Simulations of a Furnace Brazing Process Using Tera-Scale Computing*

F.M. Hosking and S.E. Gianoulakis

Sandia National Laboratories, Albuquerque, NM, USA

Abstract

Thermal responses in a production brazing furnace can be very difficult to predict or measure due to changing loading and heating conditions. An efficient approach to determining acceptable furnace brazing cycles is to apply computational models that can solve these potentially complex thermal problems. Recent developments in massively parallel computing have facilitated finer-scale temporal and spatial thermal analyses. Sandia National Laboratories has conducted tera-scale simulations to thermally characterize a production brazing process. The model accounts for thermal radiation and conduction as the principal heat transfer drivers in the batch-style hydrogen furnace. Computed peak temperatures are within one to two percent of the programmed and measured values. Thermal responses in the work zone are particularly sensitive to the thermal enclosure, defined by the furnace's heating elements. A two percent change in the radiation enclosure can yield up to an eight percent change in the peak brazing temperature. Computational data are less sensitive to differences in the inputted materials thermal properties than changes to the thermal enclosure. Examples of how the thermal model can be used to determine optimal loading and heating conditions for production brazing are discussed.

Keywords: Furnace thermal modeling; Brazing simulations; Thermal response; Model validation

1. Introduction

The thermal and metallurgical responses during furnace brazing to loading and processing conditions are usually established by empirical, trial-and-error methods. This approach is generally dependent on operator experience and the ability to identify and control the critical materials and processing parameters during brazing. Although specifications and guidelines are available to assist the design and process engineer, the ability to accurately estimate temperature responses in the work zone of a furnace requires years of experience, particularly as loading conditions are varied (part and fixture mass, location, heating uniformity, etc.). Consequently, determining the interaction effects between furnace atmosphere, heat source, internal support structure, work rack, brazing fixtures, and parts can be extremely difficult to achieve. More fundamentally-based, high fidelity algorithms are required to predict the finer-scale thermal and structural responses that occur at the braze joint level. Several general and specialized software packages have been developed to address these computational needs (Refs. 1-8). These thermal, fluid flow, and mechanical models have expanded the macro and micro predictive capabilities for furnace brazing. Typical model inputs include materials properties and processing boundary conditions (initial and transient).

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Critical to the fabrication of many high end, hermetic devices is the use of furnace brazing to join different base materials together. Several subassemblies can be sequentially processed, involving different materials, fixtures, filler metals, and brazing schedules. The higher level brazements can pose production throughput problems, because of the relative size of the final assembly in relation to furnace capacity and the its relative cost. Recent research at Sandia National Laboratories, a nonnuclear design laboratory for the U.S. Department of Energy, has investigated new brazing materials and processes, such as active metal brazing, for next generation component designs. The development activities depend on a fundamental understanding of the brazing process and the ability to predict responses to the furnace environment. The work also serves as the basis for applying predictive thermal and fluid flow codes/models (Refs. 9-12).

This paper compares the computational and experimental responses in a batch hydrogen brazing furnace. Thermal and fluid flow analyses were conducted to characterize typical furnace and joint-level responses. The macro level solutions considered the effects of materials and furnace loading on temperature response as a function of position and time. Thermal behavior in the work area was dependent on the initial and transient thermal boundary conditions, defined by the furnace's thermal radiation enclosure (i.e., heating elements). The coupled thermal and fluid flow codes can subsequently simulate local, joint level responses, such as capillary flow and fillet geometry. Sensitivity analysis and furnace heating optimization results are discussed.

