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A VISCOPLASTIC CONSTITUTIVE MODEL FOR ACTIVE BRAZE ALLOYS+

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ABSTRACT
Ceramic-to-metal brazing is simulated using finite element analysis codes to investigate the effects of braze alloy, braze process, and geometry variations on stress levels generated during brazing. The accuracy of these simulations is critically dependent on how realistically braze material behavior is understood and modeled. A viscoplastic model for braze alloys was developed. This model uses a hyperbolic sine function of effective stress in its kinetic equation for the inelastic strain rate. Evolution equations for the internal state variables describe competing mechanisms of power-law hardening and thermal recovery. Material parameters for several different braze alloys were obtained from a combination of experiments including uniaxial compression and creep compression. This paper includes a brief description of the viscoplastic model, a description of the parameter selection process, and a table with material parameters for the Ag-2Zr braze alloy.

1 INTRODUCTION

Ceramic parts are used in high temperature applications due to their superior strength and wear properties compared with metals. However, when ceramic parts are used there is often a need to join the ceramic part to a metal part. One of the most reliable joining methods is ceramic-to-metal brazing. During a typical ceramic-to-metal brazing process, residual stress is generated due to the differential thermal expansion of the ceramic, metal, and braze alloy. The effects of variations in joint geometry, materials, or cool-down profile can be investigated using finite element analyses. However, the accuracy of these analyses is critically dependent on constitutive models used to describe the behavior of braze joint materials. This paper begins with a brief description of a viscoplastic constitutive model that has been used to describe the behavior of numerous conventional and active braze alloys. Next, results from uniaxial compression experiments on the 98Ag-2Zr braze alloy are shown. The process used to obtain material parameters for this alloy is then described. Stress analysis results for typical ceramic-to-metal braze joints using the 98Ag-2Zr alloy will be compared to results obtained with other alloys in the conference presentation.

2 VISCOPLASTIC MODEL FOR BRAZE ALLOYS

A viscoplastic model was developed by Neilsen et al. [1] to describe elastic, creep, and plastic deformation of braze alloys. Our current implementation uses the unrotated Cauchy stress, $\boldsymbol{\sigma}$, and unrotated deformation rate, $\dot{\boldsymbol{\varepsilon}}$ [2, 3]. For small elastic strains, the total strain rate, $\dot{\boldsymbol{\varepsilon}}$, can be additively decomposed into elastic, $\dot{\boldsymbol{\varepsilon}}^e$, and inelastic (creep + plastic), $\dot{\boldsymbol{\varepsilon}}^{in}$, parts as follows

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^e + \dot{\boldsymbol{\varepsilon}}^{in} \tag{1}$$

We also assume that the elastic response is linear and isotropic such that

$$\boldsymbol{\sigma} = \mathbf{E} : \boldsymbol{\varepsilon}^e \tag{2}$$

where **E** is the fourth-order isotropic elasticity tensor. For braze alloys, the steady state creep rate can often be described using a hyperbolic Sine function of effective stress; thus, the viscoplastic braze model was developed using the following kinetic equation for the inelastic strain rate, $\dot{\boldsymbol{\varepsilon}}^{in}$,

$$\dot{\boldsymbol{\varepsilon}}^{in} = \frac{3}{2}\gamma\mathbf{n} = \frac{3}{2} f \sinh^p\left(\frac{\tau}{D}\right)\mathbf{n} \tag{3}$$

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where γ is a scalar measure of the inelastic strain rate, f is a function of temperature, D is an internal state variable which accounts for isotropic hardening and recovery, **n** is the normalized stress difference tensor which is given by,

$$\mathbf{n} = \frac{\mathbf{s} - \frac{2}{3}\mathbf{B}}{\tau} \tag{4}$$

where **s** is the stress deviator, **B** is the second-order state tensor which accounts for kinematic hardening and recovery, and τ is a scalar measure of the stress difference magnitude as follows

$$\tau = \sqrt{\frac{3}{2}\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right) : \left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)} \tag{5}$$

Competing power law hardening and thermal recovery mechanisms are captured with evolution equations for internal state variable D and internal state tensor **B**. Evolution of internal state variable D is given by

$$\dot{D} = \frac{A_1 \gamma}{(D - D_0)^{A_3}} - A_2 (D - D_0)^2 \tag{6}$$

where D_0, A_1, A_2, and A_3 are material parameters. Evolution of the second-order state tensor **B** is given by

