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Compression Stress-Strain Behavior of Sn-Ag-Cu Solders

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Introduction

- Pb-free soldering has become more visible due to health concerns associated with Pb-based solders.

- In the past, reliability data bases addressing solder joint degradation by TMF have been developed from long-term empirical studies.
  - Those types of resources are becoming unavailable for two reasons.
    - First, because of the large variety of existing package and I/O configurations on the market, it would be necessary to expend enormous resources to perform the empirical studies.
    - Secondly, future package designs would require data in a timely manner in order for new products to quickly reach the market place.

- Consequently, a computational model was developed at SNL to predict the TMF reliability of solder interconnects with Sn-Pb and Pb-free solders.

Introduction
Constitutive Equation for Sn-Pb Solder

$$d\varepsilon_{11}/dt = \mathrm{sgn}\,(\sigma_{11} - B_{11})\, f_o \exp(-Q/RT)\, (\lambda/\lambda o)^m$$
$$\sinh^p[(/(\sigma_{11} - B_{11}/)/\beta D]$$

- $d\varepsilon_{11}/dt$ is the inelastic strain rate (s^{-1})
- σ_{11} is the applied stress (MPa);
- B_{11} and D are the back stress and the isotropic strength, respectively:
- (1/MPa-s) β (no units) are constants;
- Q is the apparent activation energy (J/mol);
- T is temperature (K);
- R is the universal gas constant (8.314 J/mol K);
- p is the "sinh-law" exponent (no units);
- The parameter, λ, is the Pb-rich phase size at time, t,
- λo is the initial Pb-rich phase size at time t = 0.
- The subscript, 11, denotes the uniaxial case in which the applied stress and deformation occur in the same direction.

– **The model is based on a single constitutive equation, which represents the deformation response of the respective solder compositions as a function of temperature and applied stress conditions that are also observed in service or accelerated environments.**

– **For the Sn-Pb solder, Pb-rich coarsening provides a microstructural state variable (λ) for the constitutive equation.**

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Introduction
Constitutive Equation for Pb-free Solder

$$d\varepsilon_{11}/dt = \mathrm{sgn}\,(\sigma_{11} - B_{11})\, f_o \exp(-Q/RT)$$
$$\sinh^p[(/(\sigma_{11} - B_{11}/)/\beta D]$$

B_{11} and D are the back stress and the isotropic strength, respectively.

- For the Pb-free solders, a more generalized constitutive equation has been developed.

- In this case, the specific microstructure changes that occur in the material during the course of TMF are limited to observed recrystallization phenomenon along the fatigue crack path.

Outline

- Introduction
  - Long-term empirical studies no longer viable for thermal mechanical fatigue (TMF) reliability analyses
  - Computational modeling at Sandia will be the core methodology to predict Thermal Mechanical Fatigue (TMF) reliability of solder interconnects, together with minimal validation testing
- Objective
- Experimental Procedures
  - Sample Preparation
  - Test Conditions
  - Experimental Set-Up
- Test Results & Discussion
  - Microstructural Analysis
  - Time-Independent Stress-Strain Properties
  - Yield Stress Properties
  - Static Modulus Properties

Objective

- **To determine a unified creep-plasticity equation for the use in the construction of a constitutive model for predicting thermal mechanical fatigue of solder joints.**
  - **The 98.5Sn-1.0Ag-0.5Cu (SAC105) solder alloy was used in this study because it was identified by industry as a fatigue resistant alloy.**
  - **Therefore, a study was undertaken to investigate the time-independent stress-strain and time-dependent creep properties of the SAC105 solder alloy in support of the model.**
- **The properties were then compared to those observed for 95.5Sn-3.9Ag-0.6Cu (SAC396) solder alloy under similar conditions in a previous study.**