2. Description of Braze Furnace Thermal Model

The furnace model captures the thermal convection, radiation, and conduction interactions that occur within its defined workspace. The furnace atmosphere is flowing, slightly positive pressure (1-2 psia) dry hydrogen gas. A two-dimensional, axisymmetric fluid flow analysis was initially conducted, using a Sandia-developed finite element program, GOMA (Ref. 9), to assess hydrogen flow patterns in and around the work rack. GOMA is a full-Newtonian coupled heat, mass, momentum, and pseudo-solid mesh motion algorithm that simulates bulk fluid transport and interfacial physics. The code is based on the premise that any boundary can be: (a) moving or free, (b) globally fixed, or (c) moving in time and space, under defined kinematics. The model was customized to investigate the heat transfer effects of the flowing process gas. The flow analysis suggests that convection contributions to heating is very small above 400°C. Heat transfer was consequently assumed to be driven by thermal radiation from the heating elements and thermal conduction between the work rack and loaded parts.

The thermal computations are based on a nonlinear, heat conduction algorithm, COYOTE (Refs. 10-11), which was developed at Sandia to handle large, complex, transient three-dimensional finite element solutions. The furnace model simulates radiant coupling between the furnace walls, hot zone, internal support structure, and fixtured parts. Navier-Stokes energy equations determine the temperature distributions in the furnace. Advective heat transfer by the flowing hydrogen gas is assumed negligible. Since the thermal boundary conditions are controlled by the heating elements, losses to the ambient are not explicitly modeled. The enclosure radiosity, or net radiative surface flux, is described by a relatively large square matrix, which necessitates the use of massively parallel computing. The coupled radiation and conduction computations also contribute to the relatively long simulation times.

Furnace temperatures near the heating elements were inputted into the thermal model to simulate typical transient heating conditions during brazing. Temperature-dependent properties were inputted into the model for the selected furnace and work materials. Thermal data included density (ρ), specific heat (C_p), thermal conductivity (κ), and emissivity (ε). Emissivity values ranged from 0.1 to 0.3. Thermal capacitance, ($\rho \times C_p$), and diffusivity, ($\kappa \div (\rho \times C_p)$), reflect the amount of energy required to heat a unit mass of material and the thermal flux or rate at which a material absorbs heat, respectively. The radiation enclosure was established by transient and spatial temperature measurements at the main heating element and top and bottom trim heaters.

3. Experimental Conditions

Validation experiments were conducted with ASTM F19 tension test specimens and related fixturing. Each specimen consists of two tapered, brazed alumina ceramic buttons. Fixturing is composed of alumina sleeves and stainless steel and Kovar™ (Fe-29Ni-17Co, wt. %) plates. The materials and processing conditions, normally used to hydrogen braze "prototype" assemblies, were selected as the baseline boundary conditions for the computational and experimental comparisons. A schematic of the furnace's work area and test configuration is shown in Figure 1.

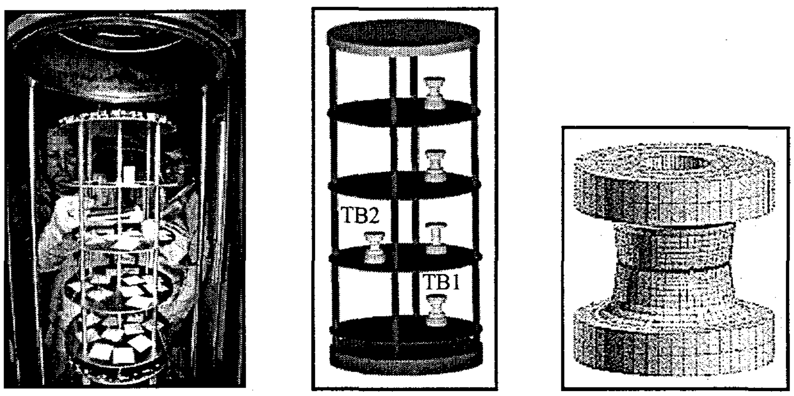

Figure 1. Brazing furnace work area, testing configuration, and ASTM F19 tension specimen.

