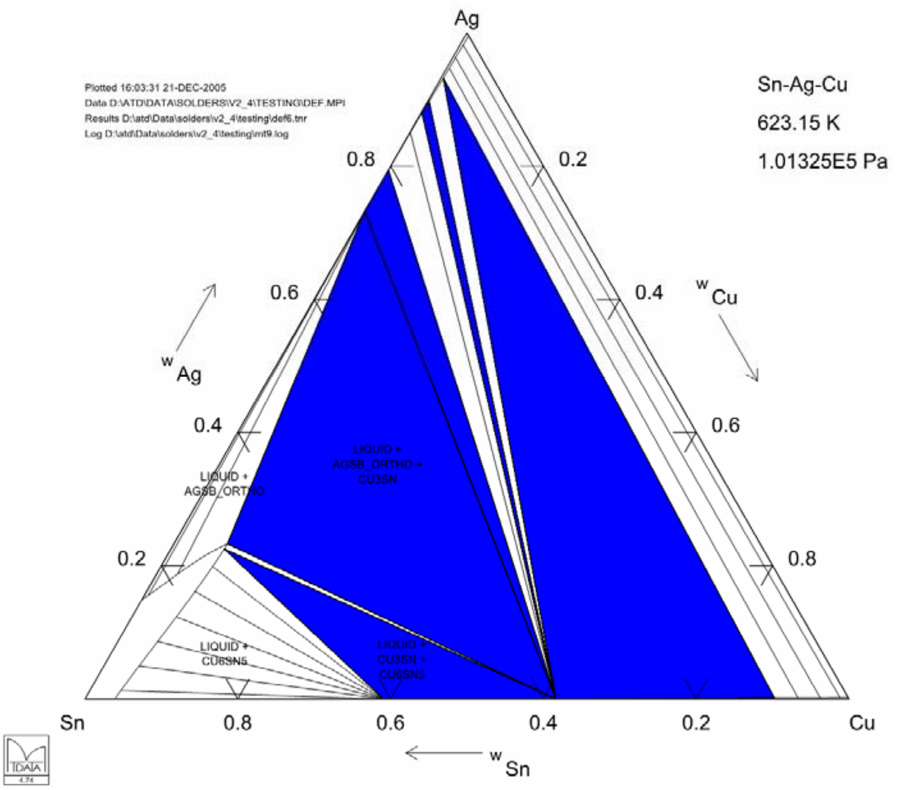
SAC - Isothermal Section at 200 °C



SAC - Isothermal Section at 250 °C



SAC - Isothermal Section at 300 °C



SAC - Isothermal Section at 450 °C

Some of the phases in the isothermal sections above were given CALPHAD – labels. These are:

AGSB_ORTHO = Ag_3Sn
HCP_A3 = Ag_4Sn
BCT_A5 = Sn
FCC_A1 = Ag or Ni

All sections of the Ag-Cu-Sn phase diagram were calculated according to the COST 531 Thermodynamic Database (A. Dinsdale, A. Watson, A. Kroupa, J.Vrestal) by Dr. Alan Dinsdale, National Physical Laboratory, UK.

Sn 3.8Ag0.7Cu

Proprietary (patented) alloy ('Ecosol TSC') of Multicore Solders

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.8}Cu_{0.7}Sn_{95.5}$ (weight per cent)
	$Ag_{4.1}Cu_{1.3}Sn_{94.6}$ (atom per cent)
Melting temperature:	217 °C (solidus) [99TSC]
	217 / 220 °C (solidus / liquidus) [00Sol]
	217 / 220 °C (solidus / liquidus) [00Lee]
	216 / 217 °C (solidus / liquidus) [calc]
	216.9 °C [03Kan]
Reflow Temperature.	238 – 248 °C [00Sol]
Density:	7.5 Mg m^{-3} [99TSC]
Wetting angle:	42 ° (Cu substr., temp. 10° C > T_m) [04Are]
Hardness:	15 HB [99TSC]
	Table taken from: [03Kan]

Microhardness Measurement on Sn-3.8Ag-0.7Cu Solder Balls.

SAC Solder Balls	Microhardness Number (HVN)*
As-received	21.9
Annealed (150 C, 500 h)	17.3
β-Sn Dendrites (0.02 °C/s)	15.2
Large Ag_3Sn Plates (0.02 °C/s)	126.5
Fine β-Sn Dendrites (Ag_3Sn dissolved + quenched)	26.5
Coarse β-Sn Dendrites (Ag_3Sn dissolved + quenched)	21.5

* VHN = Vickers hardness number is reported as an average value of 10 indentations made on the cross sections of solder balls using a 10 gf load.

Electrical Conductivity:	13 % IACS [99TSC]
Electrical Resistivity:	13 μΩ cm [99TSC]

References:

[99TSC] *Multicore Ecosol TSC Product Information (MSL Ref: 733 9/99)*

[00Lee] *N.-C. Lee and W. Casey, 'soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[03Kan] *S.K. Kang, W.K. Choi, D.-Y. Shih, D.W. Henderson, T. Gosselin, A. Sarkhel, C. Goldsmith and K.J. Puttlitz; IBM Research report, RC22717 (W0302-019), February 5, 2003*

[04Are] *Mario F. Arenas, Viola L. Acoff Journal of electronic materials, Vol. 33, No.12, 2004*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile Strength**
Institution / Author: **Multicore Ecosol**
Measurement technique: not available
Reference: *Multicore Ecosol TSC Product Information (MSL Ref: 733 9/99)*

Temperature [°C]	Test Speed [mm min^{-1}]	Stress [N mm^{-2}]
20	0.24	48

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**
Institution / Author: not available
Measurement technique: **Asymmetric Four Point Bend [AFPB] Method**
description not available; probably similar to **B8**
Reference: see *NIST Database for Solder Properties with Emphasis on Lead-Free Solders, Table 1.17*

Temperature [°C]	Test Speed [mm min^{-1}]	Gap thickness [µm]	Cooling Rate [°C s^{-1}]	Stress [N mm^{-2}]
22	0.1	76.2	10	63.8
170	0.1	76.2	10	25.1

Measured property: **Shear Strength**
Institution / Author: Iver E. Anderson et al.
Measurement technique: **Ring and Plug Method**
description not available, probably similar to **B4**
Reference: see *NIST Database for Solder Properties with Emphasis on Lead-Free Solders, Table 1.17; two sources mentioned:*

Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, 'Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Joining Applications', p.575

Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, 'Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Electronic Assemblies', IPCWorks '99: 'An International Summit on Lead-Free Electronics Assemblies', October 25-28, 1999. Minneapolis, MN

Temperature [°C]	Test Speed [mm min^{-1}]	Gap thickness [µm]	Stress [N mm^{-2}]
170	0.1	76.2	27

Measured property: **Shear Strength**
Institution / Author: **Multicore Ecosol**
Measurement technique: not available
Reference: *Multicore Ecosol TSC Product Information (MSL Ref: 733 9/99)*

Temperature [°C]	Test Speed [mm min^{-1}]	Stress [N mm^{-2}]
20	0.1	27
100	0.1	17

Measured property: **Shear Strength**
Institution / Author: J.C. Foley et al.
Ames Laboratory, 122 Metals Development
Ames,
IA 50011
Measurement technique: **B4 Ring and Plug Shear Strength Measurements**
Reference: *J.C. Foley, A.Gickler F.H. Leprevost, D. Brown., J. Electr. Mater., Vol. 29, 10, 2000*

Temperature [°C]	Test Speed [mm min^{-1}]	Average Shear Strength [N mm^{-2}]
Room Temp.	0.1	35.1
125	0.1	18.2

Measured property: **Creep Strength**
Shear Stress for 1000 hours to failure
Institution / Author: **Multicore Ecosol**
Measurement technique: not available
Reference: *Multicore Ecosol TSC Product Information (MSL Ref: 733 9/99)*

Temperature [°C]	Time [h]	Stress [N mm^{-2}]
20	1000	13
100	1000	5

Sn 0.5Ag4Cu

Englehart Alloy – high liquidus

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{0.5}Cu_4Sn_{95.5}$ (weight per cent)
	$Ag_{0.5}Cu_{7.2}Sn_{92.3}$ (atom per cent)
Melting temperature:	217 / 350 °C (solidus / liquidus) [00Lee]
	216 / 222 °C (solidus / liquidus) [Gla]
	218 / 226 °C (solidus / liquiuds) [NCMS]
	218 / >300 °C (solidus / liquidus) [NCMS]
	216 / 351 °C (solidus / liquiuds) [calc]
Density:	7.3 Mg m^{-3} [NCMS]
	7.7 Mg m^{-3} [NCMS]
Electrical Resistivity:	10 – 15 $\mu\Omega$ cm [Gla]

References:

[00Lee] *N.-C. Lee and W. Casey, 'soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

[Gla] *Judith Glazer, 'Microstructure and Mechanical Properties of Pb-free Solder Alloys for Low-Cost Electronic Assembly*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **0.2 % Yield Strength**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Yield strength [N mm^{-2}]
room temp.	0.02	25.7

Measured property: **Tensile Strength**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Stress [N mm^{-2}]
room temp.	0.02	29.7

Measured property: **Relative elongation**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Rel. elongation [%]
room temp.	0.02	27

Measured property: **Steady State Creep Properties and Mechanisms**

Institution / Author:

Y.-H. Pao et al.
Research Laboratory
Ford Motor Company
Dearborn
MI48121-2053

Measurement technique: **A11 Thermal Cycling Testing**

Reference: *Y.-H. Pao, S. Badgley, R. Govila and E. Jih, Mat. Res. Soc. Symp. Proc. Vol.* ***323****, p. 128 (MRS 1994)*

	Coefficients for Norton's Law: $\frac{d\gamma_{creep}}{dt} = B^* \cdot \tau^n \cdot \exp\left(\frac{-\Delta H}{kT}\right)$			
Deformation Mechanism	B^* [$Mpa^{-n}\ s^{-1}$]	ΔH [eV]	n (40 °C)	n (140 °C)
Athermal, short - range Cu clustering	$4.229 \cdot 10^{-12}$	0.062	8.36	8.36

$\frac{d\gamma_{creep}}{dt}$	rate of shear creep strain
τ	shear stress
n	stress exponent
ΔH	activation energy
k	Boltzmann's constant
T	absolut temperature
B^*	material constant

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**

Institution / Author:

J.C. Foley et al.
Ames Laboratory, 122 Metals Development
Ames,
IA 50011

Measurement technique: **B4 Ring and Plug Shear Strength Measurements**

Reference: *J.C. Foley, A.Gickler F.H. Leprevost, D. Brown. J. Electr. Mater., Vol. 29, 10, 2000*

Temperature [°C]	Test Speed [mm min^{-1}]	Average Shear Strength [N mm^{-2}]
Room Temp.	0.1	32

Sn 3Ag4Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_3Cu_4Sn_{93}$ (weight per cent)
	$Ag_{3.2}Cu_{7.2}Sn_{89.6}$ (atom per cent)
Melting temperature:	221 °C [NCMS]
	216 / 312 °C (solidus / liquidus) [calc]
Density:	7.4 Mg m^{-3} [NCMS]
Coefficient of linear thermal expansion:	14.83 µm m^{-1} $°C^{-1}$ [NCMS]
Specific heat capacity at 25 °C:	61 J g^{-1} [NCMS]

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **0.2 % Yield Strength**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Yield strength [N mm^{-2}]
room temp.	0.02	43.3

Measured property: **Tensile Strength**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Stress [N mm^{-2}]
room temp.	0.02	48.3

Measured property: **Relative elongation**

Institution / Author: **National Center for Manufacturing Sciences**
3025 Board Walk
Ann Arbor, MI
48108-3266
www.ncms.org

Measurement technique: **A2 Tensile Testing – NCMS**

Reference: *Lead-Free Solder Project CD-Rom, National Center for Manufacturing Sciences (NCMS), 1998*

Temperature [°C]	Test Speed [inch min^{-1}]	Rel. elongation [%]
room temp.	0.02	22

Sn 3.6Ag1Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.6}Cu_1Sn_{95.4}$ (weight per cent)
	$Ag_{3.9}Cu_{1.8}Sn_{94.2}$ (atom per cent)
Melting temperature:	217 / 217.9°C (solidus / liquidus) [NIST]
	216 / 224°C (solidus / liquidus) [calc]

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**

Institution / Author: Iver E. Anderson et al.

Measurement technique: **Asymmetric Four Point Bend [AFPB] Method**
description not available; probably similar to **B8**

Reference: *Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, 'Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Joining Applications', p.575*

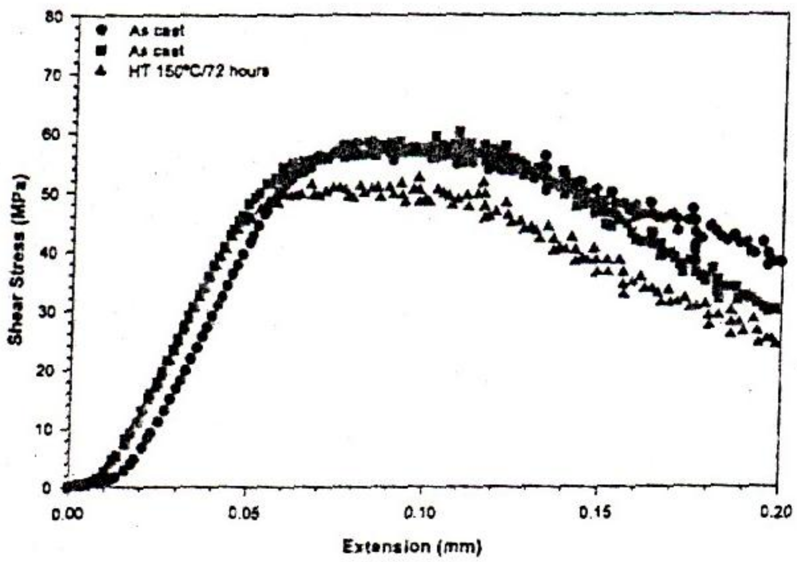
Temperature [°C]	Test Speed [mm min^{-1}]	Gap thickness [µm]	Cooling Rate [°C s^{-1}]	Stress [N mm^{-2}]
22	0.1	76.2	1.5	54
22	0.1	76.2	10	67± 2.4
22	0.1	76.2		70.8 ± 2.3
170	0.1	76.2	10	24.4
22	0.1	152.4		59.4 ± 4.4

Measured property: **Shear Strength**

Institution / Author: Ö. Ünal et al.
Iowa State University
Ames Laboratory
Ames
IA 50010

Measurement technique: **B8 Asymmetric Four Point Bend [AFPB] Shear Test**

Reference: *Ö. Ünal, I.E. Anderson, J.L. Harringa, R.L. Terpstra, B.A. Cook and J.C. Foley; J. Electr. Mater., Vol. 30 (9) (2001) p.1206-1213*



Shear strength of Sn-3.6Ag-1.0Cu results from asymmetric four point bend testing, containing results for as solidified (slow cooling) joint samples and aged at 150°C for 72 hrs.

Sn 4.7Ag1.7Cu

(Patented Composition)

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{4.7}Cu_{1.7}Sn_{93.6}$ (weight per cent)
	$Ag_{5.1}Cu_{3.1}Sn_{92.8}$ (atom per cent)
Melting temperature:	217 °C (solidus) [NIST] [98And]
	217 / 220 °C (solidus / liquidus) [00Sol]
	217 / 244 °C (solidus / liquidus) [00Lee]
	216.8 °C (solidus) [94Mil]
	216 / 261 °C (solidus / liquidus) [calc]
Reflow Temperature :	237 – 247 [00Sol]
Density:	7.4 Mg m^{-3} [NCMS]
Wetting angle:	21 ° [NIST]
	32 ° (with RMA (GF-1235) Flux) [96And]
Hardness:	10.25 HV as drawn [98And]
	12.45 HV annealed [98And]

References:

[94Mil] *Chad M. Miller, Iver E. Anderson and Jack F. Smith, 'A Viable Tin-Lead Solder Substitute: Sn-Ag-Cu', J. Electronic Matls.* **23** *(7), 595-601 (1994)*

[96And] *Iver E. Anderson, 'Tin—Silver-Copper: A Lead-Free Solder for Capacitor Interconnects', p. 16, Proc. 16th Capacitor and Resistor Technology Symposium (CARTS 96), 11-15 March, 1996*

[98And] *Iver E. Anderson, Özer Ünal, Tamara E. Bloomer and James C. Foley, 'Effects of Transition Metal Alloying on Microstructural Stability and Mechanical Property of Tin-Silver-Copper Alloys', Proc. Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3) (The Minerals, Metals and Materials Society, 1998)*

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[00Lee] *N.-C. Lee and W. Casey, 'Soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Ultimate Tensile Strength**

Institution / Author: Iver E. Anderson et al.

Measurement technique: not available

Reference: *Iver E. Anderson, Özer Ünal, Tamara E. Bloomer and James C. Foley, 'Effects of Transition Metal Alloying on Microstructural Stability and Mechanical Property of Tin-Silver-Copper Alloys', Proc. Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3) (The Minerals, Metals and Materials Society, 1998)*

Temperature [°C]	Test Speed [mm min^{-1}]	Condition of Solder	Stress [N mm^{-2}]
Not available	Not available	as drawn	44
Not available	Not available	annealed	53

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**

Institution / Author: Iver E. Anderson et al.

