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COMPUTATIONAL SIMULATIONS AND EXPERIMENTAL VALIDATION OF A FURNACE BRAZING PROCESS*

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Abstract

Modeling of a furnace brazing process is described. The computational tools predict the thermal response of loaded hardware in a hydrogen brazing furnace to programmed furnace profiles. Experiments were conducted to validate the model and resolve computational uncertainties. The results from selected furnace simulations and measured thermal events were compared. Critical boundary conditions that affect materials and processing response to the furnace environment were determined. "Global" and local issues (i.e., at the furnace/hardware and joint levels, respectively) are discussed. The ability to accurately simulate and control furnace conditions is examined.

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Introduction

The thermal response of batch furnace brazing to loading and processing conditions is typically established through empirical, trial-and-error methods. The success of this approach is generally proportional to operator experience and the ability to identify and control the critical materials and processing parameters that affect braze joint producibility and reliability. Although industry specifications and guidelines have been developed to assist the process engineer, predicting temperatures within the work zone of a loaded furnace remains a relative "black art". This is especially true as the complexity of furnace loading (i.e., mass, location, heating uniformity, etc.) increases. Consequently, determining the interaction effects between the furnace atmosphere, heat source, internal support structure, work rack, brazing fixtures, and parts is extremely difficult to achieve when a "best guess" approach is utilized. A more fundamental algorithm will be needed to predict the thermal response of higher reliability, military and commercial products processed in a furnace environment. A variety of general and specific software programs have been developed by industry, academia, and the federal government to address these computational needs (Refs. 1-11). The resulting thermal and structural models have enhanced the prediction of furnace (macro or global) and joint (micro or local) level responses, given materials properties, processing variables, and brazing boundary conditions (initial and transient).

Sandia National Laboratories is a science and engineering-based laboratory that supports the U.S. Department of Energy's Defense Programs. Typical work involves basic and applied research for designing, developing, and manufacturing nonnuclear electrical and electromechanical components. Such an example is a neutron tube assembly. Critical to its fabrication is furnace brazing. Several tube subassemblies are usually processed per furnace run, involving different materials, fixturing, filler metal, and brazing schedule requirements. The higher level braze assemblies can pose production throughput problems, due to their relative size in relation to furnace capacity. Recent laboratory-funded projects have explored new brazing materials and processing conditions, such as active metal brazing, for next generation neutron tube designs. These interrelated activities form the basis for the development and experimental validation of predictive codes/models for furnace environments.

This paper discusses the results of the modeling and experimental validation effort for a batch hydrogen brazing furnace. An important element of the investigation is the resolution of computational uncertainties, such as furnace boundary conditions, since the predicted values depend on the accuracy and completeness of these model inputs. The solution can be approached from two levels. The first views the process from a global level, where multiple assemblies are loaded into the furnace. The global boundary conditions of the furnace environment define and determine the thermal response of the fixtured units. The second level is at a finer or local scale, where the physical and thermal responses during brazing (e.g., fixture/part stack-up, heating/cooling rates and gradients, interfacial reactions, joint microstructure, and residual stress/strains) are considered. The performance of the brazed assembly depends on these local boundary conditions and related thermal issues. A coupled global-local series of algorithms would yield more accurate, structured solutions for predicting furnace thermal responses, with a minimum of computational errors. Expensive and lengthy "best guess", iterative development efforts could be replaced by more efficient and reliable braze process simulations. These issues are considered in the following sections. Emphasis is placed on the experimental validations of a baseline thermal model for predicting the transient thermal histories of a simple part geometry.

Braze Furnace Modeling

The initial modeling approach considered the effects of gas flow and temperature on the transient response of a loaded production furnace. The furnace atmosphere is a flowing dry hydrogen at a slightly positive pressure, 1-2 psi. A two-dimensional, axisymmetric fluid flow analysis was conducted, using a Sandia-developed finite element program, GOMA (Ref. 9), to assess hydrogen flow patterns in the work zone of the furnace. 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. Preliminary results suggested that the flowing hydrogen atmosphere has a negligible effect on heat transfer between the furnace heating elements and the work structure. Heating occurs primarily through thermal radiation from the elements. The principal role of the dry gas appears to be the reduction of oxides on the base metal and braze alloy surfaces, which promotes braze wettability and flow.