Measured temperature data were compared with computed results. Furnace and part temperatures were measured with three control and six work thermocouples (Type K, chromel-alumel). The work thermocouples were located near the braze interface (TB1 and TB2 in Figure 1) and on the test fixtures. The work rack consisted of four stacked molybdenum shelves. Heating was controlled with the three control thermocouples that were located above, below, and to the side of the work rack, i.e., next to the corresponding molybdenum top trim heater, bottom trim heater, and main heating element. The main heating element was controlled by the side thermocouple. The dry hydrogen gas flow rate was 5 liters/minute, with a chamber volume of 110 liters (4 ft^3).

Additional experiments were conducted to evaluate the thermal response to different materials (94% alumina and Kovar™), sample geometry (large and small solid bars), and parts/shelf locations in the furnace. Sensitivity analyses were performed to determine the effect of variations in the materials thermal properties and boundary conditions on predicted temperature values.

Finally, the model was used to optimize temperature uniformity in the work area by modifying the programmed brazing cycle.

4. Results and Discussion

Typical measured and computed temperature profiles for the TB1 and TB2 test specimens are shown in Figure 2. The computed data lagged the recorded temperatures during initial heating.

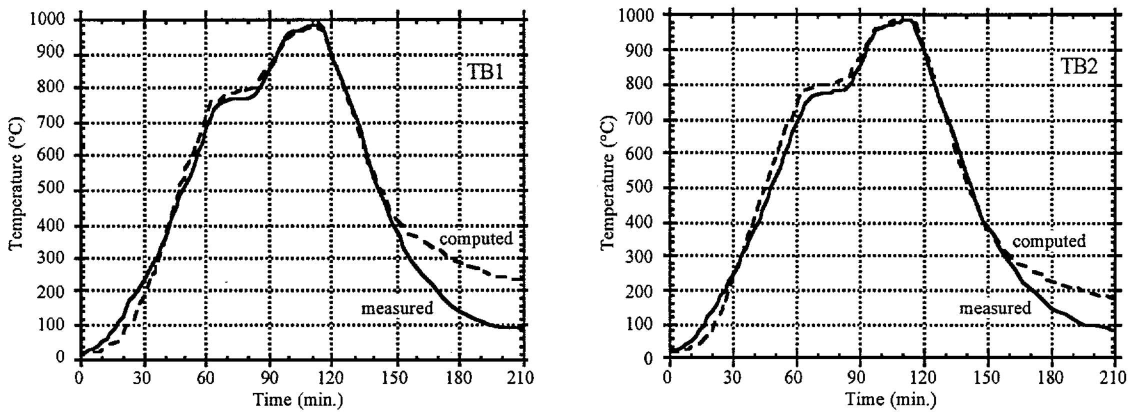

Figure 2. Computed (dash line) and measured (solid line) temperatures at the F19 braze interface.

Once above 300-400°C, however, the two values converged within 1-2% of the brazing peak temperature. On cooling, the measured/computed ΔT again increased, with the measured values reaching ambient conditions sooner. The ΔT below 400°C was attributed to the assumption that convective heating by the flowing hydrogen gas was negligible. Subsequent fluid flow analysis has shown that convective cells do develop between the work shelves at the lower heating range, with buoyancy dominating the flow. Other researchers have reported similar results on the effective range of convective gas heating (Refs. 13-14).

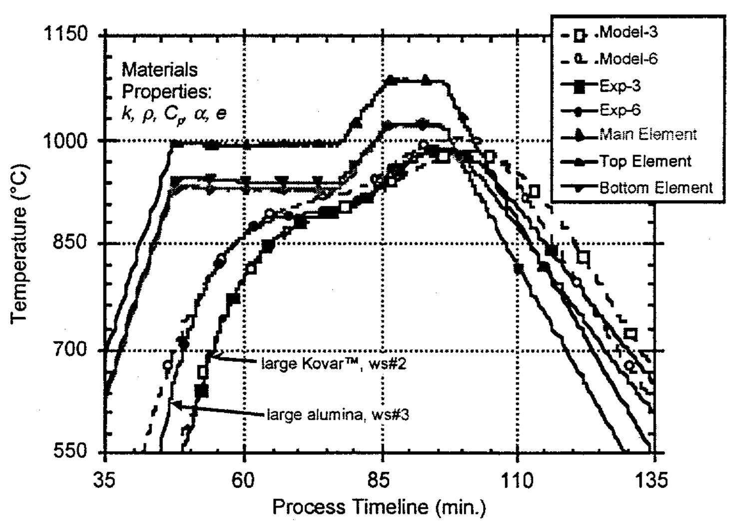

Figure 3. Comparison of computed and measured temperature data for large Kovar™ & alumina test pieces. The upper curves are the control temperatures near the furnace heating elements.