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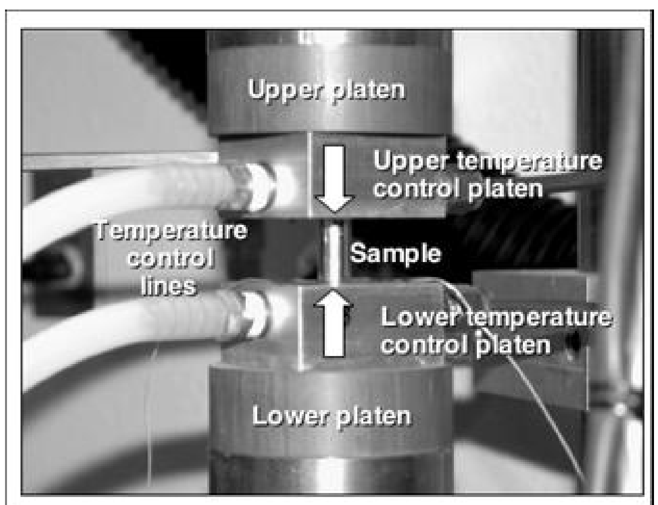
Experimental

- Test samples were first cast into samples with a cylindrical geometry and then machined to 10 mm in diameter & 19 mm in length dimensions.
- Samples (2 ea.) were tested in the either the as-cast condition or after aging at 125ºC, 24 hours or 150ºC, 24 hours.
- The tests were performed at -25ºC, 25ºC, 75ºC, 125ºC and 160ºC using strain rates of 4.2 X 10^{-5} s^{-1} and 8.3 X 10^{-4} s^{-1}.
  - These relatively slower strain rates represent the strain-rate regime characteristic of TMF.
- The experiments were performed with a servo-hydraulic frame.

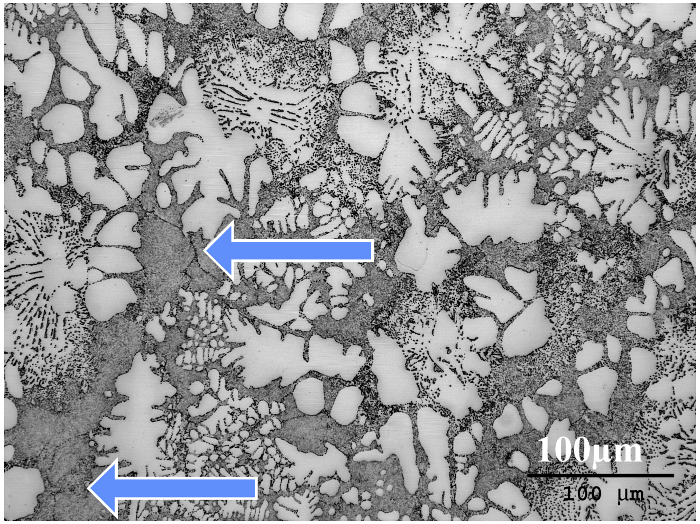


The temperature was controlled by passing heated or cooled air through the upper and lower platens.

Test Results
Microstructures of As-Cast Un-aged and Aged SAC Alloys

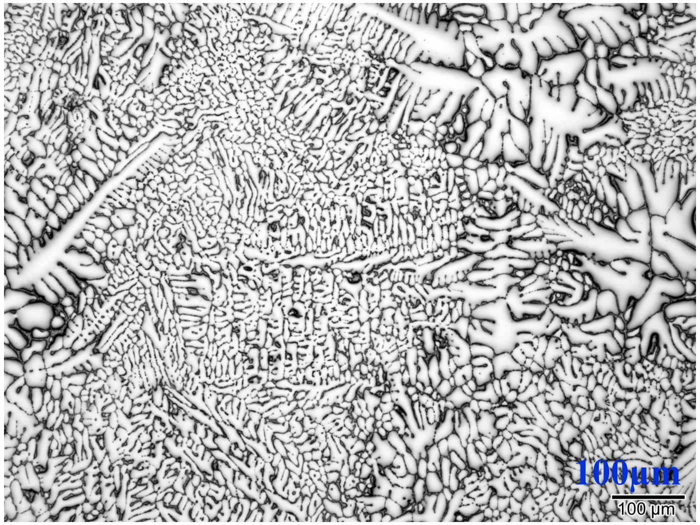
- There were no indications of large-scale deformations or cracks at either strain rate for either solder alloy.
- Finer microstructures developed at the higher strain rates versus the slower strain rate.