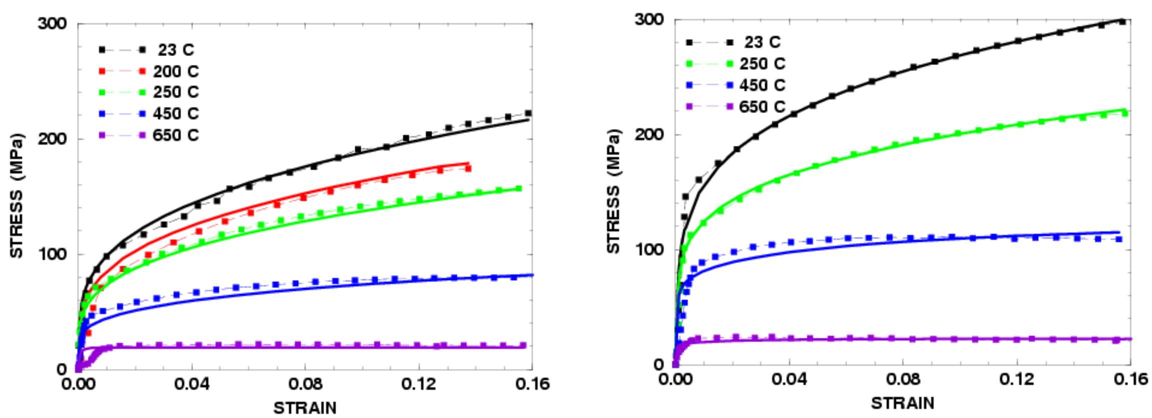
$$\dot{\mathbf{B}} = \frac{A_4\, \mathbf{d}^{in}}{b^{A_6}} - A_5 b \mathbf{B} \tag{7}$$

where A_4, A_5, and A_6 are material parameters and b is the magnitude of **B** as follows

$$b = \sqrt{\frac{2}{3}\mathbf{B} : \mathbf{B}} \tag{8}$$

3 UNIAXIAL AND CREEP COMPRESSION

A series of uniaxial compression and creep compression experiments were performed at various temperatures to investigate the elastic and inelastic response of the 98Ag-2Zr and 97Ag-1Cu-2Zr braze alloys. True stress-true strain curves obtained from the uniaxial compression experiments are the symbols shown in Figure 1. These curves show a significant and expected large reduction in compressive strength with increases in test temperature.



(a) Ag-2Zr (b) Ag-1Cu-2Zr

Figure 1. True stress-strain curves generated by constant rate, isothermal, uniaxial compression experiments compared with viscoplastic model predictions for (a) 98Ag-2Zr and (b) 97Ag-1Cu-2Zr. Symbols represent experiments and solid lines represent model predictions.

Selection of material parameters for viscoplastic constitutive models can be quite complex [4]. Parameters for the 98Ag-2Zr and 97Ag-1Cu-2Zr braze alloys were obtained from a non-linear least squares fit to the uniaxial compression data presented in Fig. 1 and the creep compression data. The non-linear least squares fit to this data was performed using the Levenberg and Marquardt Nonlinear Least Squares Algorithm [5] and a driver program for the viscoplastic braze model. Young's modulus data from Koster [6] and Poisson's ratio data from Wawra [7] were used as input to this fitting process. Also, initial estimates for material parameters were based on steady state creep correlations. Material parameters obtained from the non-linear least squares fitting process on Ag-2Zr are summarized in Table 1. Since, the uniaxial and creep compression data was monotonic, separation of kinematic hardening and recovery from isotropic hardening and recovery was not possible. For the fits tabulated here, purely isotropic hardening and recovery was assumed.

Temperature (°C)	23	250	450	650
Young's Modulus (GPa)	83.5	75.0	65.0	54.5
Poisson's Ratio	0.368	0.374	0.380	0.388
Flow Rate, ln(*f*)	-86.29	-64.10	-30.36	-18.12
Sinh Exponent, *p*	12.00	11.26	5.81	5.81
Isotropic Hardening, A_1 (MPa^{A3+1})	15840	12290	3245	3087
Isotropic Recovery, A_2 1/(MPa-sec)	2.117×10^{-11}	8.469×10^{-8}	9.641×10^{-6}	6.457×10^{-3}
Isotropic Exponent, A_3	1.7278			
Kinematic Hardening, A_4 (MPa^{A6+1})	0.00			
Kinematic Recovery, A_5 1/(MPa-sec)	0.00			
Kinematic Exponent, A_6	1.7278			
Flow Stress, D_0 (MPa)	5.00			

Table 1. 98Ag-2Zr Material Parameters.

4 CONCLUSIONS

A viscoplastic braze model has been developed for the 98Ag-2Zr and a new 98Ag-1Cu-2Zr braze alloys. This model can be used to simulate ceramic-to-metal brazing and subsequent environmental heating or cooling. Material parameters for this new model are based on results from a combination of uniaxial compression and creep compression experiments which were performed at a variety of temperatures between 23 ^{o}C and 750 ^{o}C, inclusively. In the future, cyclic loading experiments should be completed at a variety of temperatures to allow for the modeling of both isotropic and kinematic hardening and recovery. The current parameters assume that the hardening and recovery is purely isotropic.

The new model was used to simulate the ceramic-to-metal brazing of an alumina ceramic rod to a Fe-Ni-Co alloy rod with 98Ag-2Zr, 97Ag-1Cu-2Zr and 63Ag-35.25Cu-1.75Ti. The interesting result from these simulations was that the predicted peak and residual tensile stress on the outside surface of the ceramic was actually highest when the lower temperature 63Ag-35.25Cu-1.75Ti braze alloy was used. The transient peak tensile stress on the surface of the ceramic was lowest when the 98Ag-2Zr braze alloy was used. Results from these simulations will be presented at the conference.

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