Measurement technique: **Asymmetric Four Point Bend [AFPB] Method**
description not available; probably similar to **B8**

Reference: *Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, 'Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Joining Applications', p.575*

Temperature [°C]	Test Speed [mm min^{-1}]	Gap thickness [µm]	Cooling Rate [°C s^{-1}]	Stress [N mm^{-2}]
22	0.1	76.2	1.5	47
22	0.1	76.2	10	58
170	0.1	76.2	10	21.6

Measured property: **Shear Strength**

Institution / Author:

J.C. Foley et al.
Ames Laboratory
122 Metals Development
Ames
IA 50011

Measurement technique: **B4 Ring and Plug Shear Strength Measurements**

Reference: *J.C. Foley, A.Gickler F.H. Leprevost, D. Brown. J. Electr. Mater., vol. 29, 10, 2000*

Temperature [°C]	Test Speed [mm min^{-1}]	Average Shear Strength [N mm^{-2}]
Room Temp.	0.1	40.5
125	0.1	17.2

Sn 3.5Ag0.7Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{0.7}Sn_{95.8}$ (weight per cent)
	$Ag_{3.8}Cu_{1.3}Sn_{94.9}$ (atom per cent)
Melting temperature:	217.5 °C [02Kim]
	216 / 217.7 °C [calc]
Wetting angle:	48.5 ° (see Technique **C2**) [04Yu]
Electrical Conductivity:	13 % IACS [98Bio]

Reference:

[98Bio] *Peter Biocca, 'Global Update on Lead-Free Solders', Proc. Surface Mount International (San Jose, CA, 1998), p. 705-709*

[02Kim] *K. S. Kim, S. H. Huh, K. Suganuma, Material science and engineering, A 333 (2002), 106 – 114*

[04Yu] *D.Q. YU, J. Zhao and L. Wang; J. Alloys and Compounds, 376 (2004) p.170-175*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: Tensile Strength
Institution / Author: not available
Measurement technique: not available
Reference: *Peter Biocca, 'Global Update on Lead-Free Solders', Proc. Surface Mount International (San Jose, CA, 1998), p. 705-709*

Temperature [°C]	Test Speed [mm min^{-1}]	Stress [N mm^{-2}]
20	0.24	48

Measured property: Creep Strength
Institution / Author: not available
Measurement technique: not available
Reference: *Peter Biocca, 'Global Update on Lead-Free Solders', Proc. Surface Mount International (San Jose, CA, 1998), p. 705-709*

Temperature [°C]	Test Speed [mm min^{-1}]	Stress [N mm^{-2}]
20	0.1	13
100	0.1	5

Measured property: Tensile property
Institution / Author: D.Q. Yu et al.
Department of Materials Engineering
Dalian University of Technology
Dalian 116024
PR China
Measurement technique: A10 Tensile Testing
References: *D.Q. YU, J. Zhao and L. Wang; J. All. Comp., 376 (2004) p.170-175*

Temperature [K]	Test Speed [not mentioned]	Process	Stress [Mpa]
298	1.5x 10^{-2}	Aging (373 K for 5 h)	58.5

Measured property: **Tensile Strength**

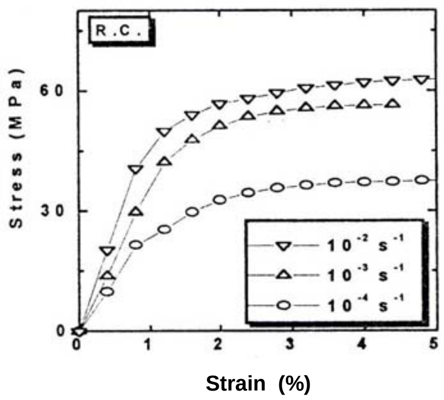
Institution / Author:

K.S. Kim et al.
Department of Adaptive Machine Systems
Osaka University
Yamadaoka 1-1, Suita, Osaka 565-0871, Japan
Tel.: +81 6 6879 8520
Fax.: +81 6 6879 8522
Email: kskimm12@sanken.osaka-u.ac.jp

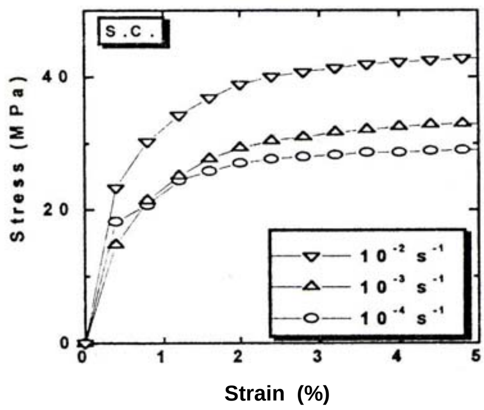
Measurement technique: **A4 Tensile Test – K.S.Kim**

Reference:

K. S. Kim, S. H. Huh, K. Suganuma, Mater. Sci. Eng. A, 333 (2002), 106 – 114



(a) Rapid cooling 8.3 °C/s



(b) Slow cooling 0.012 °C/s

Engineering stress-strain curves in tensile tests at different strain rates and cooling speeds for Sn-3.5Ag-0.7Cu

Sn 3.2Ag0.8Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.2}Cu_{0.8}Sn_{96}$ (weight per cent)
	$Ag_{3.5}Cu_{1.5}Sn_{95}$ (atom per cent)
Melting temperature:	216 / 218 °C (solidus / liquidus) [calc]
	217 °C [01Mad]

References:

[01Mad] *http://www.boulder.nist.gov/div853/Publication%20files/NIST_ASM_Pb_free_casting.pdf*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: Yield Strength

Institution / Author:

J. Madeni and S. Liu
Center for Welding, Joining and Coatings Research
George S. Ansell Department of Metallurgical & Materials Engineering
Colorado School of Mines
Golden, Colorado 80401, USA

T. Siewert
Materials Reliability Division, NIST
Boulder, Colorado 80305, USA

Measurement technique: A8 Tensile Testing – J. Madeni

Reference: *J. Madeni, S. Liu, and T. Siewert, 'Casting of lead-Free Solder Specimens with Various Solidification Rates', ASM-International Conference, Indianapolis 2001*

See also: http://www.boulder.nist.gov/div853/Publication%20files/NIST_ASM_Pb_free_casting.pdf

Temperature [°C]	Test Speed [inch min^{-1}]	Process	Stress [N mm^{-2}]
Room temp.	0.01	water quenched	26
Room temp.	0.01	water quenched	32
Room temp.	0.01	water quenched	25
Average of the above			28
Room temp.	0.01	Air cooled	20

Measured property: Ultimate Tensile Strength

Institution / Author:

J. Madeni and S. Liu
Center for Welding, Joining and Coatings Research
George S. Ansell Department of Metallurgical & Materials Engineering
Colorado School of Mines
Golden, Colorado 80401, USA

T. Siewert
Materials Reliability Division, NIST
Boulder, Colorado 80305, USA

Measurement technique: A8 Tensile Testing – J. Madeni

Reference: *J. Madeni, S. Liu, and T. Siewert, 'Casting of lead-Free Solder Specimens with Various Solidification Rates', ASM-International Conference, Indianapolis 2001*

See also: http://www.boulder.nist.gov/div853/Publication%20files/NIST_ASM_Pb_free_casting.pdf

Temperature [°C]	Test Speed [inch min^{-1}]	Process	Stress [N mm^{-2}]	Uniform Elongation [%]	Total Elongation [%]
Room temp.	0.01	water quenched	31	4.2	24.5

Room temp.	0.01	water quenched	34	1.9	21.6
Room temp.	0.01	water quenched	30	4.0	20.2
Average of the above			32	3.4	22.1
Room temp.	0.01	Air cooled	30	6.2	26.1

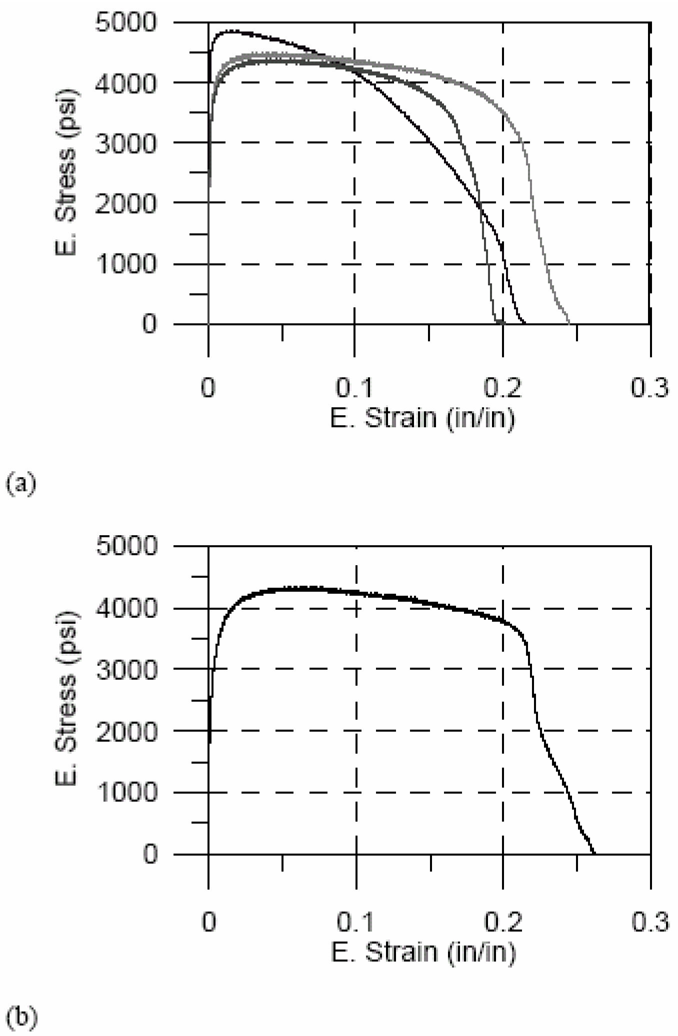
Measured property: **Engineering Stress Strain Curves**

Institution / Author: J. Madeni et al.

Measurement technique: **A8 Tensile Testing – J. Madeni**

Reference: *J. Madeni, S. Liu, and T. Siewert, 'Casting of lead-Free Solder Specimens with Various Solidification Rates', ASM-International Conference, Indianapolis 2001*

See also: http://www.boulder.nist.gov/div853/Publication%20files/NIST_ASM_Pb_free_casting.pdf



Engineering Stress – Strain curves for the Sn-3.2Ag-0.8Cu specimens (a) water-quenched and (b) air-cooled.

Sn 3Ag0.5Cu

(Patented Composition)

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_3Cu_{0.5}Sn_{96.5}$ (weight per cent)
	$Ag_{3.3}Cu_{0.9}Sn_{95.8}$ (atom per cent)
Melting temperature:	220 °C [00Sol] [Comp]
	217°C / 219°C (solidus / liquidus) [02Kan]
	217°C / 219°C (solidus / liquidus) [02Zha]
	217.6 – 220 °C [02Kim]
	216 / 220 °C (solidus / liquidus) [calc]
Reflow Temperature:	238 – 248 °C [00Sol]
Young's Modulus:	54 GPa [02Kan], [02Zha]
Hardness:	13.3 HV [02Kan], [02Zha]

References:

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[02Kan] *C. Kanchanomai, Y. Miyashita and Y. Mutoh; J. Electr. Mater., 31 (5) (2002) p.456-465*

[02Kim] *K. S. Kim, S. H. Huh, K. Suganuma, Mater. Sci. Eng. A, 333 (2002), 106 – 114*

[02Zha] *J. Zhao, Y. Mutoh, Y. Miyashita and S.L. Mannan; J. Electr. Mater., 31 (8) (2002) p.879-886*

[Comp] *See also: Phase Diagrams & Computational Thermodynamics, Metallurgy Division of Materials Science and Engineering Laboratory, NIST*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile Properties**

Institution / Author: J. Zhao et al.
Dalian University of Technology
116023 Dalian
Republic of China

Measurement technique: **A3 Tensile testing – J.Zhao**

Reference: *J. Zhao,Y. Mutoh, Y. Miyashita, S. L. Mannan, J. Electr. Mater., Vol. 31, No. 8, 2002*

Test Speed [mm s^{-1}]	Tensile Strength Stress [MPa]	Yield Strength Stress [MPa]	Elongation %
0.004	41.8	-	42.2
0.04	50.6	25.3	52.9

Measured property: **Tensile Properties**

Institution / Author: Chaosuan Kanchanomai et al.
Department of Mechanical Engineering, Nagaoka University of Technology, Nagaoka 940-2188, Japan

Measurement technique: **A9 Tensile and Fatigue Testing**

Reference: *C. Kanchanomai, Y. Miyashita and Y. Mutoh; J. Electr. Mater., 31 (5) (2002) p.456-465*

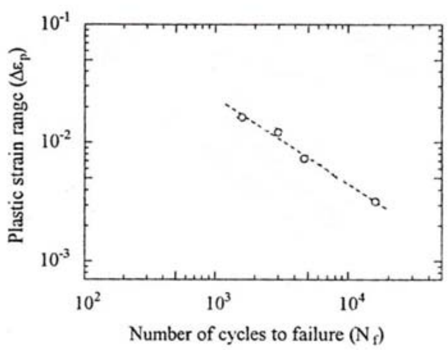
Temperature [°C]	Test Speed [mm s^{-1}]	Tensile Strength Stress [MPa]	Yield Strength Stress [MPa]
20	0.004	50.6	25.3

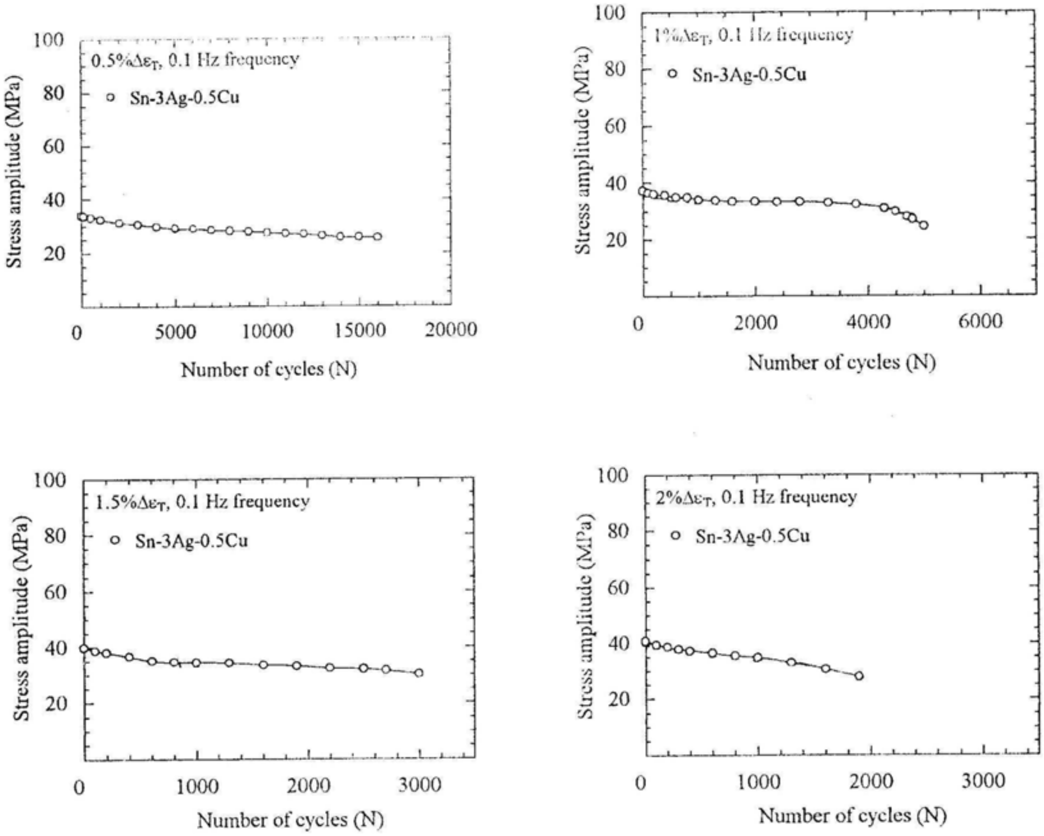
Measured property: **Fatigue behaviour (S- N Curve, etc.)**

Institution / Author: Chaosuan Kanchanomai et al.
Department of Mechanical Engineering, Nagaoka University of Technology, Nagaoka 940-2188, Japan

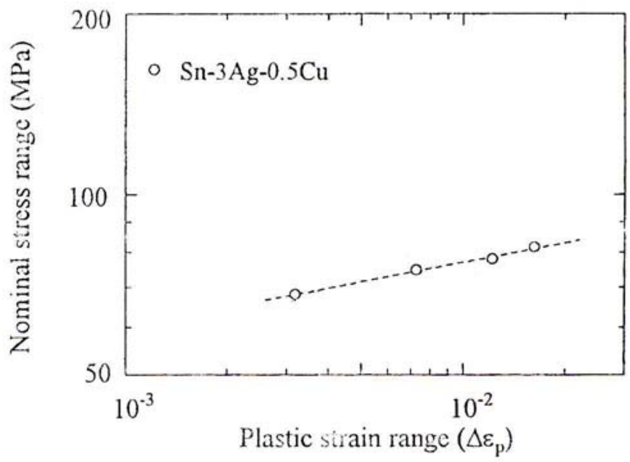
Measurement technique: **A9 Tensile and Fatigue Testing**

Reference: *C. Kanchanomai, Y. Miyashita and Y. Mutoh; J. Electr. Mater., 31 (5) (2002) p.456-465*





Relationship between stress amplitudes and number of cycles.



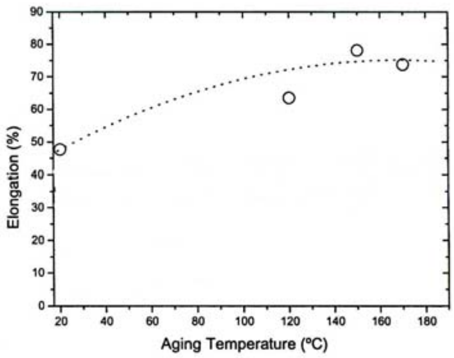
Relationship between nominal stress range and plastic strain range.