SAC396, Test at 160ºC, Strain Rate = 8.3 X 10^{-4} s^{-1}



Grain growth was evident at all test temperatures at the fast strain rate within the Sn-rich phase regions. The black particles are Cu_6Sn_5 particles.

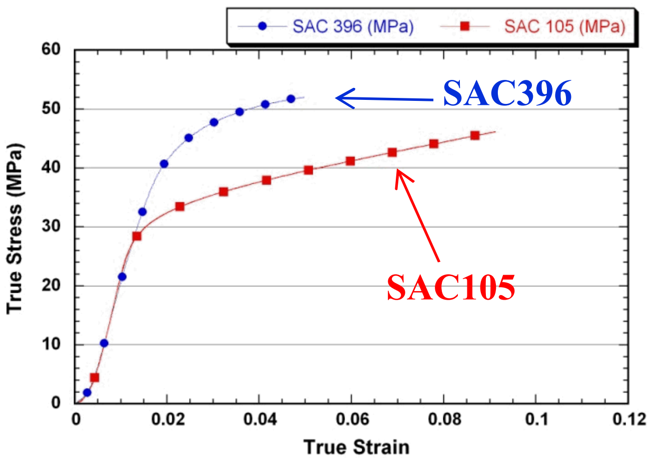
SAC105, Test at 160ºC, Aged 24 hrs. at 150ºC, Strain Rate = 8.3 X 10^{-4} s^{-1}



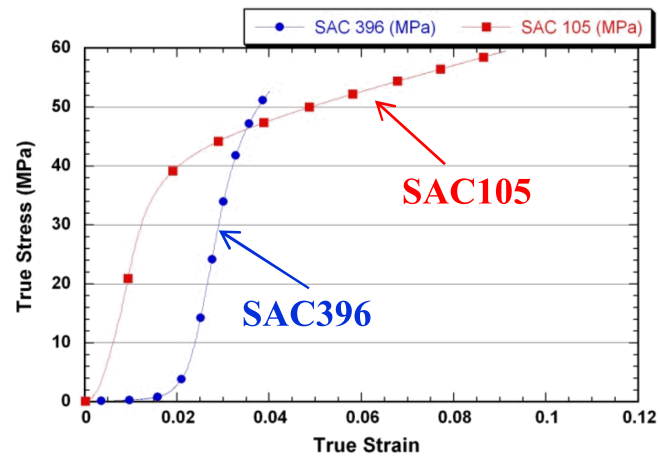
Finer microstructures developed at higher test temperatures for faster strain rates versus slower rates.

Test Results
Time Independent Stress-Strain

Strain Rate = 4.2 X 10^{-5} s^{-1}, Temp = -25ºC



Strain Rate = 8.3 X 10^{-4} s^{-1}, Temp = -25ºC



- **Work hardening was observed during plastic deformation for both solders.**

- **The slower strain rate curve shows a slight rollup (incr. in strain rate) from the start of the test for both alloys.**

- **At the faster strain rate, the rollup is much less pronounced for the SAC105 solder versus the SAC396 solder.**

- **A second feature of the curve was the gradual transition from the initial linear behavior to the plastic deformation region.**