Additional furnace experiments were conducted to predict the thermal response to different materials and loading conditions. The investigation varied materials type, part size, quantity, and furnace location. The test pieces consisted of 94% alumina and Kovar™ monolithic bars. Transient thermal responses were measured and computed as a function of furnace and part location. The computed and measured data clearly demonstrated the materials effect on heating and cooling. Kovar™ has a greater thermal capacitance and lower thermal diffusivity than alumina and, consequently, took longer to heat up and cool down (Figure 3). Similar thermal trends were observed during the other furnace runs. For example, the smaller test bars heat more uniformly and quicker than the larger test pieces, regardless of materials type. The results suggest the importance of knowing and controlling these different temperature responses, which directly affect interfacial brazing reactions, joint structure, and properties.

Furnace materials also contribute significantly to heating during brazing. For example, the molybdenum work rack has a relatively low thermal capacitance and high thermal diffusivity. The work shelves can, therefore, absorb heat quickly from the heating elements and then conduct that heat into the parts. This coupled radiation and conduction heating mechanism can cause thermal gradients in larger parts on heating and cooling. Spatial temperature differences can be usually equilibrated through prescribed furnace soaks.

Sensitivity analyses demonstrated the effects of materials properties and heating (i.e., radiation enclosure) variations on furnace response. Property variations considered for the study included a ± 20% variation in emissivity and specific heat values. The furnace radiation enclosure was varied by ± 2% with respect to the programmed furnace values. The analyses were conducted with fixtured production hardware. The simulations suggest that the brazing process is relatively tolerant to reasonable variations in furnace wall and work rack emissivity and specific heat values. Other thermal properties were found to have a similar impact on the brazing temperature. The enclosure analysis did reveal a strong coupling between the predicted thermal responses and the heating boundary conditions. A ± 2% variation in temperature, relative to the furnace control parameters, can result in an 8% variation in peak temperature at the part.

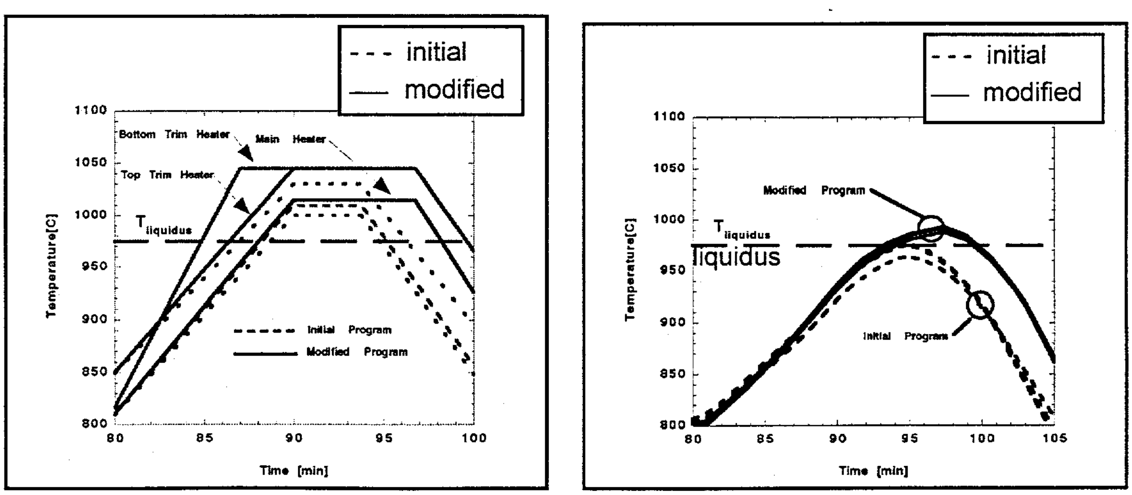

Figure 4. Modified program cycles and furnace simulations that yield uniform heating.