Measured property: Aging Behaviour and Tensile Properties

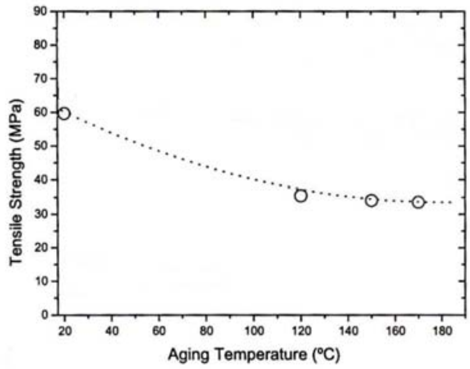
Institution / Author:
J. Zhao et al.
Dalian University of Technology
116023 Dalian
Ann Arbor, MI
48108-3266
Republic of China

Measurement technique: A3 Tensile Testing – J. Zhao

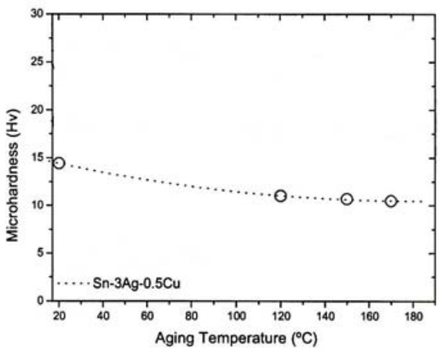
Reference: *Jie Zhao, Lin Qi, Xiu-min Wang, Lai Wang, J. All. Comp., 375 (2004) 196-201*



(a) The elongation of Sn-3Ag-0.5Cu alloy as a function of aging temperature



(b) The tensile strength of Sn-3Ag-0.5Cu alloy as a function of aging temperature



(c) The micro hardness of Sn-3Ag-0.5Cu alloy as a function of aging temperature

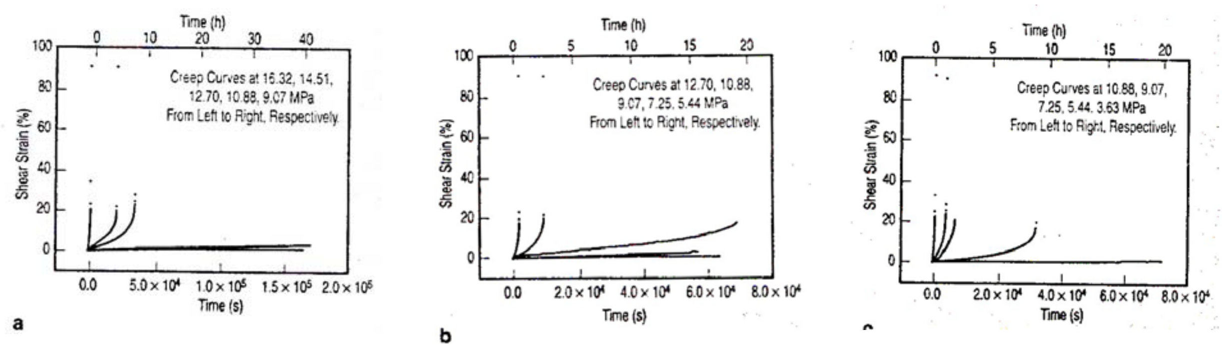
MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Creep behaviour**

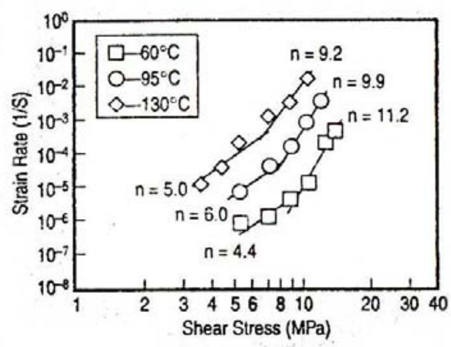
Institution / Author: H.G. Song et al.
University of California, Dept. of materials Science and Engineering
See Section B3 for full address details

Measurement technique: **B3 Creep Testing of Solder Joints**

Reference:: *H.G. Song, J.W. Morris and F. Hua, Creep properties of lead free solder Joint, JOM,54(6) (2002) p.30-33*



Creep curves of Sn-3Ag-0.5Cu at (a) 60°C (b) 95°C (c)130°C



Log-Log plot of the steady-state strain rate as function of stress
Relation between plastic strain ranges and number of cycles to failure

PROPERTIES OF ASSEMBLED BOARDS

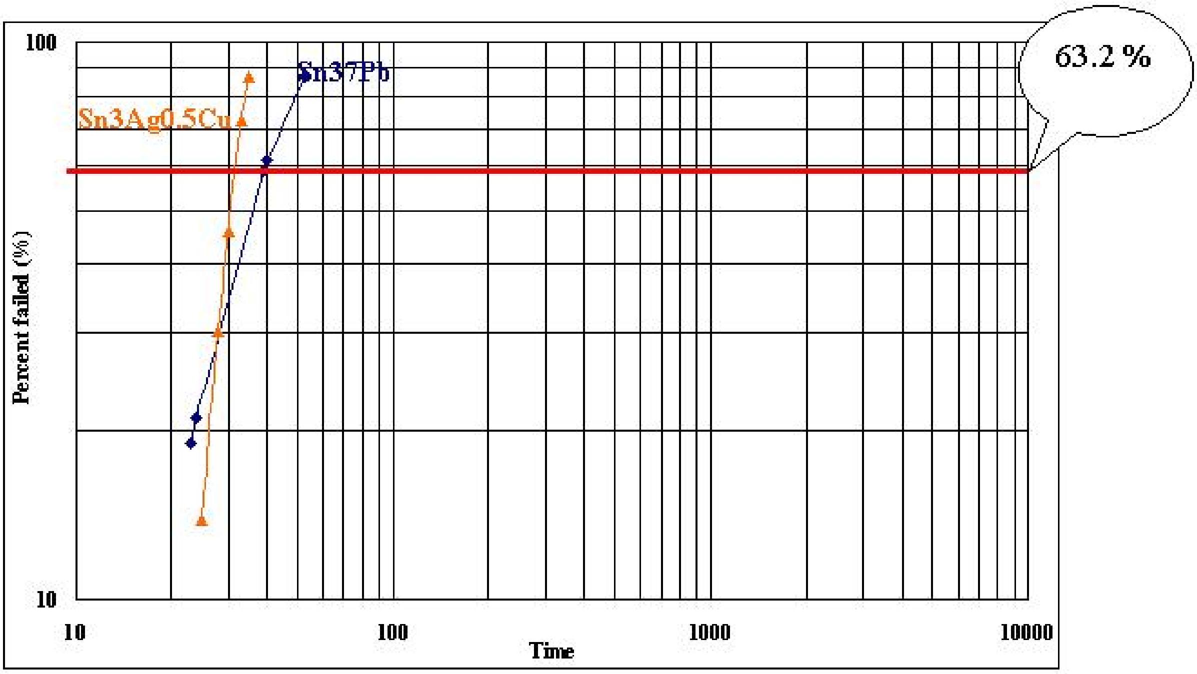
Measured property: Life of Drop of BGA Joints

Institution / Author: Kwang-Lung Lin
Department of Materials Science and Engineering
National Cheng Kung University
Tainan, Taiwan 701
Email: matkllin@mail.ncku.edu.tw

Measurement technique: D1 Life of Drop Test

Reference: *Kwang-Lung Lin; JEDEC JESD22-B110 Subassembly Mechanical Shock*

“Time” refers to drop times



Sn 3.2Ag0.7Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.2}Cu_{0.7}Sn_{96.1}$ (weight per cent)
	$Ag_{3.5}Cu_{1.3}Sn_{95.2}$ (atom per cent)
Melting temperature:	216 / 218.5 °C (solidus / liquidus) [calc]
Density:	7.3 Mg m^{-3} [NCMS]

Sn 3.2Ag0.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.2}Cu_{0.5}Sn_{96.3}$ (weight per cent)
	$Ag_{3.5}Cu_{0.9}Sn_{95.6}$ (atom per cent)
Melting temperature:	217 / 218 °C (solidus / liquidus) [00Sol]
	217 / 218 °C (solidus / liquidus) [00Lee]
Reflow Temperature.	238 – 248 °C [00Sol]

References:

[00Lee] *N.-C. Lee and W. Casey, 'soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

Sn 3.5Ag0.75Cu

(Patented Composition)

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{0.75}Sn_{95.75}$ (weight per cent)
	$Ag_{3.8}Cu_{1.4}Sn_{94.8}$ (atom per cent)
Melting temperature:	218 °C [00Sol]
	216 / 217.5 °C (solidus / liquidus) [calc]
Reflow Temperature.	238 – 248 °C [00Sol]
Density:	7.5 g cm^{-3} [04Kim]
Young's Modulus:	54.9 GPa [04Kim]
Poisson's Ratio:	0.40 [04Kim]

References:

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[04Kim] *Jong-Wong Kim, Seung-Boo Jung, Materials Science Engineering A 371 (2004) 267-276*

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: Effects of Shear Speed on SAC solder joints

Institution / Author:
J.W. Kim
Department of Advanced Materials Engineering
Sungkyunkwan University
300 Chunchun-dong
Jangan-gu, Suwon 440-746
South Korea

Measurement technique: B5 Shear Force Tests

Reference: J.W. Kim, S.-B. Jung; Mater. Sci. Eng. A, 371 (2004) p.267-276

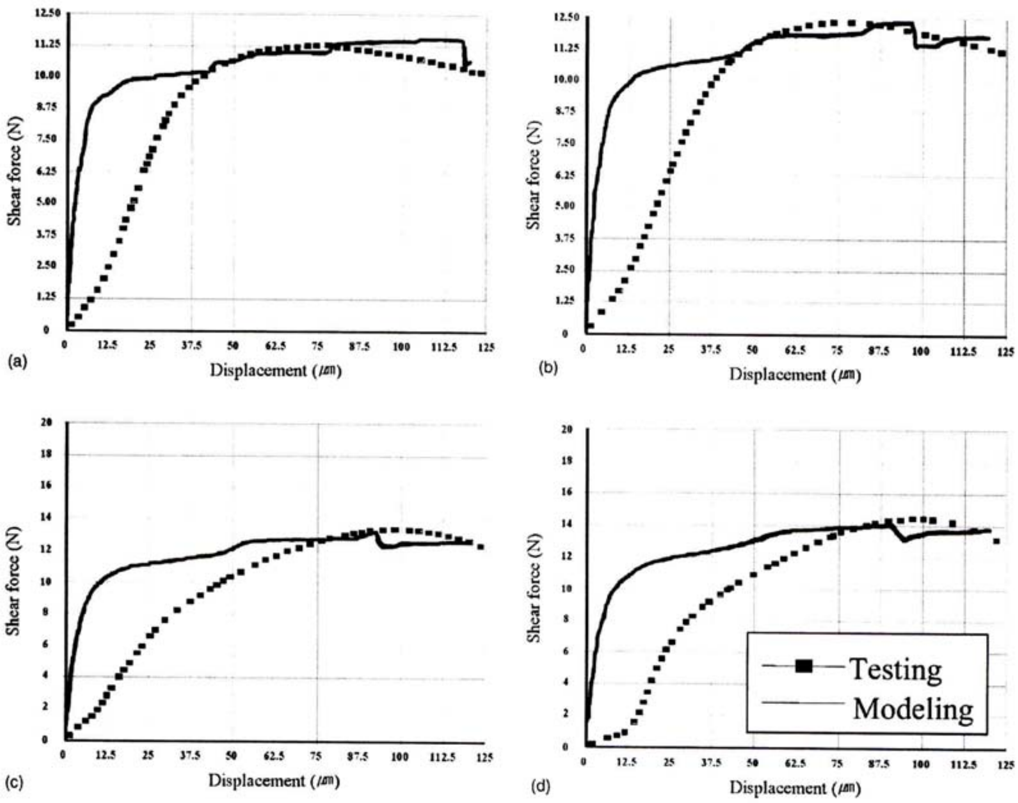
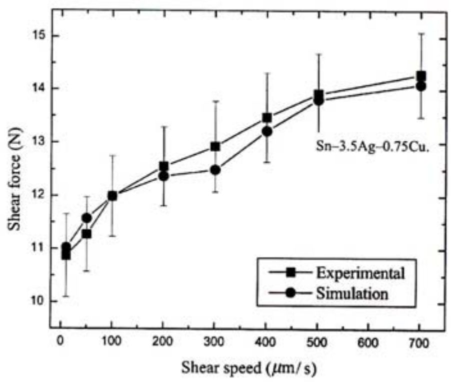


Fig. 5. Force–displacement graphs of Sn–3.5Ag–0.75Cu at various shear speeds: (a) 50 μm/s, (b) 200 μm/s, (c) 400 μm/s, (d) 700 μm/s.



Shear force variations with increasing shear speed

Sn 4Ag0.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_4Cu_{0.5}Sn_{95.5}$ (weight per cent)
	$Ag_{4.4}Cu_{0.9}Sn_{94.7}$ (atom per cent)
Melting temperature:	217 / 219 °C (solidus / liquidus) [00Sol]
	217 / 225 °C (solidus / liquidus) [00Lee]
	217 / 218 °C (solidus / liquidus) [00anon]
Density:	7.39 Mg m^{-3} [00Rae]
	7.44 Mg m^{-3} [00anon]
Wetting angle:	34 – 51 ° [92Via]

References:

[92Via] P.T. Vianco, F.M. Hosking, J.A. Regent; Wettability Analysis of tin-based lead-free solders, Proc. Of the Technical Program – National Electronic Packaging and Production Conference, Vol. 3. Published by Cahner Exposition Group, 1992, Anaheim, CA, pp.1730-1738

[00Lee] *N.-C. Lee and W. Casey, 'soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

[00Rae] *Alan Rae and Ronald C. Lasky, 'Economics and Implications of Moving to Lead-Free Assembly', Proc. NEPCON WEST (February 27 – March 2, 2000), Anaheim, CA*

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[00anon] *'Lead-Free Alloy Trends for the Assembly of Mixed Technology PWBs', Proc. NEPCON-WEST (February 27 – March 2, 2000), Anaheim, CA*

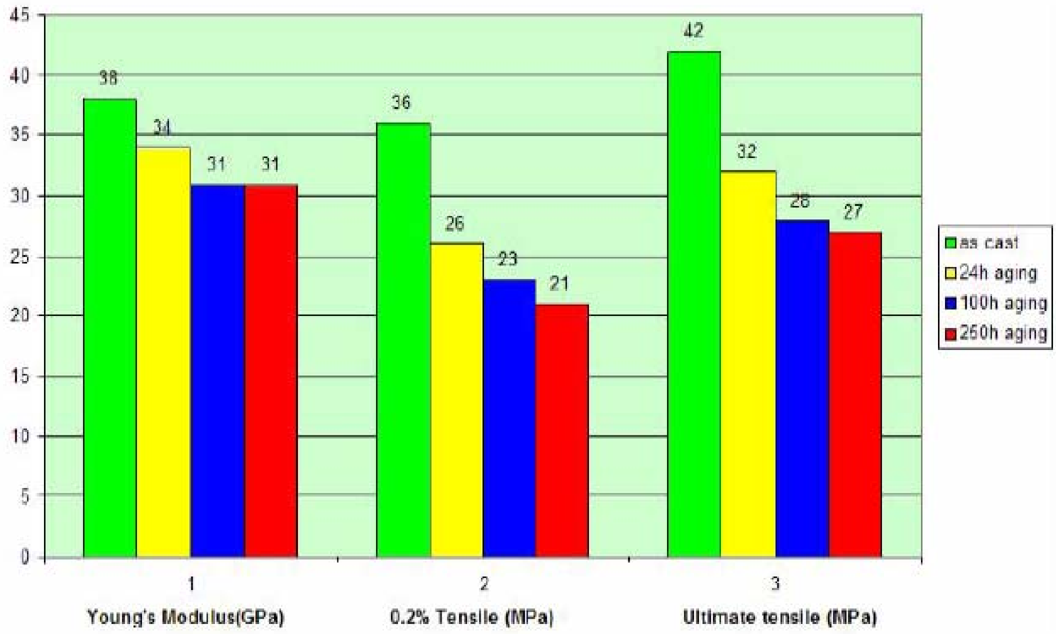
MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile Properties**

Institution / Author: Q. Wang et al.
Auburn University 162 Broun Hall/ECE Dept.
See Section **A6** for full details

Measurement technique: **A6 Tensile Testing – Auburn University Method**

Reference: *Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder' June 24, 2005*



Tensile properties change with aging time at 125°C for Sn-4Ag-0.5Cu

Measured property: **Fatigue life**

Institution / Author: C. Anderson et al.
Swedish Microsystem Integration Technology (SMIT) Center
Division of Electronics Productions
Chalmers University of Technology
c/o IVF, Argongatan 30, SE 431 53 Mölndal
Sweden

Measurement technique: **A5 Low cycle fatigue testing**

Reference: *C. Anderson, Z. Lai, J. Liu, H. Jiang and Y. Yu; Mater. Sci. Eng. A, 394 (2005) p.20-17*

Testing conditions : Room temperature, 0.2 Hz for all tests

Bulk Solder				
$\Delta\varepsilon_t$	$\Delta\varepsilon_p$	N_f	α	C
0.10	0.0912	154	0.6659	2.8530
0.04	0.0325	1024		
0.02	0.0139	3048		
0.01	0.0044	15028		

$\Delta\varepsilon_t$ = Total strain range
$\Delta\varepsilon_p$ = Plastic strain range; N_f = Plastic strain range; α = Fatigue ductility exponent
C = Fatigue ductility coefficient

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Fatigue life**

Institution / Author:

C. Anderson et al.
Swedish Microsystem Integration Technology (SMIT) Center
Division of Electronics Productions
Chalmers University of Technology
c/o IVF, Argongatan 30, SE 431 53 Mölndal
Sweden

Measurement technique: **B6 Low cycle fatigue testing**

Reference: *C. Anderson, Z. Lai, J. Liu, H. Jiang and Y. Yu; Mater. Sci. Eng. A, 394 (2005) p.20-17*

Testing conditions : Room temperature, 0.2 Hz for all tests

Solder Joint		
$\Delta\varepsilon_t$	$\Delta\varepsilon_p$	N_f
0.180	0.0950	325
0.100	0.0405	1913
0.075	0.0308	8384
0.034	0.0152	17018

$\Delta\varepsilon_t$ = Total strain range
$\Delta\varepsilon_p$ = Plastic strain range
N_f = Plastic strain range

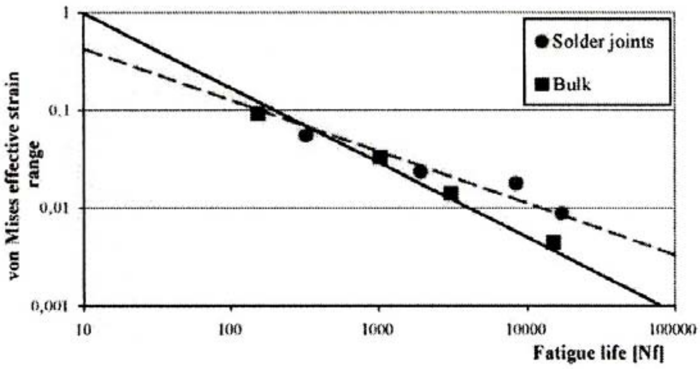
COMPARISON OF BULK AND SOLDER JOINT DATA

Measured property: **Fatigue life vs. von Mises effective strain**

Institution / Author:

C. Anderson et al.
Swedish Microsystem Integration Technology (SMIT) Center
Division of Electronics Productions
Chalmers University of Technology
c/o IVF, Argongatan 30, SE 431 53 Mölndal
Sweden

Reference: *C. Anderson, Z. Lai, J. Liu, H. Jiang and Y. Yu; Mater. Sci. Eng. A, 394 (2005) p.20-17*



Fatigue life vs von Mises effective strain range for Sn-4.0Ag-0.5Cu bulk solder and solder joint.