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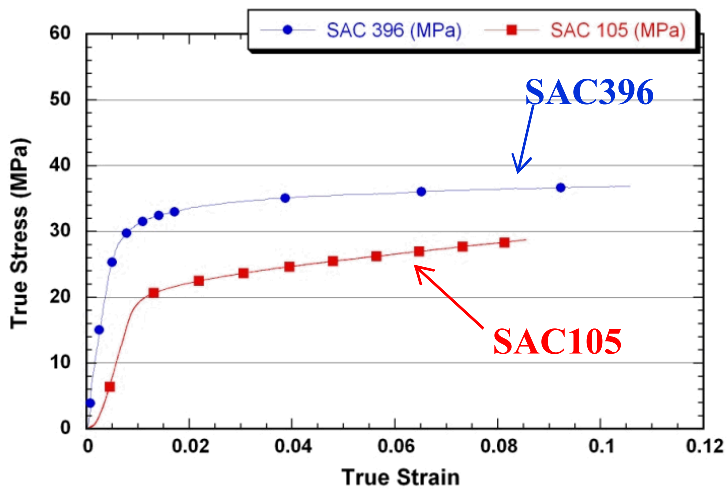
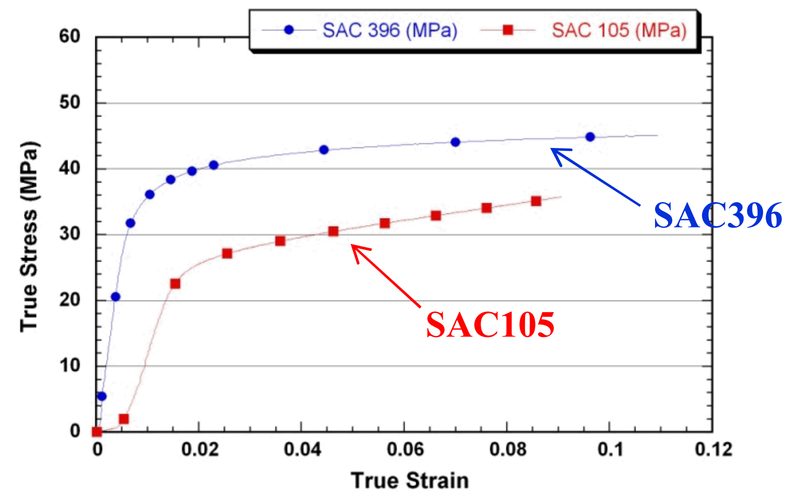
Test Results
Time Independent Stress-Strain

As-Cast, Strain Rate = 4.2 X 10^{-5} s^{-1}, Temp = 25ºC



As Cast, Strain Rate = 8.3 X 10^{-4} s^{-1}, Temp = 25ºC



- Work hardening decreased with increasing temperature for both solders.
- Work hardening was stronger at the faster strain rate.
- A slight rollup was noted for the SAC105 solder while the SAC396 solder proceeded directly into the linear segment.

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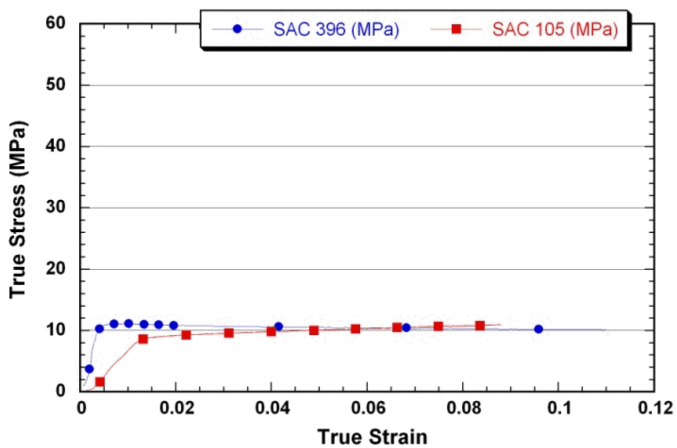
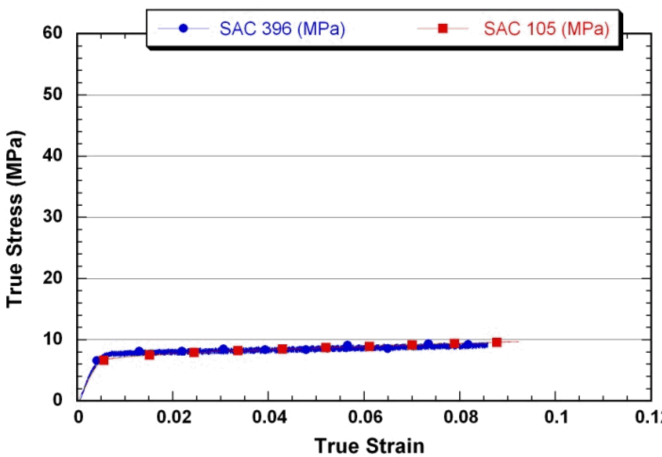
Test Results
Time Independent Stress-Strain