Temperature uniformity is a common problem for most furnaces. Temperature differences in the hot zone can cause incomplete melting of the brazing alloy and variable brazing reactions at the bond interface, if not properly controlled. To demonstrate the utility of the above thermal model, production brazing cycles were optimized by simulating the programmed process parameters and then modifying the control inputs, using the simulation data, to achieve the targeted brazing temperatures and times in the work area. The results are summarized in Figure 4.

5. Summary and Conclusions

A thermal model was developed and validated for predicting brazing responses in a hydrogen furnace. Furnace and joint-level simulations were compared to measured values. Thermal properties and processing boundary conditions influence the brazing responses, particularly the thermal enclosure. Heating is controlled by radiation from the heating elements and conduction to the parts from the molybdenum work shelf. Gas flow convection contributes to heat transfer in the furnace at lower temperatures. Sensitivity analyses revealed that temperature variations are less tolerant to changes in the thermal enclosure than materials properties. The validated models provide a quick, efficient means to better control and optimize the furnace brazing process.

6. Acknowledgments

The authors would like to acknowledge the contributions of Doug Foldie, Lou Malizia, Matt Senkow, and John Stephens. The manuscript was reviewed by Charlie Robino.

7. References

1. T.W. Abouarab, W. Richter, M. Seeger, Int. J. Eng. Fluid Dynamics 4(1) (1991) 111-126.
2. C. Batur, R.B. Sharpless, W.M.B. Duval, B.N. Rosenthal, Int. J. Adaptive Control and Signal Processing 6(2) (1992) 127-138.
3. M.J. Robert, B. L'Hote, R. Holoboff, Industrial Heating 59(11) (1992) 50-55.
4. A. Charette, A. Haidekker, Y.S. Kocaefe, Can. J. Chem. Eng. 70(6) (1992) 1198-1207.
5. C. Grillenzoni, J. Amer. Statistical Assoc. 89(427) (1994) 777-787.
6. D.L. Qualey, J.R. Welty, M.K. Drost, Num. Heat Transf. Part A Apps. 31(2) (1997) 131-142.
7. E.G. Seebauer, R. Ditchfield, Solid State Tech. (Oct. 1997) 111-120.
8. C. Porter, A. Laser, J. Hertle, P. Pandey, M. Erickson, S. Shah, Solid State Tech. (Nov. 1996) 119-131.
9. P.R. Schunk, et al., GOMA - A Full-Newton Finite Element Program for Free and Moving Boundary Problems with Coupled Fluid/Solid Momentum, Energy, Mass, and Chemical Species Transport: User's Guide, Sandia National Laboratories Report SAND95-2937, Jan. 1996.
10. D.K. Gartling, R.E. Hogan, COYOTE - A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part I - Theoretical Background, Sandia National Laboratories Report SAND94-1173, Oct. 1994.
11. D.K. Gartling, R.E. Hogan, COYOTE - A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part II - User's Manual, Sandia National Laboratories Report SAND94-1179, Oct. 1994.
12. F.M. Hosking, S.E. Gianoulakis, R.C. Givler, R.P. Schunk, Advanced Brazing and Soldering Technologies, IBSC 2000 Proceedings, Albuquerque, NM (April 2000) 389-397.
13. N.J. Orzechowski, D.L. Hughes, Industrial Heating (Sept. 1999) 45-49.
14. F.H. Jeddy, M.A. Jog, J.A. Sekhar, R.D. Markle, V. Sarvepalli, R. Burada, Adv. Mtrls. & Processes (Oct. 1999) 213-215.