Sn 4Ag1Cu

(Patented Composition)

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_4Cu_1Sn_{95}$ (weight per cent)
	$Ag_{4.3}Cu_{1.8}Sn_{93.8}$ (atom per cent)
Melting temperature:	217 / 220 °C (sol. / liquidus) [00Sol] [Comp]
	217 / 220 °C (solidus / liquidus) [00Lee]
	216 / 223 °C (solidus / liquidus) [calc]
Reflow Temperature:	238 – 248 °C [00Sol]

References:

[00Lee] *N.-C. Lee and W. Casey, 'Soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

[00Sol] *V. Solberg, 'No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing', Proc. NEPCON West 2000 Conf. (Feb. 28 – Mar. 2, 2000) Anaheim, CA (Source: Indium Corporation)*

[Comp] *See also: Phase Diagrams & Computational Thermodynamics, Metallurgy Division of Materials Science and Engineering Laboratory, NIST*

Sn 2Ag0.75Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_2Cu_{0.75}Sn_{97.25}$ (weight per cent)
	$Ag_{2.2}Cu_{1.4}Sn_{96.4}$ (atom per cent)
Melting temperature:	217 / 219 °C (solidus / liquidus) [00Lee]
	216 / 222 °C (solidus / liquidus) [calc]

References:

[00Lee] *N.-C. Lee and W. Casey, 'Soldering Technology for Area Array Packages', Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

Sn 3.6Ag1.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.6}Cu_{1.5}Sn_{94.9}$ (weight per cent)
	$Ag_{3.9}Cu_{2.8}Sn_{93.3}$ (atom per cent)
Melting temperature:	225 °C (solidus) [94Loo]
	225 °C (solidus) [50Geb]
	216 / 254 °C (solidus / liquidus) [calc]

References:

[50Geb] *E. Gebhardt and G. Petzow; Z. Metallkde.* **50**, *597 (1950)*

[94Loo] *M.E. Loomans, S. Vaynman, G. Ghosh, M.E. Fine; J. Electr. Mater. 23 (8)(1994), 741-746*

Sn 4.1Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{4.1}Cu_{0.9}Sn_{95}$ (weight per cent)
	$Ag_{4.5}Cu_{1.7}Sn_{93.9}$ (atom per cent)
Melting temperature:	216.5 °C (solidus) [94Mil]
	216 / 222 °C (solidus / liquidus) [calc]

References:

[94Mil] *Chad M. Miller, Iver E. Anderson and Jack F. Smith; J. Electr. Mater.* **23** *(7), 595-601 (1994),*

Sn 3.8Ag2.3Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.8}Cu_{2.3}Sn_{93.9}$ (weight per cent)
	$Ag_{4.1}Cu_{4.2}Sn_{91.7}$ (atom per cent)
Melting temperature:	217.4 °C (solidus) [94Mil2]
	216 / 289 °C (solidus / liquidus) [calc]

References:

[94Mil2] *Miller, Anderson and Smith, Note added in proof, J. Electronic Matls.* **23***(7), 601 (1994)*

Sn 3.5Ag1Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{1}Sn_{95.5}$ (weight per cent)
	$Ag_{3.8}Cu_{1.8}Sn_{94.4}$ (atom per cent)
Melting temperature:	216 / 225 °C (solidus / liquidus) [calc] 204.26 / 215.47(Onset solidification / onset melting) [05Lu]
Wetting angle:	36 ° (250 °C, Kester Rosin Flux No. 197)
	44 ° (250 °C, 20 % Rosin dissolved in Isopropanole) [94Loo]

References:

[94Loo] *M.E.Loomans, S. Vaynman, G. Ghosh and M.E. Fine; J. Electr. Mater.* **23***(8), 741 (1994)*
[05Lu] *Henry Y. Lu, Haluk Balkan, K.Y. Simon Ng, JOM, Vol.57(6) (2005) p.30-35*

Sn 3.5Ag1.3Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{1.3}Sn_{95.2}$ (weight per cent)
	$Ag_{3.8}Cu_{2.4}Sn_{93.8}$ (atom per cent)
Melting temperature:	216 / 243.5 °C (solidus / liquidus) [calc]
Density:	7.4 Mg m^{-3} [NCMS]

Sn 2.1Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{2.1}Cu_{0.9}Sn_{97}$ (weight per cent)
	$Ag_{2.3}Cu_{1.7}Sn_{96}$ (atom per cent)
Melting temperature:	216.9°C
	216 / 222 °C (solidus / liquidus) [calc]
Hardness:	17.7 HVN [04Kan]

References:

[04Kan] *Sung K. Kang, Paul Lauro Material Transactions, 45 No.3 2004, 695-702*

Sn 2.5Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{2.5}Cu_{0.9}Sn_{96.6}$ (weight per cent)
	$Ag_{2.7}Cu_{1.7}Sn_{95.6}$ (atom per cent)
Melting temperature:	216.8°C [04Kan]
	216.8 °C [03Kan]
	216 / 220.5 °C (solidus / liquidus) [calc]
Hardness:	19.3 HVN [04Kan]

References:

[03Kan] *S.K. Kang, W.K. Choi, D.-Y. Shih, D.W. Henderson, T. Gosselin, A. Sarkhel, C. Goldsmith and K.J. Puttlitz; IBM Research report, RC22717 (W0302-019), February 5, 2003*

[04Kan] *Sung K. Kang, Paul Lauro MaterialTtransactions, 45(3) (2004), p.695-702*

Sn 3.95Ag0.65Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.95}Cu_{0.65}Sn_{95.4}$ (weight per cent)
	$Ag_{3.5}Cu_{1.3}Sn_{95.2}$ (atom per cent)
Melting temperature:	216.35°C [05Sob]
Wetting angle:	59° (see technique **C1**; 503K, vacuum)[05Sob]

References:

[05Sob] *N. Sobczak, J. Sobczak, R. Nowak, A. Kudyba, P. Darlak; J. Mater. Sci., 40 (2005), p.2547-2551*

MECHANICAL PROPERTIES OF SOLDER JOINTS

Measured property: **Shear Strength**

Institution / Author

N. Sobczak et al.
Foundry Research Institute
73 Zakopianska Street, 30-418 Cracow
Poland
Fax: 48-12-2660870
Tel: 48-12-2618526
e-mail: natalie@iod.krakow.pl

Measurement technique: **B2 Push-off Shear Test**

References:

N. Sobczak, J. Sobczak, R. Nowak, A. Kudyba, P. Darlak; J. Mater. Sci., 40 (2005), p.2547-2551

Temperature [°C]	τ (MPa)	
	Before thermal cycling	After thermal cycling
300	32.7	30.1

Sn 2.5Ag0.7Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition: $Ag_{2.5}Cu_{0.7}Sn_{96.8}$ (weight per cent)

$Ag_{2.7}Cu_{1.3}Sn_{96.0}$ (atom per cent)

Wetting angle: 53.5° (see technique **C2**) [04Yu]

References:

[04Yu] *D.Q. Yu, J. Zhao and L. Wang; J. All. Comp., 376 (2004) p.170-175*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile property**

Institution / Author:

D.Q. Yu et al.
Department of Materials Engineering
Dalian University of Technology
Dalian 116024
PR China

Measurement technique: **A10 Tensile Testing**

References: *D.Q. Yu, J. Zhao and L. Wang; J. All. and Comp., 376 (2004) p.170-175*

Temperature [K]	Test Speed [not mentioned]	Process	Stress [Mpa]
298	$1.5x\ 10^{-2}$	Aging (373 K for 5 h)	53.8

Sn 3.9Ag0.6Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.9}Cu_{0.6}Sn_{95.5}$ (weight per cent)
	$Ag_{4.3}Cu_{1.1}Sn_{94.6}$ (atom per cent)
Melting temperature:	217.5 – 218.5°C [02Kim]
Wetting angle:	59° (see technique **C1**; 503K, vacuum)[05Sob]

References:

[02Kim] *K. S. Kim, S. H. Huh, K. Suganuma, Mater. Sci. Eng. A, 333 (2002), p.106 – 114*

[05Sob] *N. Sobczak, J. Sobczak, R. Nowak, A. Kudyba, P. Darlak; J. Mater. Sci., 40 (2005), p.2547-2551*

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile Properties of Aged Solders**

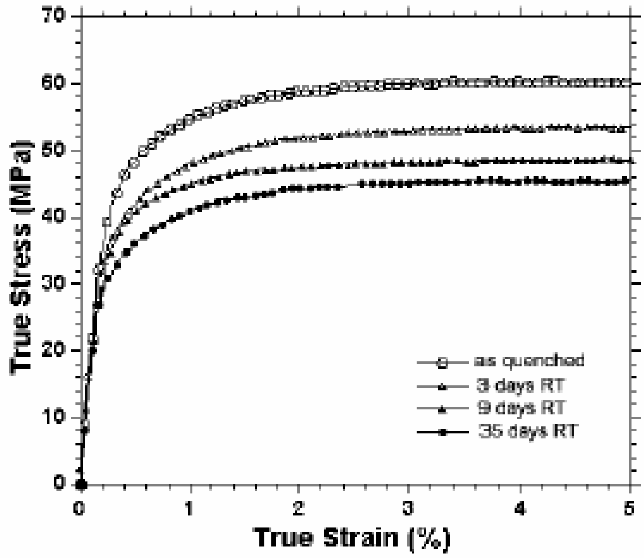
Institution / Author: Q. Xiao et al.

Department of Mechanical Engineering, University of Wyoming

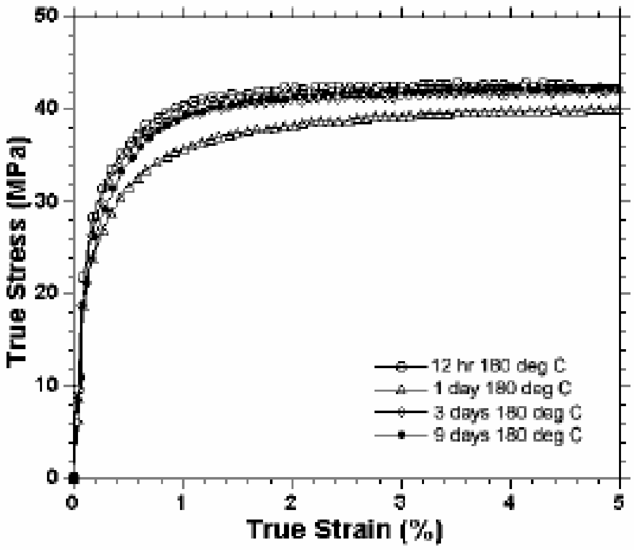
Laramie, WY 82071

Measurement technique: **A12 Tensile and Creep Properties Testing**

Reference: *Q. Xiao, Luu Nguyen, W. D. Armstrong, Electronic Component and Technology Conference.*



(a) aging at RT



(b) aging at 180 deg C

True stress versus true strain data Sn3.9Ag0.6Cu lead free solder

Sn 2.0Ag0.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition: $Ag_{2.0}Cu_{0.5}Sn_{97.5}$ (weight per cent)

$Ag_{2.2}Cu_{0.9}Sn_{96.9}$ (atom per cent)

References:
none

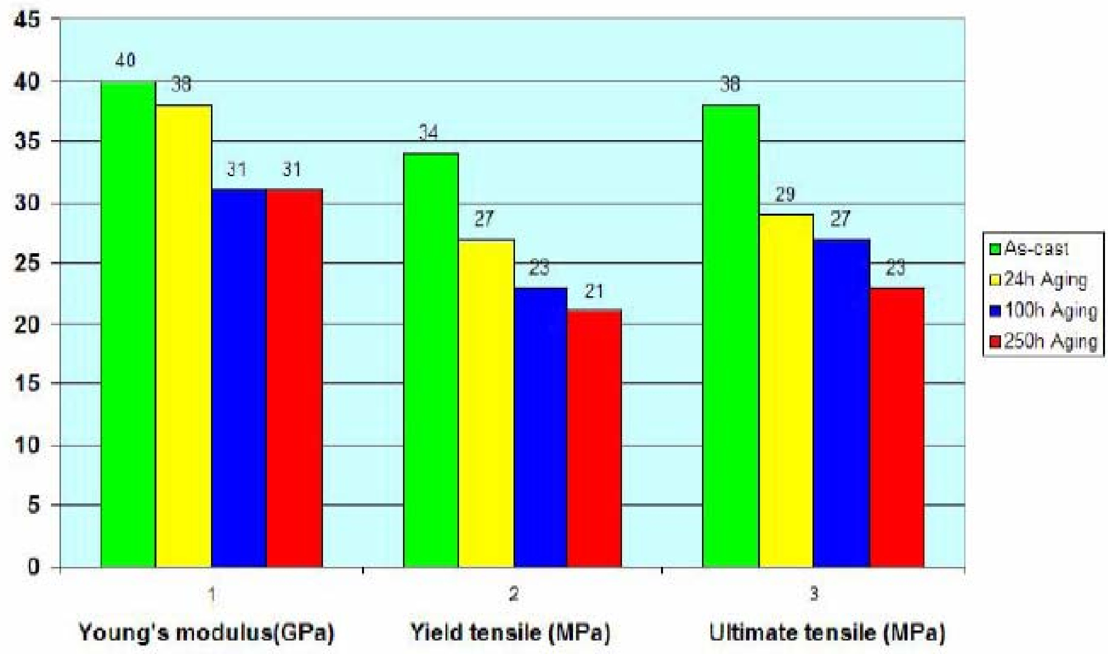
MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: Tensile Properties

Institution / Author: Q. Wang et al.
Auburn University 162 Broun Hall/ECE Dept.
See Section **A6** for full details

Measurement technique: A6 Tensile Testing – Auburn University Method

Reference: *Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder' June 24, 2005*



Tensile properties change with aging time at 125°C for Sn 2Ag 0.5Cu

MECHANICAL PROPERTIES OF SOLDER JOINTS

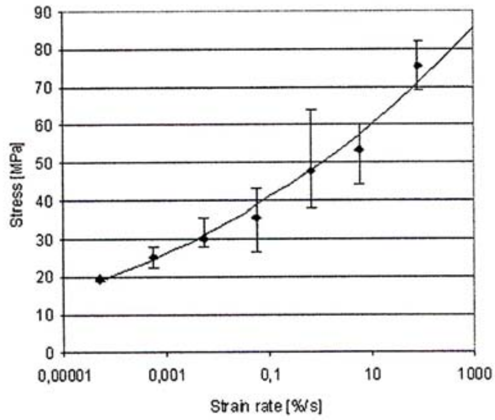
Measured property: Flow stress

Institution / Author: **Deparment of Electrical and Communication Engineering, Helsinki University of Technology**, Espoo, FIN-02015 TTK Finland

Measurement technique: not mentioned

Reference: *T.T. Mattila and J. K. Kivilathi, J. Electr. Mater., Vol. 34 No. 7, 2005*

Flow stress versus strain rate of Sn 2Ag 0.5Cu solder joint at room temperature



Sn 2.0Ag1.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition: $Ag_{2.0}Cu_{1.5}Sn_{96.5}$ (weight per cent)

$Ag_{2.2}Cu_{2.8}Sn_{95.1}$ (atom per cent)

Reference:
none

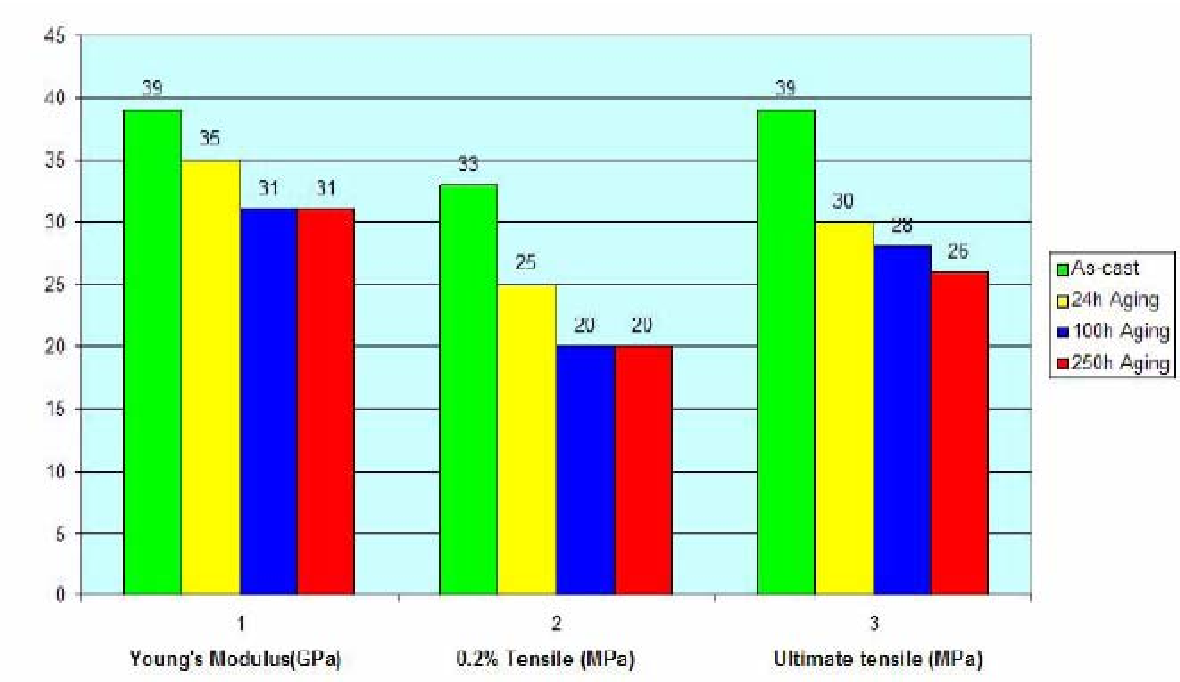
MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: Tensile Properties