The next step was to model the thermal process with a nonlinear, heat conduction algorithm. The selected program, COYOTE (Refs. 10-11), is based on a coarse, transient three-dimensional thermal, finite element analysis. A finite element mesh of the braze furnace was developed. The model simulates the radiant coupling between the furnace walls, hot zone, internal support structure, and loaded contents. Mock-ups of representative production fixtures and parts were designed into the model. The model mesh consisted of approximately 24,000 nodes with approximately 13,000 surfaces on the radiation enclosure. Figure 1 illustrates an example of the work rack loaded with small and large cylindrical test pieces.

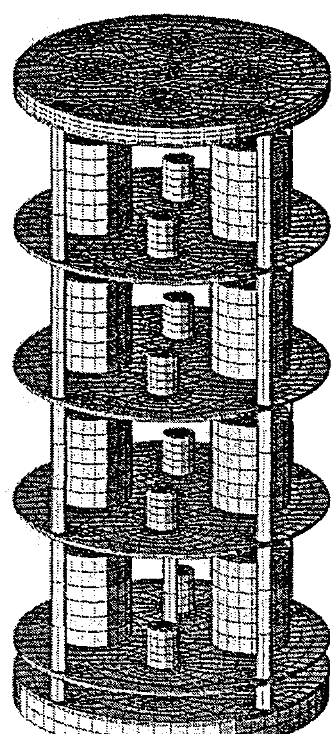

Figure 1: Finite element mesh of furnace work rack and loaded test pieces.

Furnace thermal profiles were inputted into the model to simulate typical transient heating conditions. The profiles investigated in this study are listed in Table I. They represent furnace schedules for brazing with pure Cu, 100Cu, and 50Au-50Cu (wt. %) filler metals.

Table I. Programmed Main Element Computational and Experimental Furnace Profiles

Time (min)	50Au-50Cu Run Temperature (°C)	100Cu Run Temperature (°C)
0	10	10
44	580	1030
60	800	1030
65	800	1030
77	800	1100
81	800	1100
90	930	1100
92	960	1060
105	960	800
117	960	570
126	995	400
132	995	285
144	800	70
147	735	10
162	400	---
183	10	---

The model neglects advective heat transfer by the flowing hydrogen gas between the furnace walls, elements, and work area. Heat is allowed to conduct between the internal structure and components on the work shelves. Since the thermal boundary conditions were controlled, losses to the ambient were not explicitly modeled. It was also assumed that the active control of the furnace temperature accounted for any thermal gains or losses in the system.

Table II. Materials Properties for Molybdenum

Temperature (°K)	Density (kg/m^3)	Thermal Conductivity (W/m·°K)	Specific Heat (J/kg·°K)	Emissivity
constant	10,200.0	------	------	0.30
200		143.0	224.0	
400		134.0	261.0	
600		126.0	275.0	
800		118.0	285.0	
1000		112.0	295.0	
1200		105.0	308.0	
1500		98.0	330.0	
2000		90.0	380.0	
2500		86.0	459.0	

Temperature-dependent properties were inputted into the model for the selected materials. Critical parameters included density, specific heat, thermal conductivity, and emissivity. The test piece was a molybdenum crucible. Nominal properties for molybdenum are listed in Table II. Preliminary experimental analyses established transient and spatial thermal boundary conditions for the thermal model.

Experimental Conditions

The initial validation experiments were conducted with a simple test geometry to ensure accuracy in measuring its response to the heat load. The materials and processing parameters and boundary conditions normally associated with brazing "prototype" assemblies in a hydrogen furnace environment were the baseline for the subsequent computational and experimental comparisons. A monolithic test piece was used to characterize the transient thermal conditions. Preliminary furnace runs identified potential problems and uncertainties in the model, under a variety of experimental loading conditions. These initial scoping experiments were designed to address global (macro-level) heat management issues.