Strain Rate = 4.2 X 10^{-5} s^{-1}, Temp. = 160ºC, As Cast



Strain Rate = 4.2 X 10-5 s^{-1}, Temp. = 160ºC, Aged 24 hrs at 150ºC



- **As the temperature was further increased, there was loss of work hardening.**
- **In effect, work hardening was essentially negligible at both strain rates.**
- **Zero work hardening suggests a simultaneous occurrence of dynamic recovery, i.e., it implies that rate of defect generation and annihilation are equal.**
- **Similar trends were observed at the faster strain rates.**

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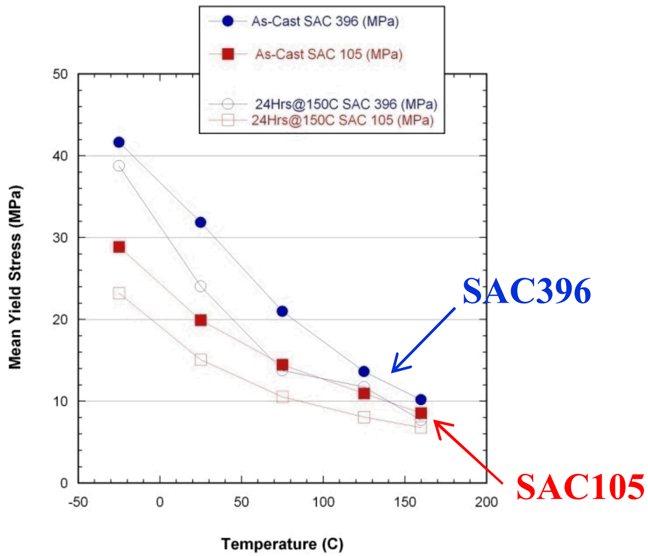
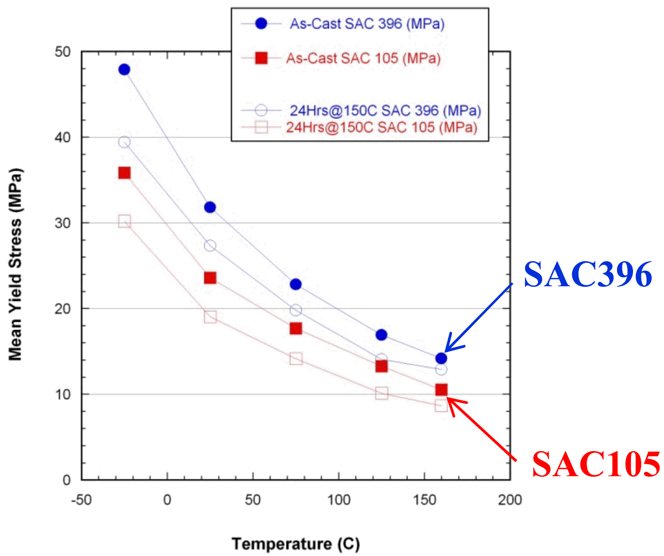
Test Results
Yield Stress Properties

Strain Rate = 4.2 X 10^{-5} s^{-1}



Strain Rate = 8.3 X 10^{-4} s^{-1}



- As suggested by the stress-strain curves, the SAC105 alloy has a lower yield strength than the 396 solder particularly at the lower test temperatures.
- The yield stresses of SAC105 were lower than those of SAC396.
- The yield stress decreased as temperature was increased so that at the highest temp., there was minimal yield stress difference between the two compositions.