Institution / Author: Q. Wang et al.
Auburn University 162 Broun Hall/ECE Dept.
See Section **A6** for full details

Measurement technique: A6 Tensile Testing – Auburn University Method

Reference: *Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder' June 24, 2005*



Tensile properties change with aging time at 125°C for Sn 2Ag 1.5Cu solder

Sn 3.5Ag0.8Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition: $Ag_{3.5}Cu_{0.8}Sn_{95.7}$ (weight per cent)

$Ag_{3.8}Cu_{1.5}Sn_{94.7}$ (atom per cent)

References:
none

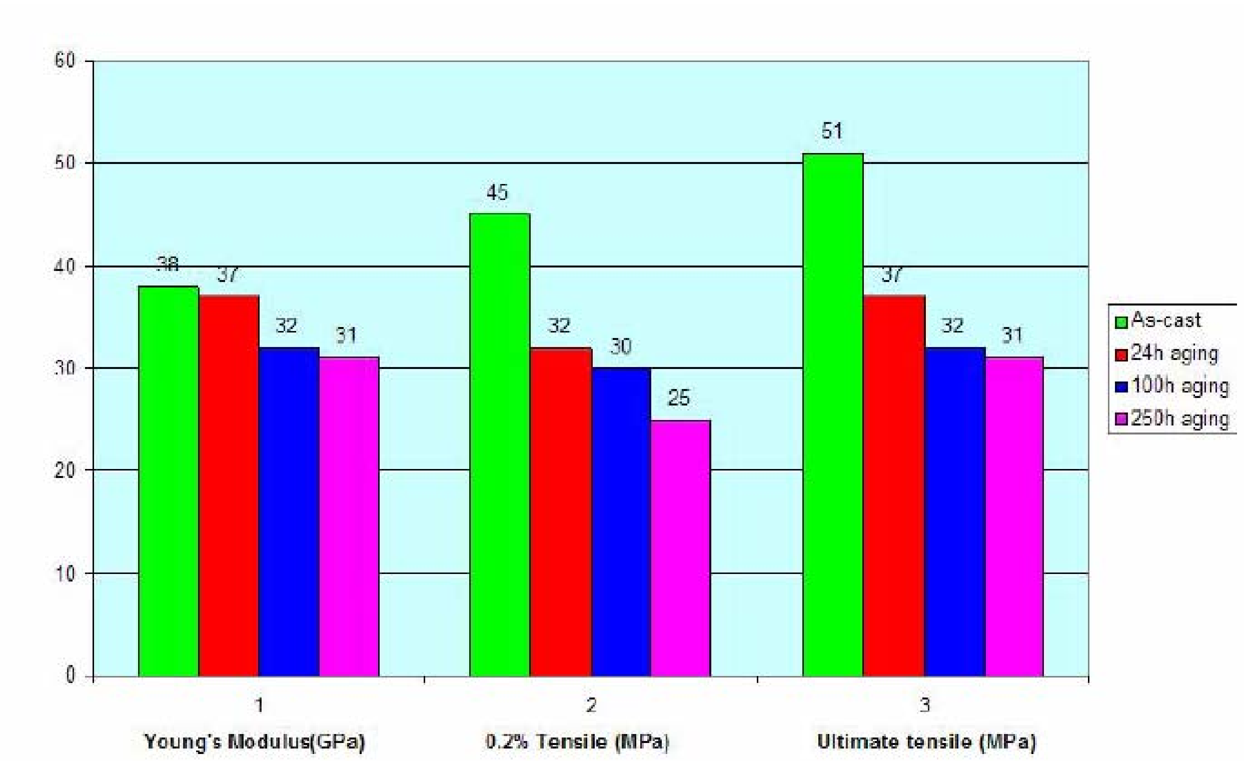
MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: **Tensile Properties**

Institution / Author: Q. Wang et al.
Auburn University 162 Broun Hall/ECE Dept.
See Section **A6** for full details

Measurement technique: **A6 Tensile Testing – Auburn University Method**

Reference: *Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder' June 24, 2005*



Tensile properties change with aging time at 125°C for Sn-3.5Ag-0.8Cu

Sn 3.4Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.4}Cu_{0.9}Sn_{95.7}$ (weight per cent)
	$Ag_{3.7}Cu_{1.7}Sn_{94.6}$ (atom per cent)
Melting temperature:	217 °C [03Kan]

References:

[03Kan] S.K. Kang, W.K. Choi, D.-Y. Shih, D.W. Henderson, T. Gosselin, A. Sarkhel, C. Goldsmith and K.J. Puttlitz; IBM Research report, RC22717 (W0302-019), February 5, 2003

Sn 3.0Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.0}Cu_{0.9}Sn_{96.1}$ (weight per cent)
	$Ag_{3.3}Cu_{1.7}Sn_{95.0}$ (atom per cent)
Melting temperature:	216.8 °C [03Kan]

References:

[03Kan] S.K. Kang, W.K. Choi, D.-Y. Shih, D.W. Henderson, T. Gosselin, A. Sarkhel, C. Goldsmith and K.J. Puttlitz; IBM Research report, RC22717 (W0302-019), February 5, 2003

Sn 2.0Ag0.9Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{2.0}Cu_{0.9}Sn_{97.1}$ (weight per cent)
	$Ag_{2.2}Cu_{1.7}Sn_{96.2}$ (atom per cent)
Melting temperature:	216.9 °C [03Kan]

References:

[03Kan] S.K. Kang, W.K. Choi, D.-Y. Shih, D.W. Henderson, T. Gosselin, A. Sarkhel, C. Goldsmith and K.J. Puttlitz; IBM Research report, RC22717 (W0302-019), February 5, 2003

Sn 4.0Ag1.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition: $Ag_4Cu_{1.5}Sn_{94.5}$ (weight per cent)

$Ag_{4.3}Cu_{2.8}Sn_{92.9}$ (atom per cent)

References:

None

MECHANICAL PROPERTIES OF BULK SOLDER

Measured property: Creep Properties

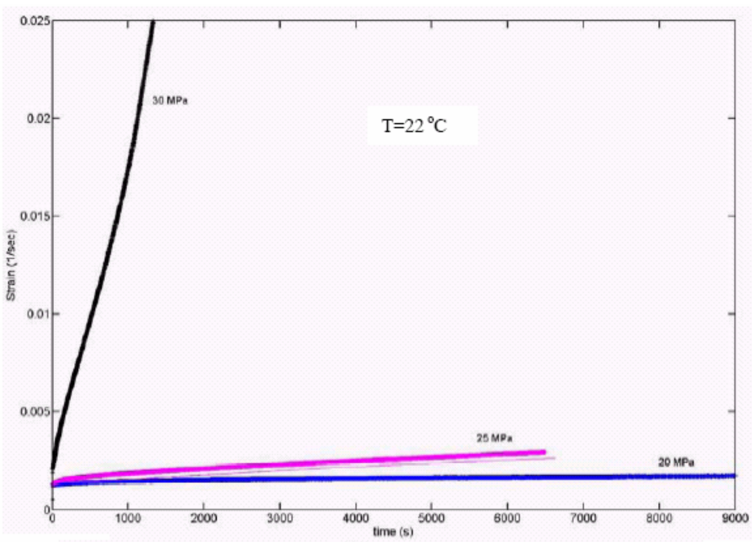
Institution / Author: Q. Wang et al.

Auburn University 162 Broun Hall/ECE Dept.

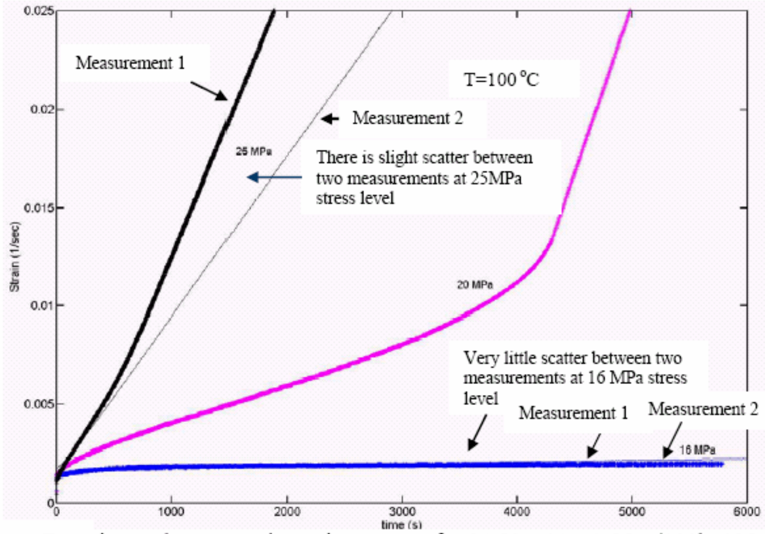
See Section A7 for full details

Measurement technique: A7 Creep Test – Auburn University Method

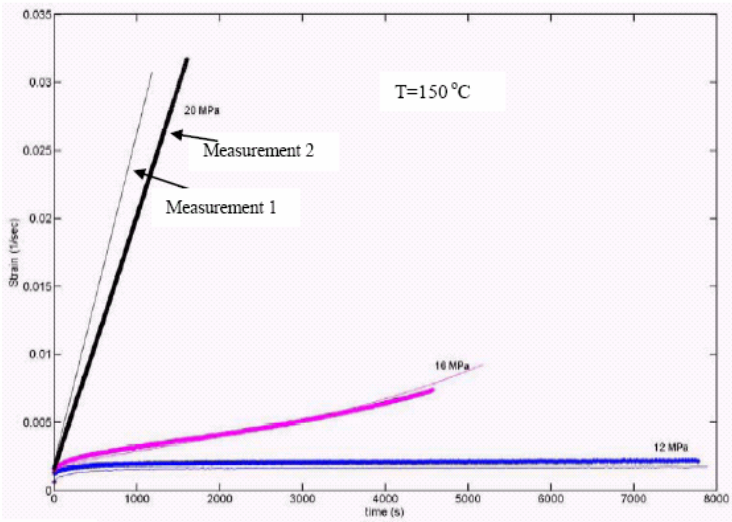
Reference: *Qing Wang, William F. Gail, R. Wayne Johnson, 'Mechanical Properties and Microstructure Investigation Of Lead Free Solder' June 24, 2005*



Experimental creep strain vs time curves for 94.5Sn-4Ag-1.5Cu (100h, 125 °C aging) at T=22 °C



Experimental creep strain vs time curves for 94.5Sn-4Ag-1.5Cu (100h, 125 °C aging) at T=100 °C



Experimental creep strain vs time curves for 94.5Sn-4Ag-1.5Cu (100h, 125 °C aging) at T=150C

Sn 3.5Ag0.5Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{1}Sn_{95.5}$ (weight per cent)
	$Ag_{3.8}Cu_{0.9}Sn_{95.3}$ (atom per cent)
Melting temperature:	205.15 / 215.85 (Onset solidification / onset melting) [05Lu]

References:

[05Lu] *Henry Y. Lu, Haluk Balkan, K.Y. Simon Ng, JOM, Vol.57(6) (2005) p.30-35*

Sn 3.5Ag2.0Cu

PHYSICAL PROPERTIES OF BULK SOLDER

Alloy composition:	$Ag_{3.5}Cu_{1}Sn_{95.5}$ (weight per cent)
	$Ag_{3.8}Cu_{3.7}Sn_{92.6}$ (atom per cent)
Melting temperature:	203.43 / 216.02 (Onset solidification / onset melting) [05Lu]

References:

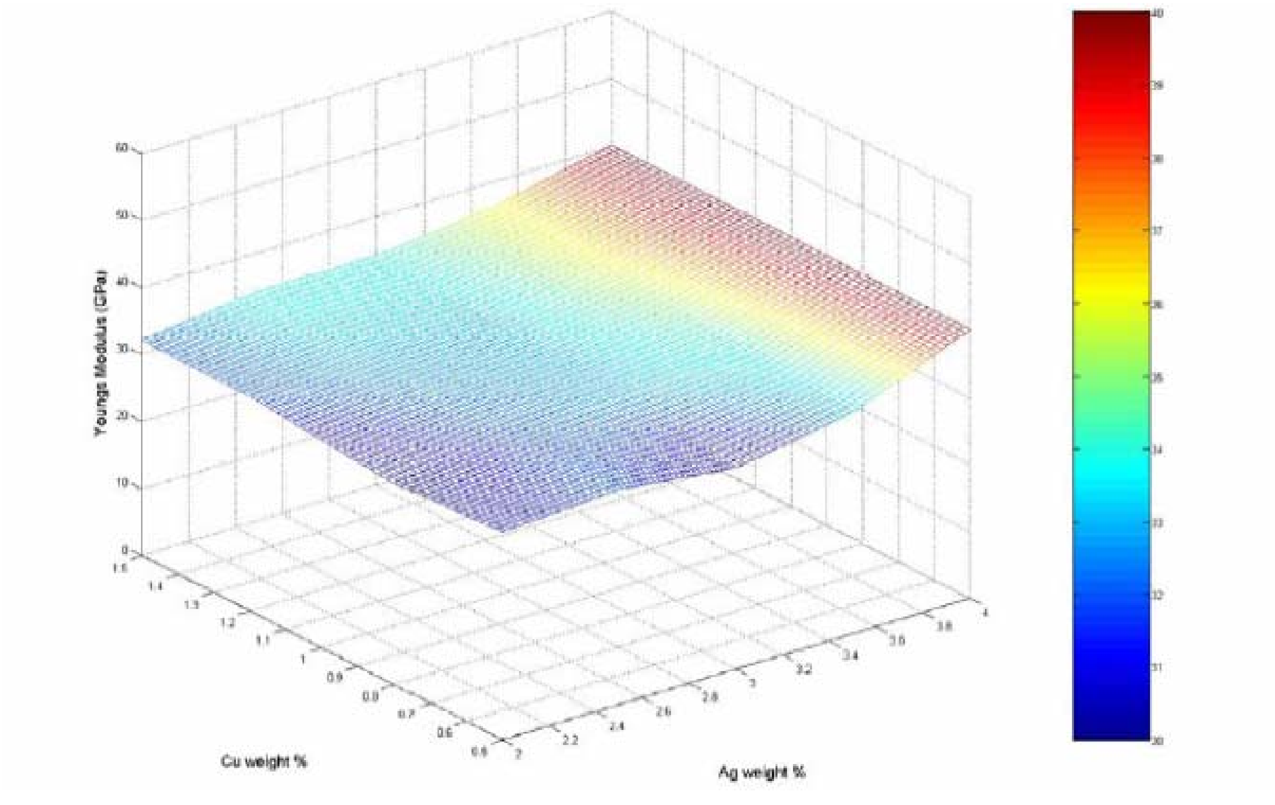
[05Lu] *Henry Y. Lu, Haluk Balkan, K.Y. Simon Ng, JOM, Vol.57(6) (2005) p.30-35*

Comparison of mechanical properties of SAC alloys and solder joints

COMPARISON OF YOUNG'S MODULUS OF WATER QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

Method: **A6 Tensile Testing – Auburn University Method**

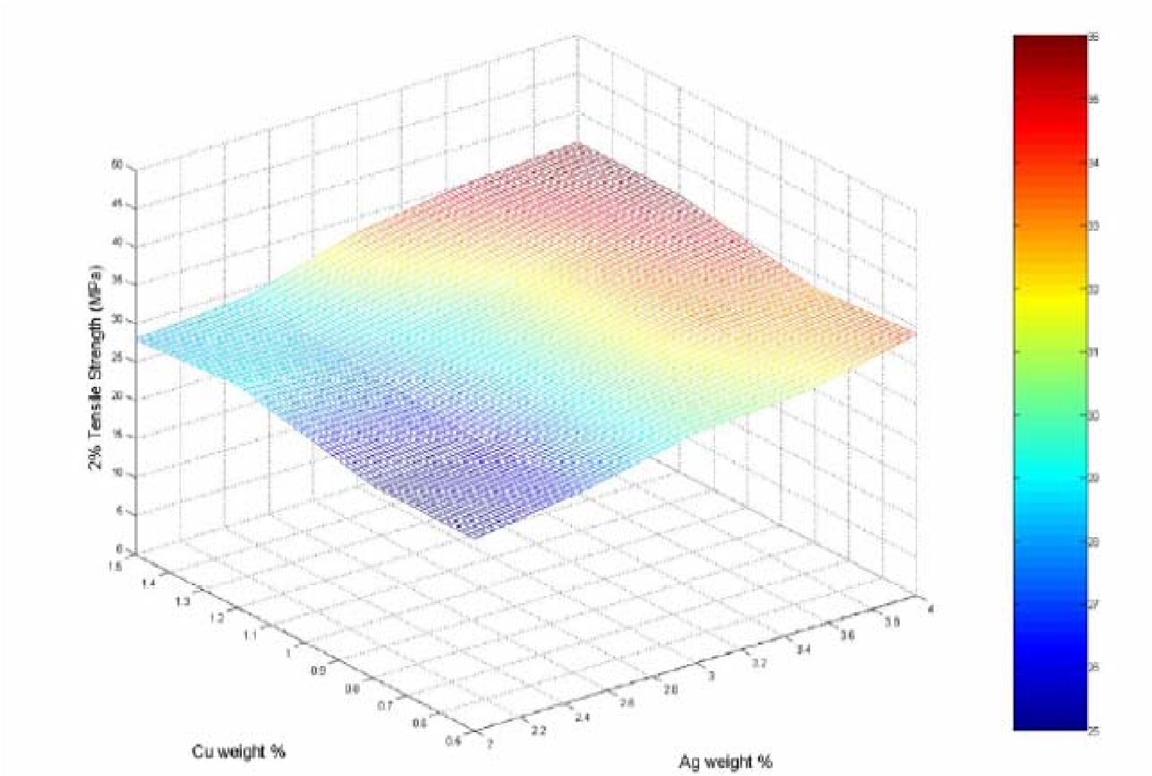


Distribution of Young's modulus as a function of alloy composition

COMPARISON OF 0.2% TENSILE STRENGTH OF WATER QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