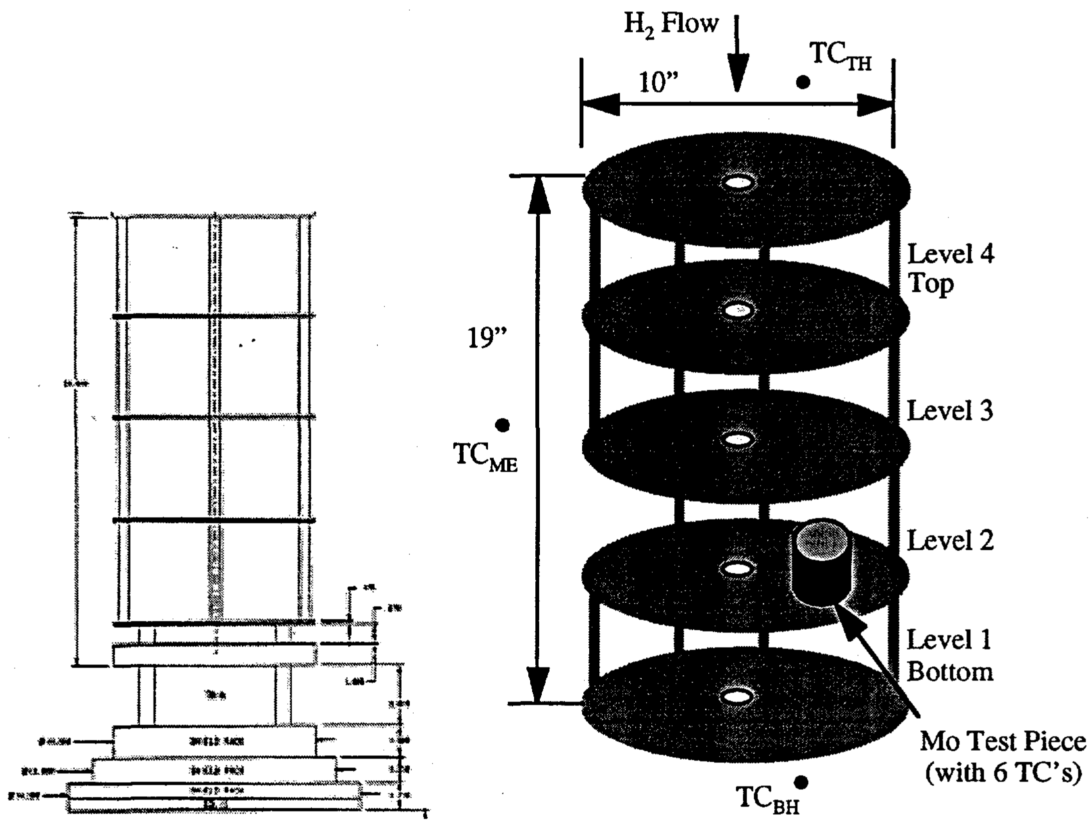

Figure 2: Schematic of hydrogen brazing furnace.

A molybdenum test piece was used to study the furnace response. Furnace and part temperature were measured with three control and six work thermocouples (Type K, chromel-alumel), respectively. The work thermocouples were inserted into six symmetrically-spaced holes in the 31.8 mm dia. x 25.4 mm high (1.25 inch dia. x 1 inch) molybdenum crucible. The test piece was placed on the second shelf of the work rack, approximately 25 mm (1 inch) from the shelf edge. Measured thermal histories were compared with the predicted results. Thermal and physical uncertainties caused by systematic and random errors in the braze model were resolved by analyzing the baseline experimental data and comparing the results to the predicted temperatures. Additional experiments are planned to investigate joint-level thermal and structural responses (micro-level), including interfacial reactions and post-braze mechanical strength. A schematic of the furnace's experimental set-up is shown in Figure 2.

The molybdenum work rack consists of four stacked levels. There are three control thermocouples located above, below, and to the side of the work rack, next to the corresponding molybdenum top trim heater, bottom trim heater, and main heating element, respectively. The side thermocouple is located directly between the main element and the work rack. It serves as the principal control for the programmed furnace schedule. 100Cu and 50Au-50Cu brazing cycles were selected for this investigation. The 50Au-50Cu alloy melts between 950 and 970°C. Pure Cu has a single melt point of 1083°C. For the baseline surveys, a furnace peak temperature just above each melting temperature was selected. A constant dry hydrogen flow rate of 5 liters/minute was used. The gas enters from the furnace top and exits from its base. The programmed schedules are listed in Table I.