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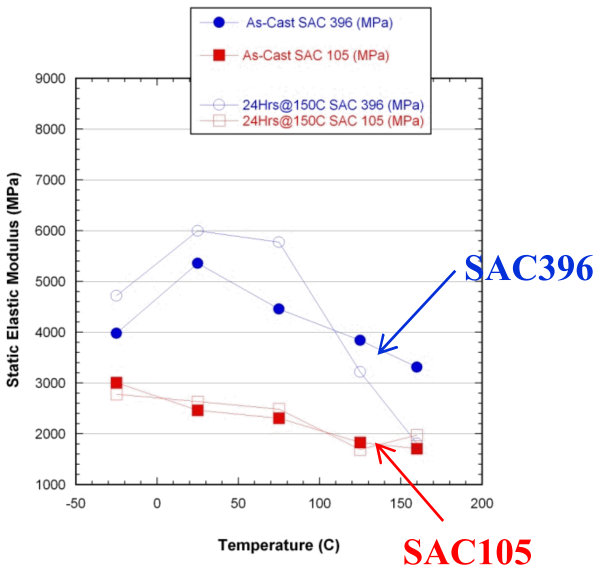
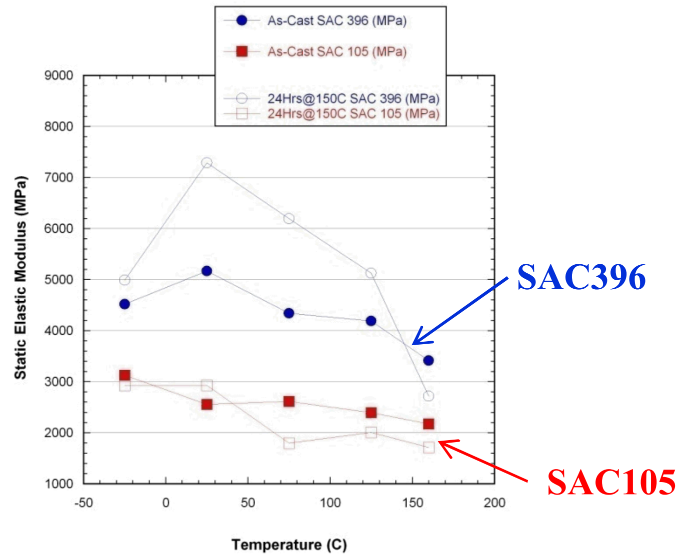
Test Results
Static Elastic Modulus Properties

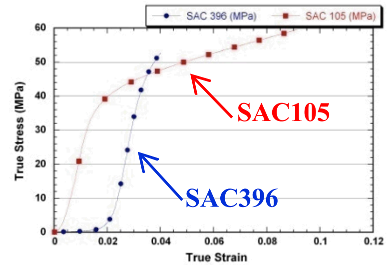
Strain Rate = 4.2 X 10^{-5} s^{-1}



Strain Rate = 8.3 X 10^{-4} s^{-1}



- Modulus values calculated from initial linear segment of stress-strain curve.



- The SAC105 modulus values exhibited the expected monotonic decrease with increased temperature.
- A more complex temperature dependence was observed for the SAC396 solder.
- More importantly, the values were significantly greater than those of the SAC105 solder .
- Lastly, aging had a negligible effect on the modulus values of the SAC105 alloy.

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Summary

- The time-independent (stress-strain) deformation properties of yield stress, and static Young's modulus were measured for the SAC105 solder at two strain rates and were compared to SAC396 solder.
- The properties were samples in the as-cast condition and following aging treatments of 125ºC, 24 hours or 150ºC, 24 hours.
- Under either strain rate, the stress-strain curves indicated decreases with work hardening with increased test temperature.
- The yield stresses of the SAC105 solder were lower than the SAC396 solder.
- The values decreased as a function of test temperature and aging treatment so that, at the highest test temperature of 160ºC, there was minimal yield stress between the two compositions.

Conclusions

- The compliant test results for SAC105 support industrial studies and suggest that the alloy would be a suitable fatigue resistant solder under thermal creep conditions.
- The test data suggested the increased occurrence of dynamic recrystallization during the test.
- The static modulus of the SAC105 alloy showed the same behavior as the SAC396 alloy.
- Moreover, the SAC105 values are significantly less than the SAC396 values, given the slight compositional differences.
- Finally, the SAC105 data indicated that concurrent processes such as dynamic recrystallization, occur at the start of the tests under these strain rates that result in an apparent softening of the material.

Acknowledgements

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