Method: **A6 Tensile Testing – Auburn University Method**

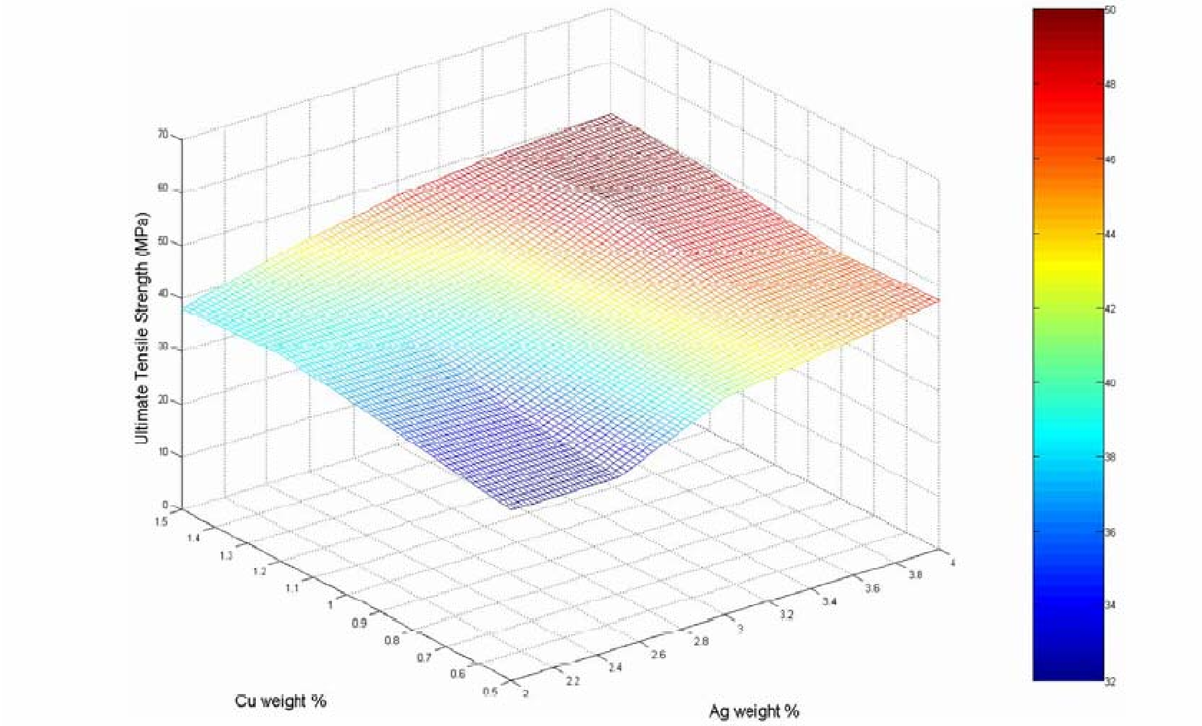


Distribution of 0.2% tensile strength as a function of alloy composition

COMPARISON OF ULTIMATE TENSILE STRENGTH OF WATER QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

Method: **A6 Tensile Testing – Auburn University Method**

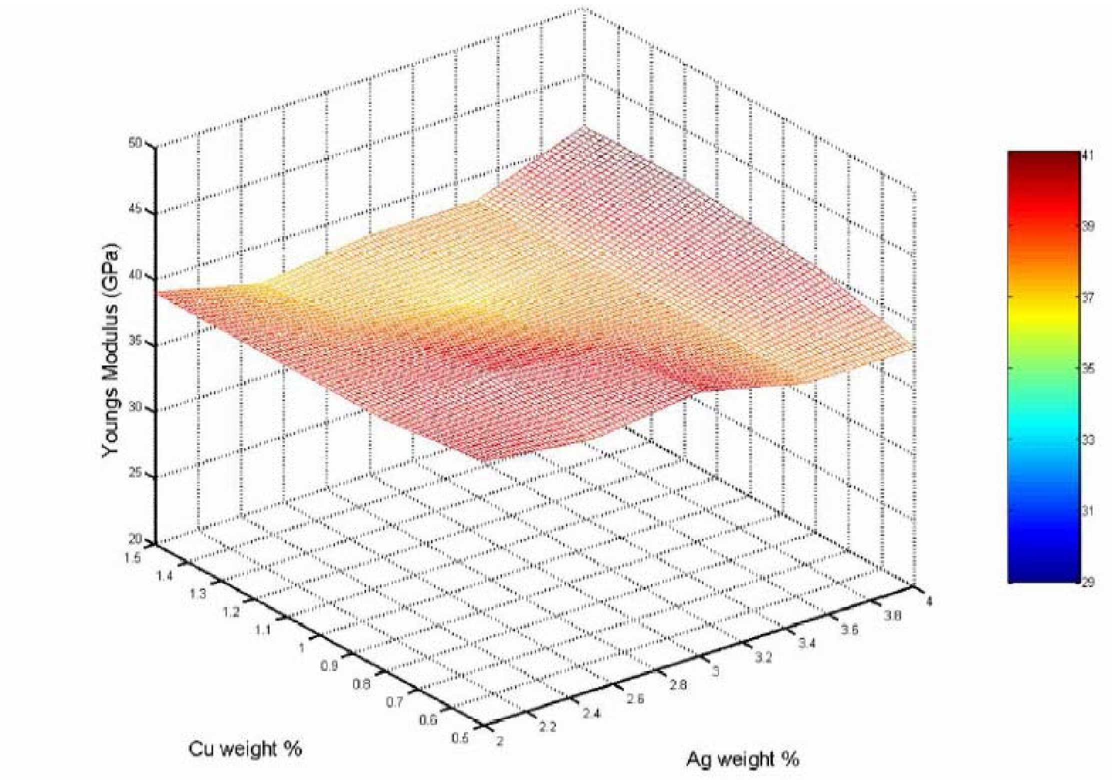


Distribution of ultimate tensile strength as a function of alloy composition

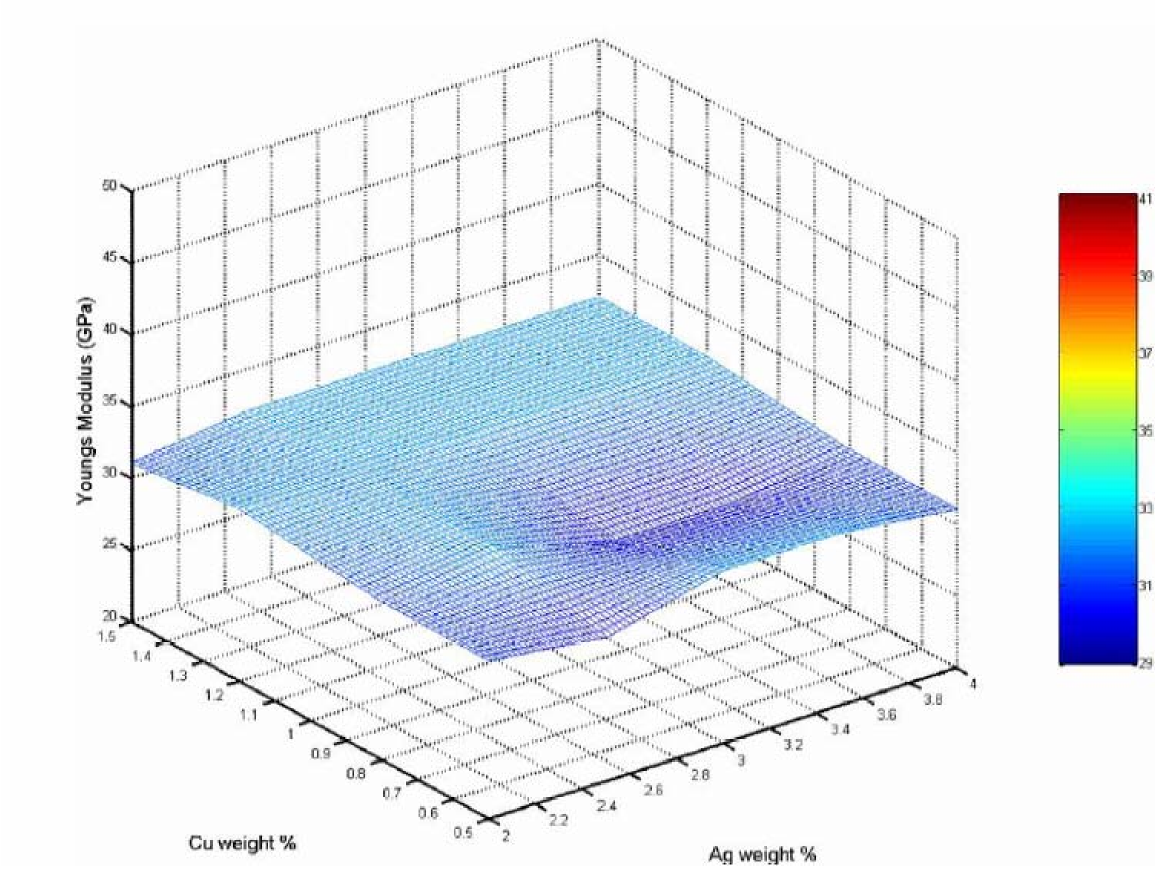
COMPARISON OF YOUNG'S MODULUS OF OIL QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

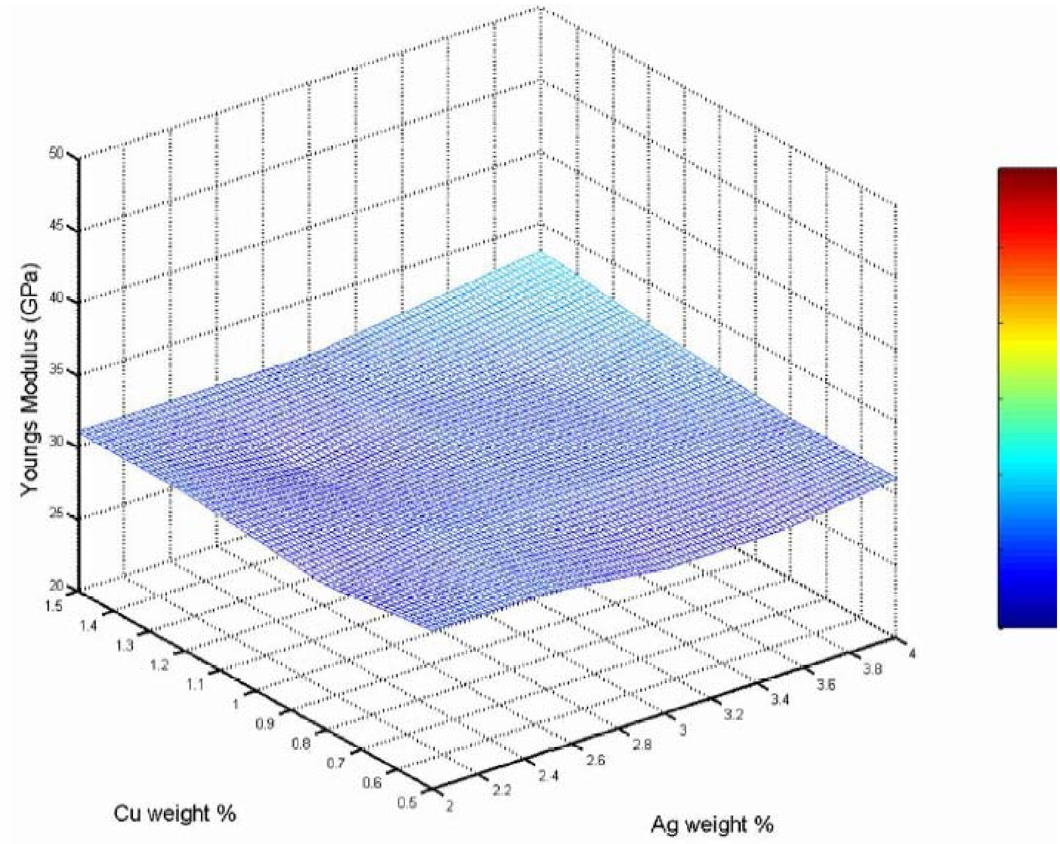
Method: **A6 Tensile Testing – Auburn University Method**



Distribution of Young's modulus as a function of alloy composition (as-cast)



Distribution of Young's modulus as a function of alloy composition (125° C, 100h aging)

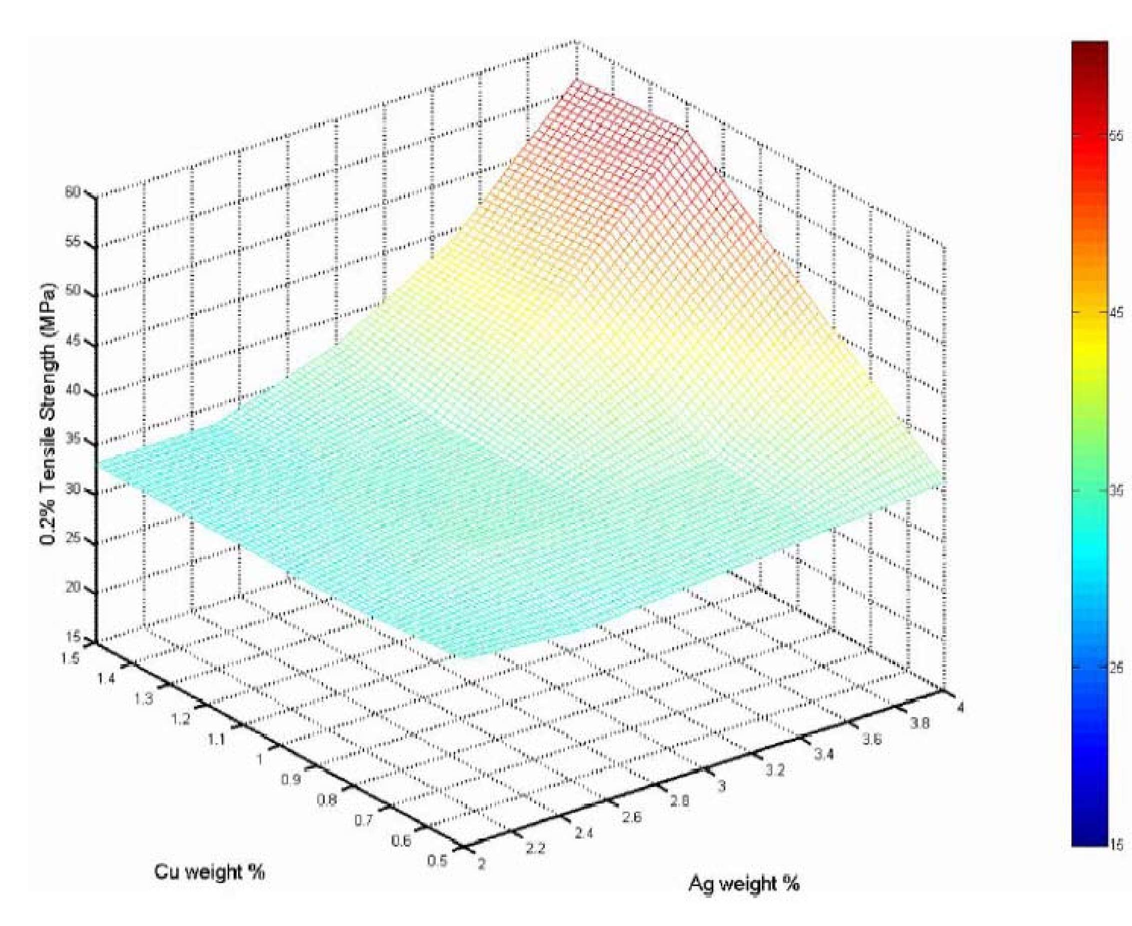


Distribution of Young's modulus as a function of alloy composition (125° C, 250 h aging)

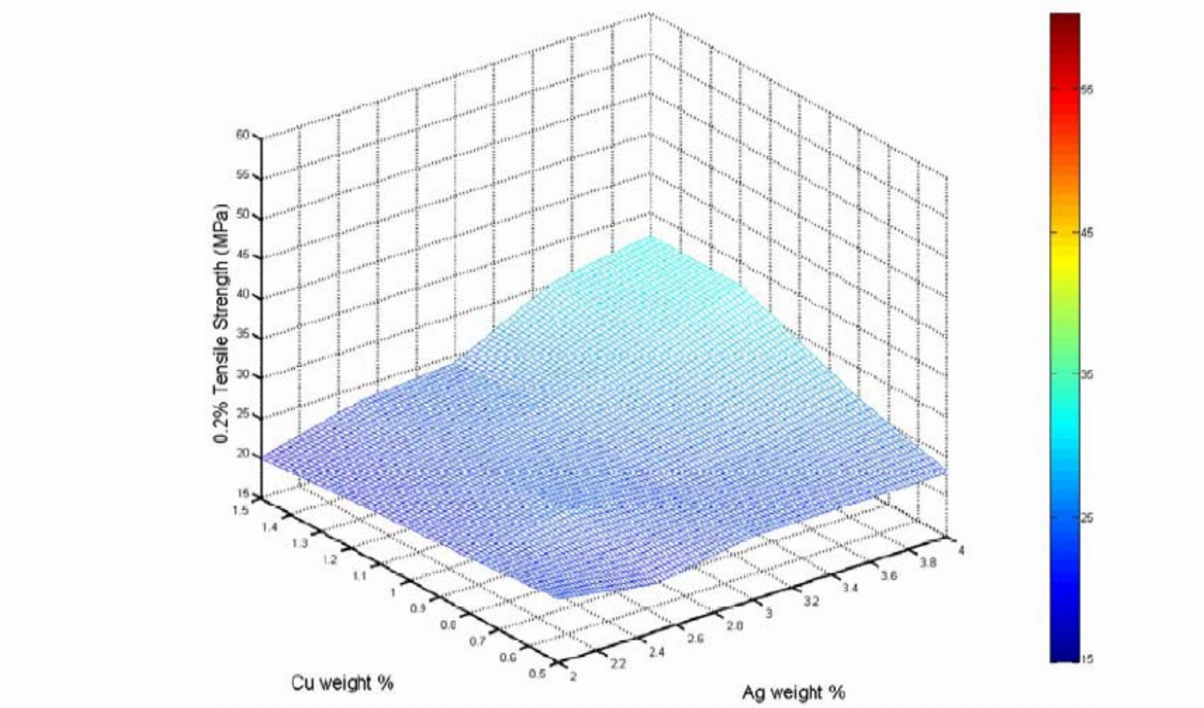
COMPARISON OF 0.2% STRAIN YIELD STRESS OF OIL QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

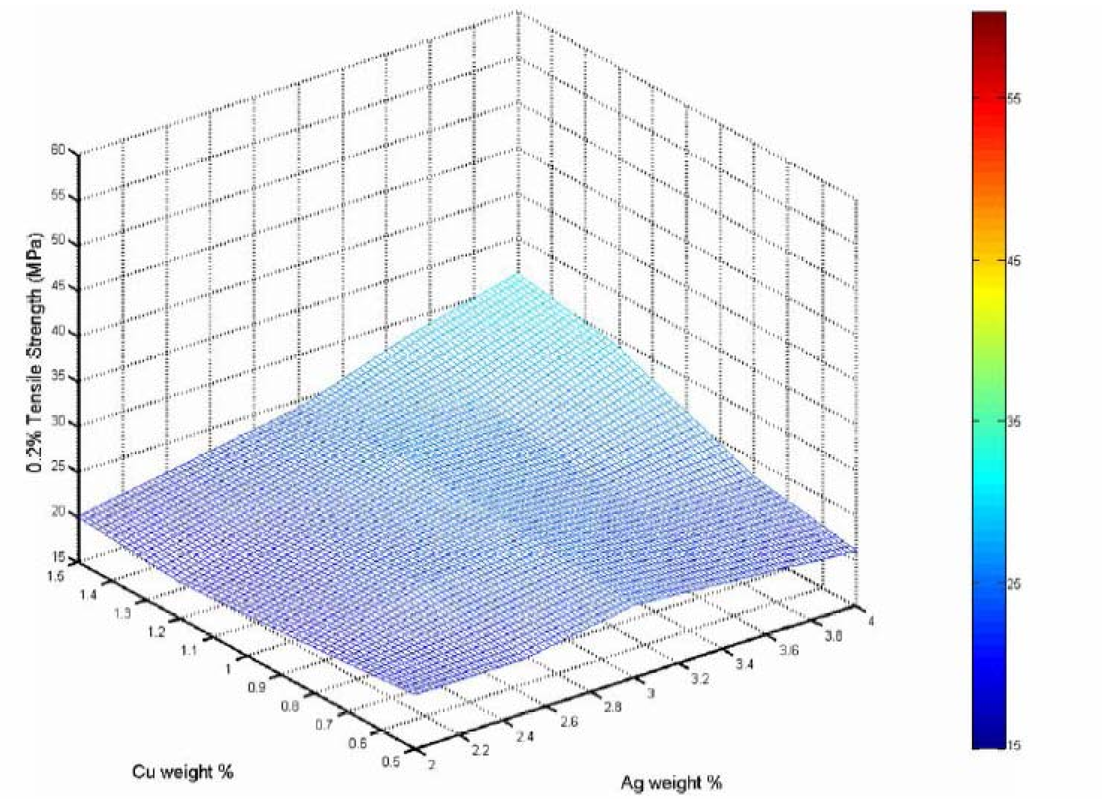
Method: **A6 Tensile Testing – Auburn University Method**



Distribution of 0.2% strain yield stress as a function of alloy composition (as-cast)



Distribution of 0.2% strain yield stress as a function of alloy composition (125 °C, 100h aging)

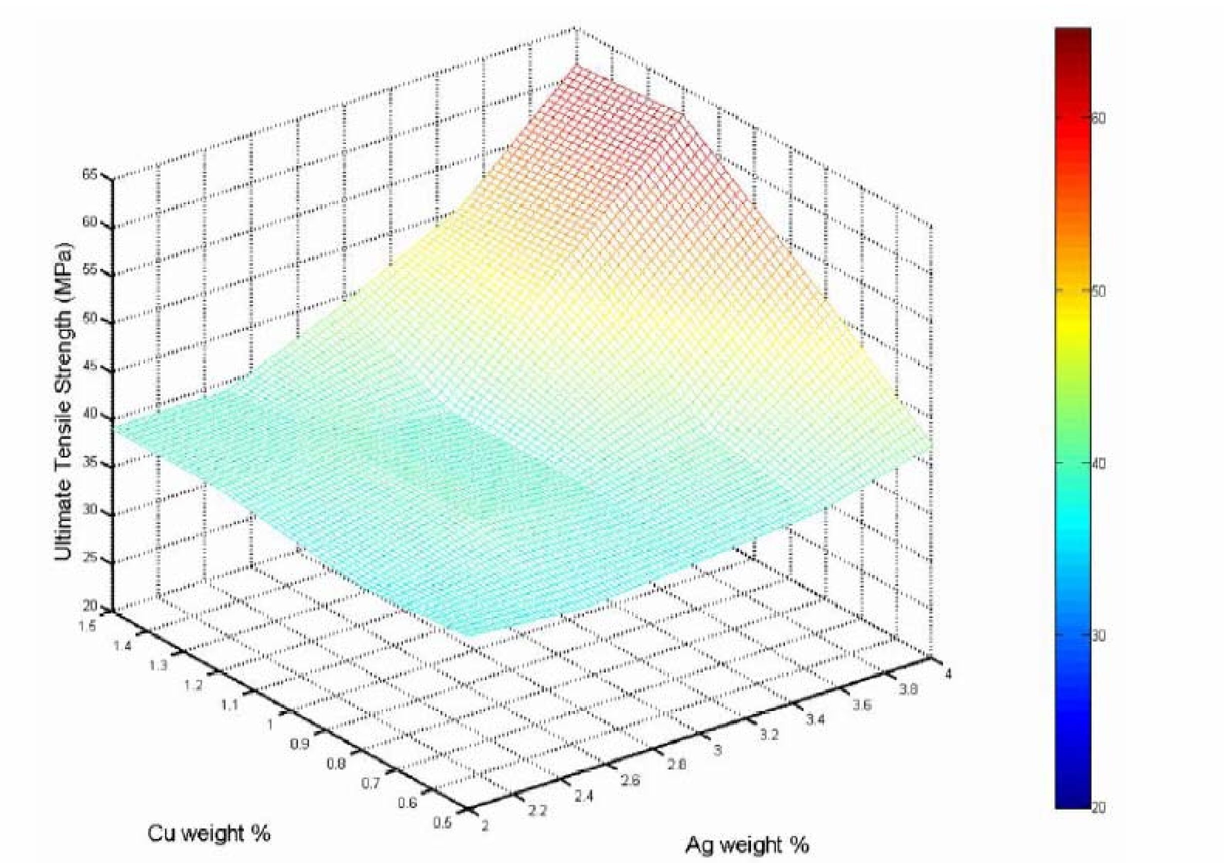


Distribution of 0.2% strain yield stress as a function of alloy composition (125 °C, 250h aging)

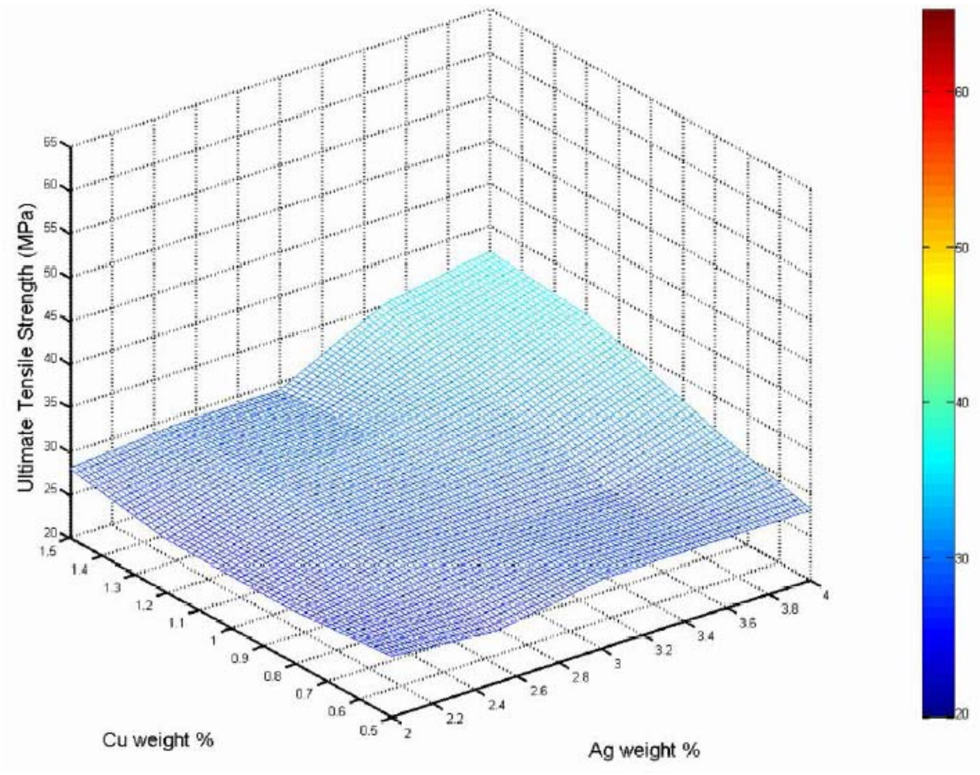
COMPARISON OF ULTIMATE TENSILE STRENGTH OF OIL QUENCHED SAMPLES

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

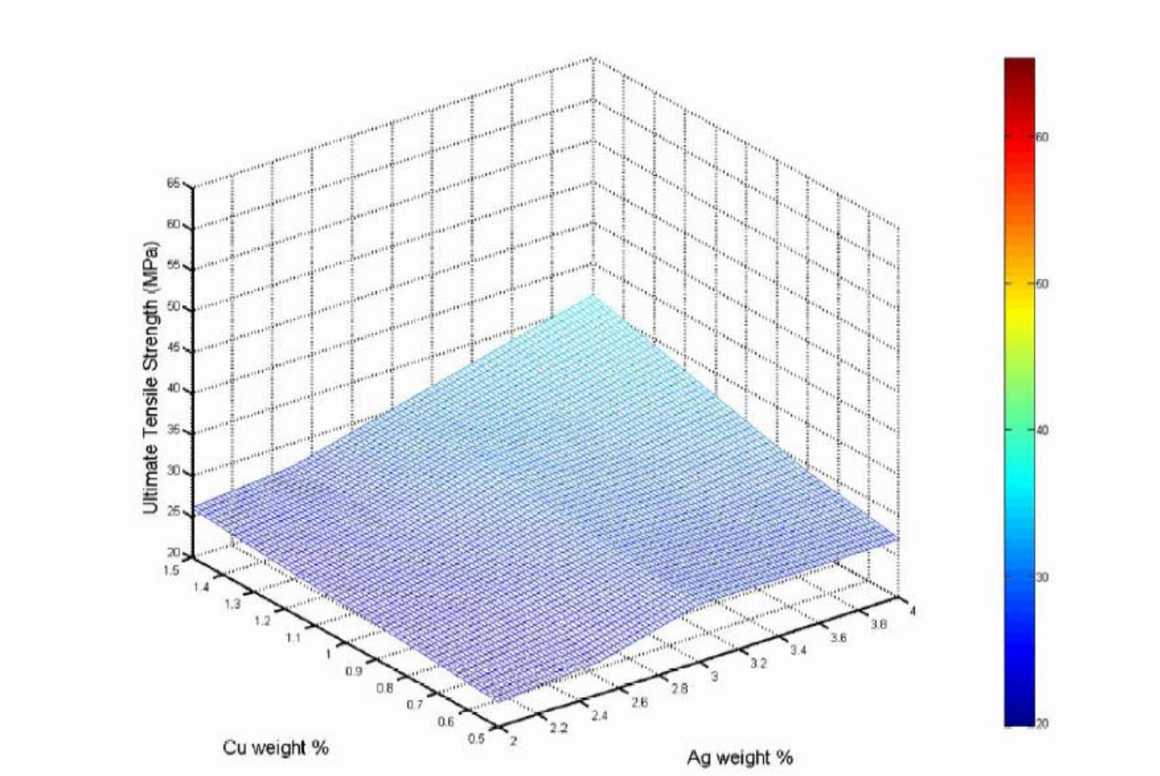
Method: **A6 Tensile Testing – Auburn University Method**



Distribution of ultimate tensile strength as a function of alloy composition (as cast)



Distribution of ultimate tensile strength as a function of alloy composition (125 °C, 100h aging)

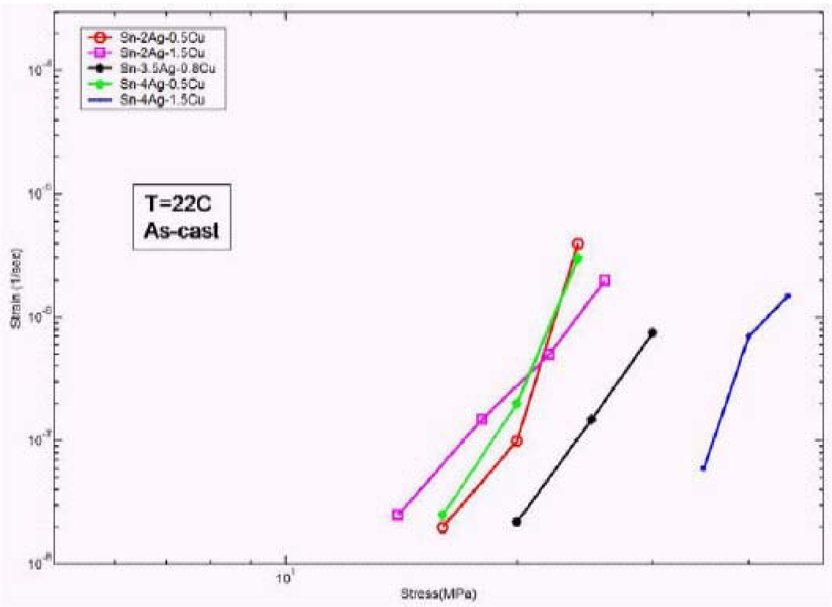


Distribution of ultimate tensile strength as a function of alloy composition (125°C, 250h aging)

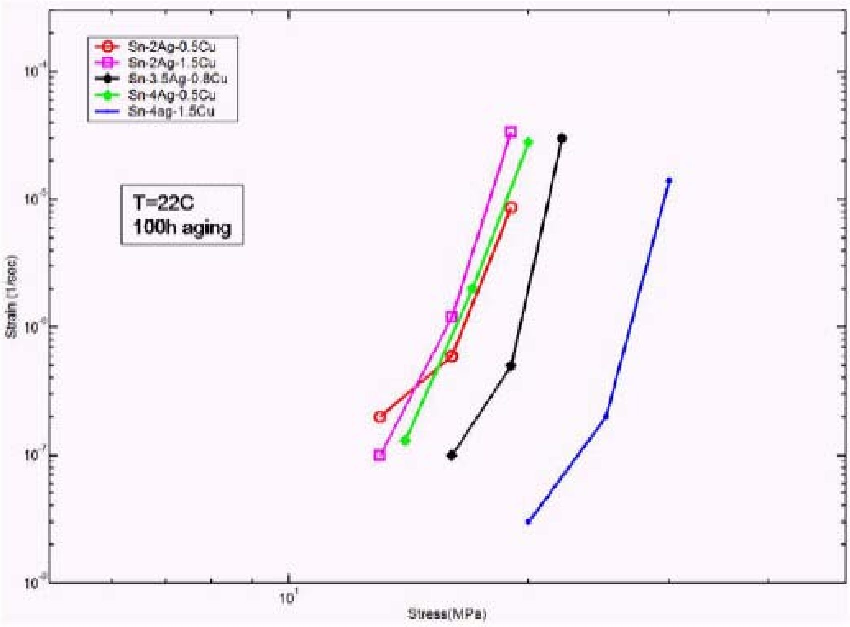
COMPARISON OF CREEP DATA

Reference: Qing Wang, William F. Gail, R. Wayne Johnson
Auburn University 162 Broun Hall/ECE Dept.
Auburn, AL 36849 334-844-1880
johnson@eng.auburn.edu
Mark Strickland NASA/MSFC, Jim Blanche
NASA/MSFC/Allied Aerospace
June 24, 2005

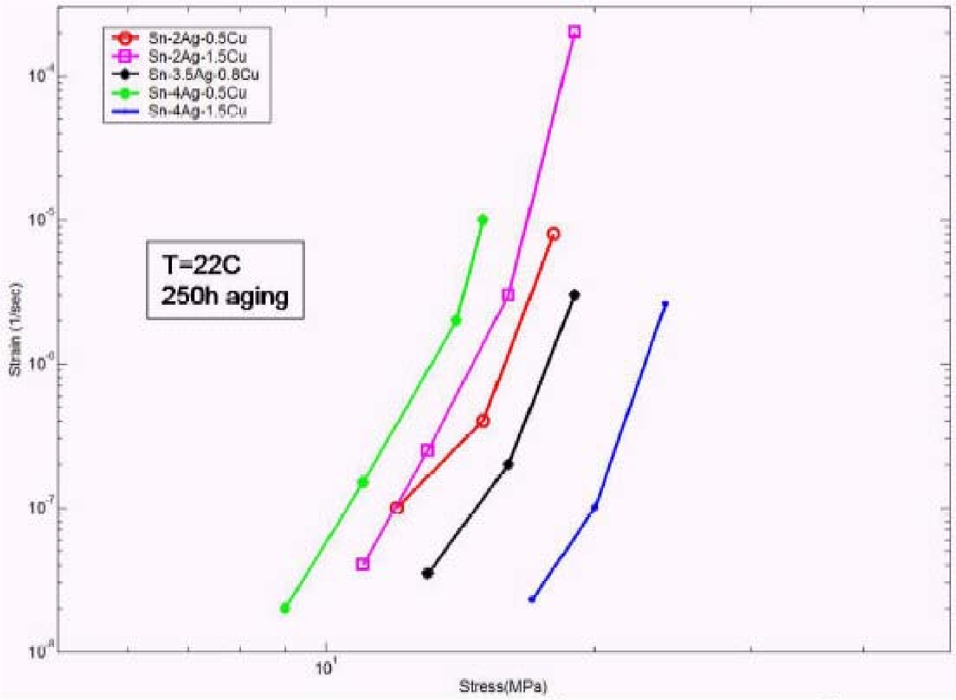
Method: A7 Creep Test – Auburn University Method



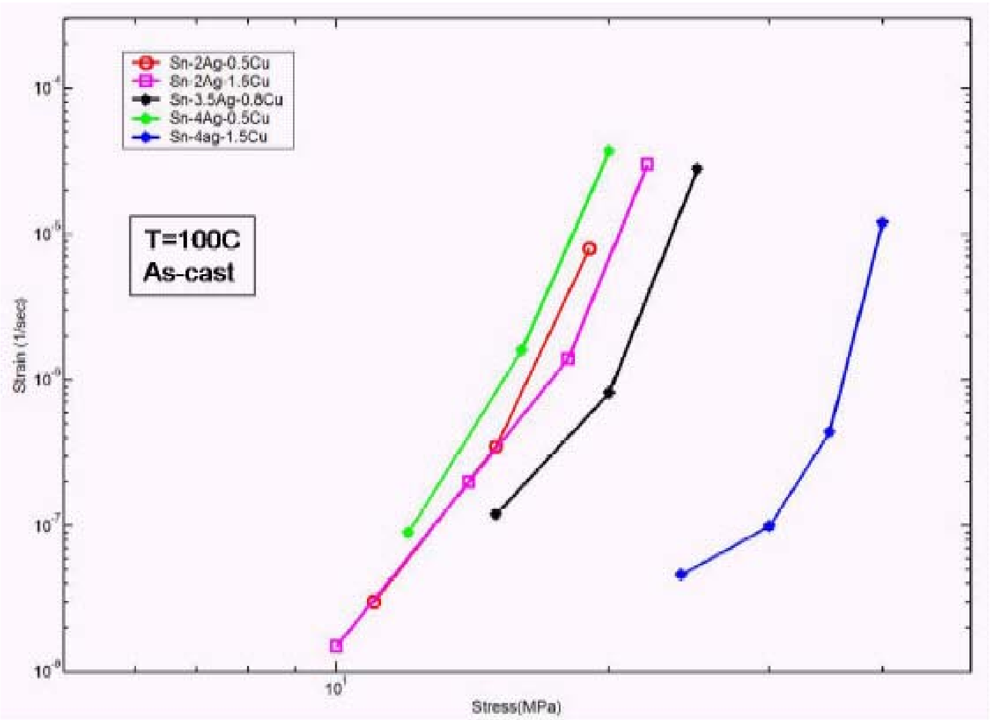
Comparison of creep data at T=22°C (as-cast)



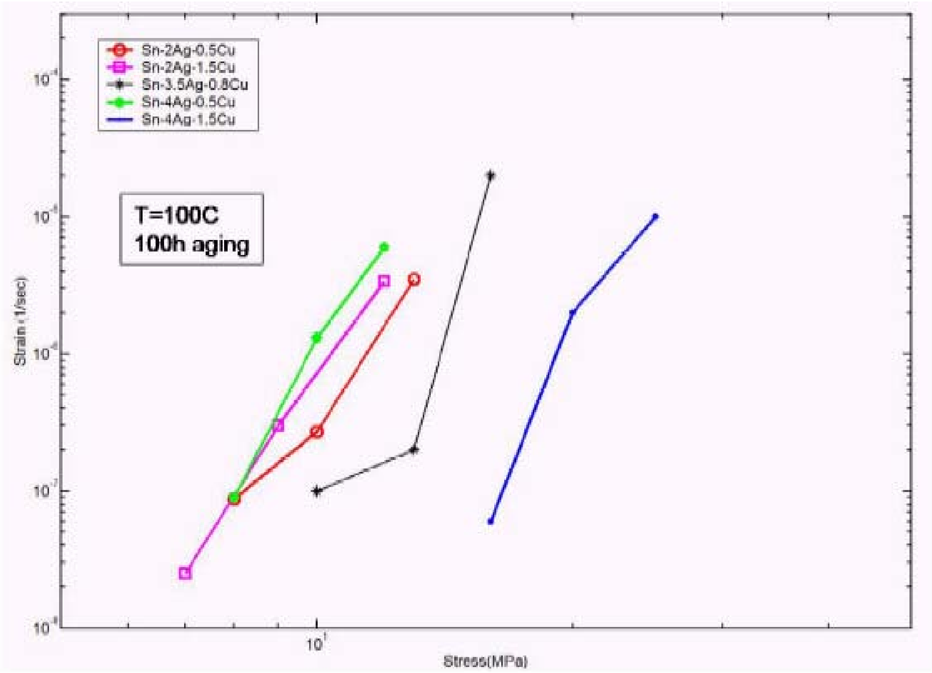
Comparison of creep data at T=22°C (100h aging at 125°C)



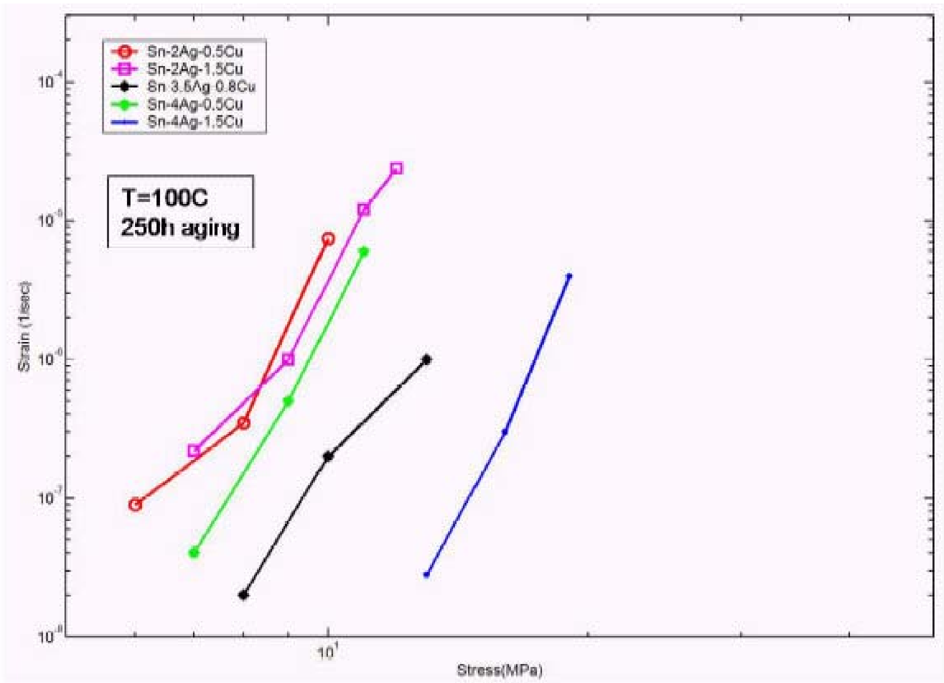
Comparison of creep data at T=22 °C (250h aging at 125°C)



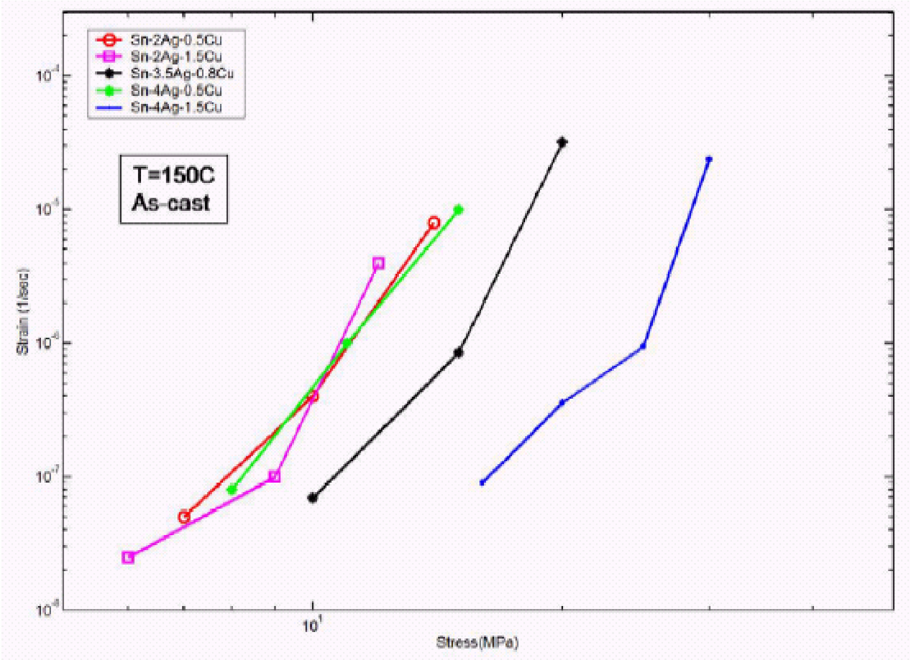
Comparison of creep data at T=100°C (as-cast)



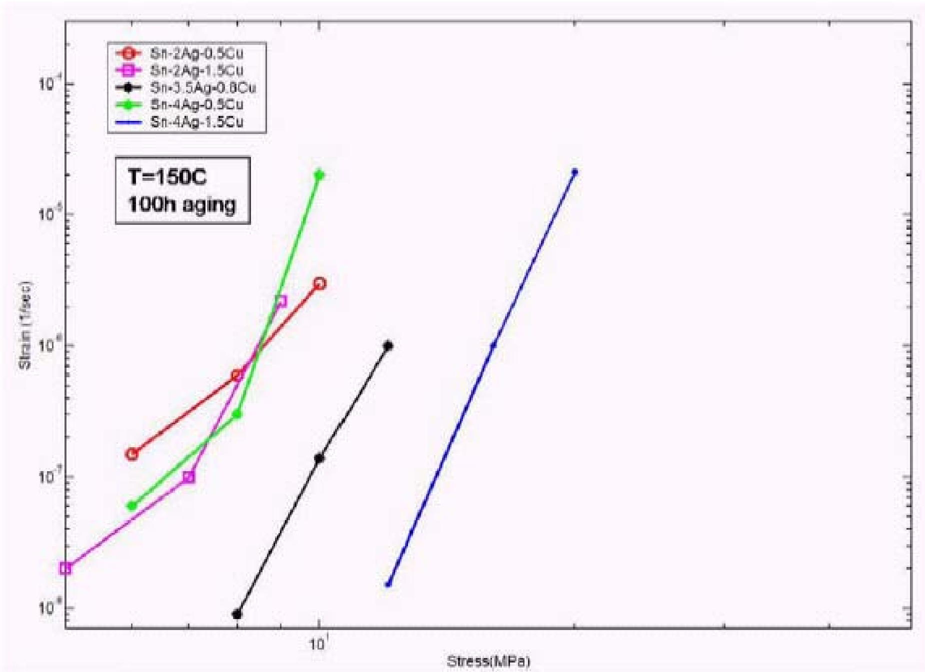
Comparison of creep data at T=100°C (aging 100h at 125°C)



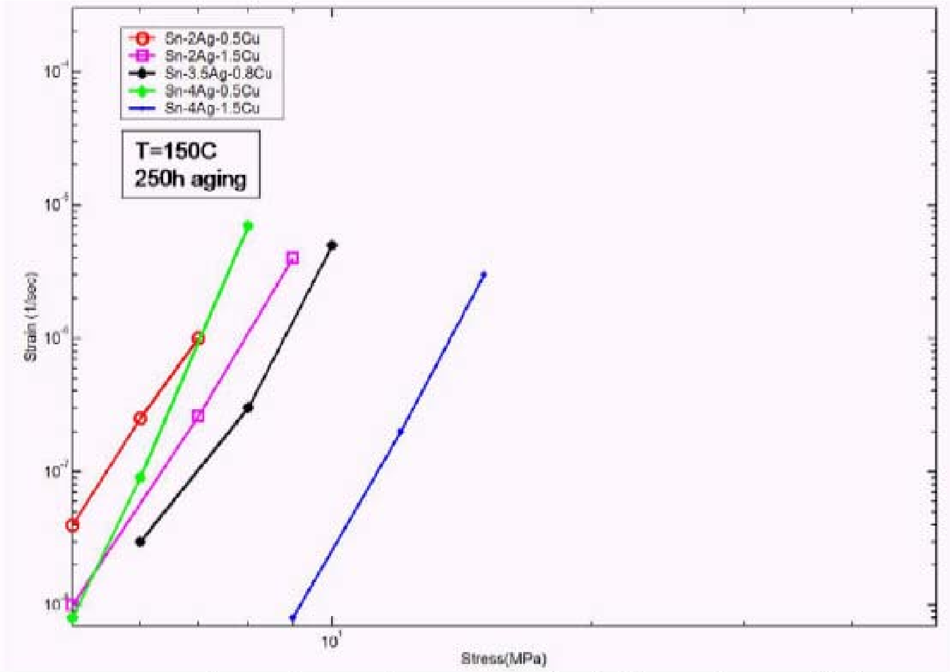
Comparison of creep data at T=100°C (aging 250h at 125°C)



Comparison of creep data at T=150°C (as-cast)



Comparison of creep data at T=150°C (aging 100h at 125°C)



Comparison of creep data at T=150°C (aging 250h at 125°C)

COMPARISON OF TENSILE PROPERTIES OF Sn 3.0Ag 0.5 Cu, Sn 3.5Ag 0.7Cu AND Sn 3.9Ag 0.6Cu

Measured property: **Tensile properties**

Institution / Author: K.S. Kim et al.
Department of Adaptive Machine Systems, Osaka University
Yamadaoka 1-1, Suita, Osaka 565-0871
Japan
Tel.:+81-6-6879-8521
Fax.: +81-6-6879-8522
Email: kskimm12@sanken.osaka-u.ac.jp

Measurement technique: **B7 Tensile and Shear Testing of Solder Joints**

Reference: *K.S. Kim, S.H. Huh, K. Suganuma; J. All. and Comp., 352 (2003) p.226-236*

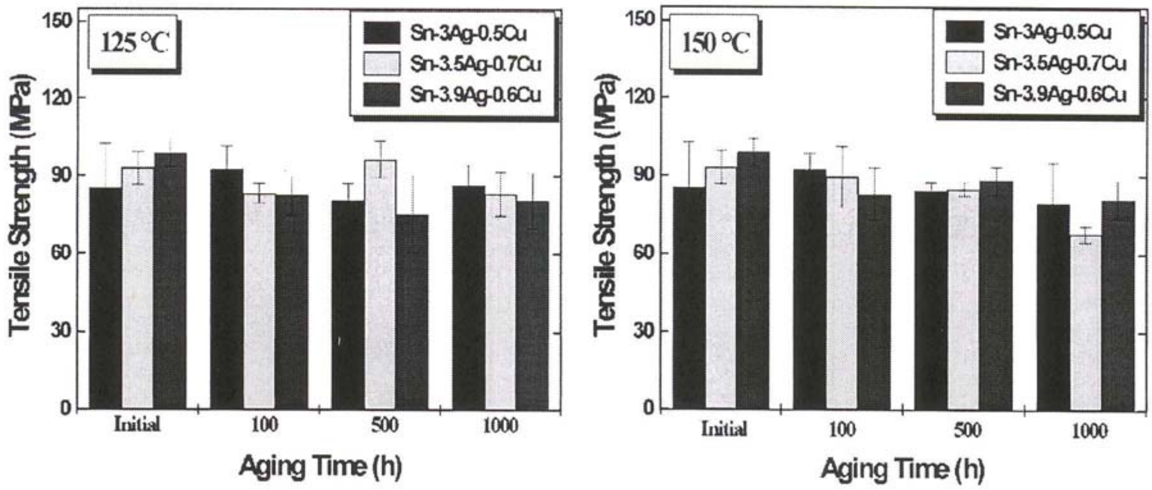


Fig. 10. Tensile data of various Cu–Sn–Ag–Cu solder–Cu joints after thermal aging at 125 and 150 °C.

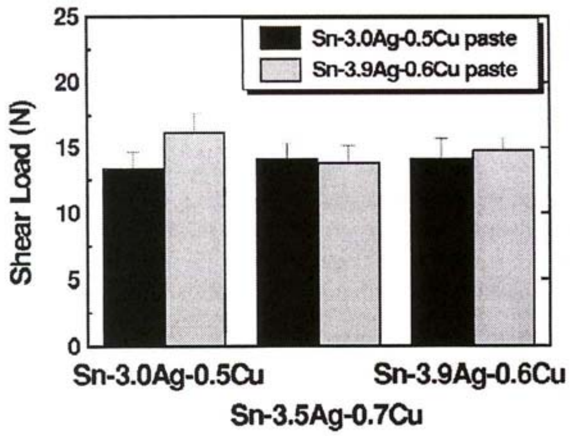


Fig. 15. Shear data of various Sn–Ag–Cu solder ball–Cu joints.

COMPARISON OF MICROHARDNESS OF VARIOUS SAC ALLOYS

Measured property: Microhardness

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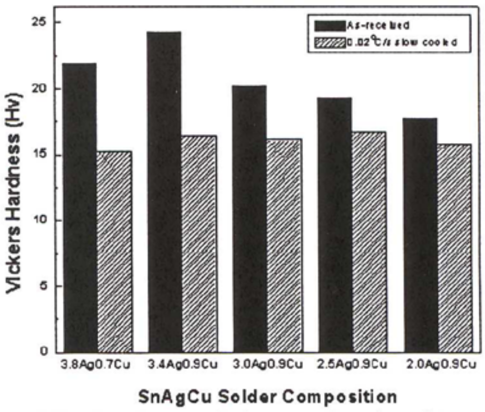
Reference: IBM Research Report, RC22717 (W0302-019) Feb. 5, 2003

Comments: Microhardness tests were carried out using a 10 gf load on cross sections of multiple solder balls. Each value reported is an average of 10 or more indentations.



Microhardness variations as a function of Ag content in Sn-Ag-Cu alloys; as-received vs. slow-cooled (at 0.02 °C/s)