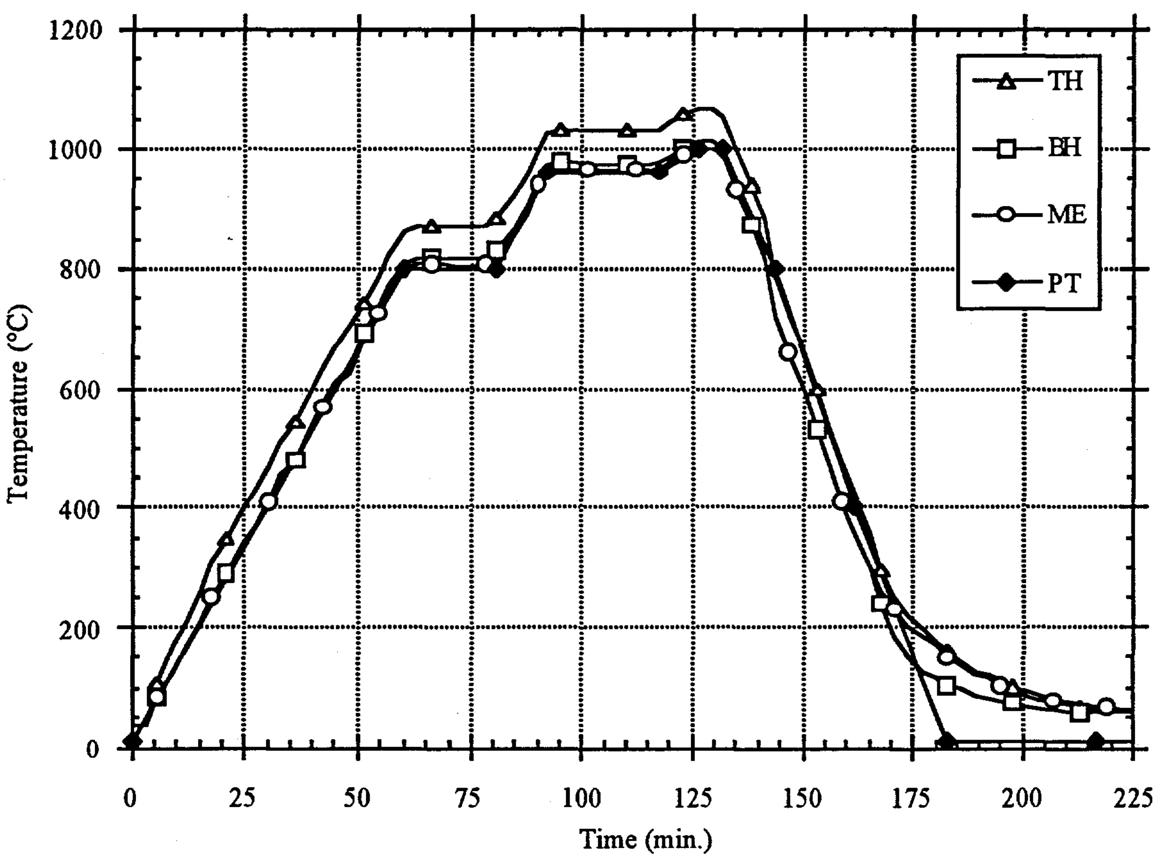

Figure 3: Temperature profiles for a 50Au-50Cu furnace survey (TH - top heater, BH - bottom heater, ME - main element control temperatures; PT - programmed temperature).

Results and Discussion

The control temperature, TC_{ME}, next to the main heating element, generally corresponded closely to the programmed furnace temperature for both heating cycles. The exception occurred on furnace cooling below 250°C, where the thermal mass of the furnace caused TC_{ME} to lag behind the programmed value. Typical profiles for the 50Au-50Cu and 100Cu furnace runs are shown in Figures 3 and 4. The top and bottom trim heater temperatures, TC_{TH} and TC_{BH}, respectively, were set higher than the main element to compensate for potential "cool" spots at the top and bottom of the effective furnace work zone. The model's boundary conditions were based on these baseline TC_{ME}, TC_{TH}, and TC_{BH} time-temperature measured profiles.

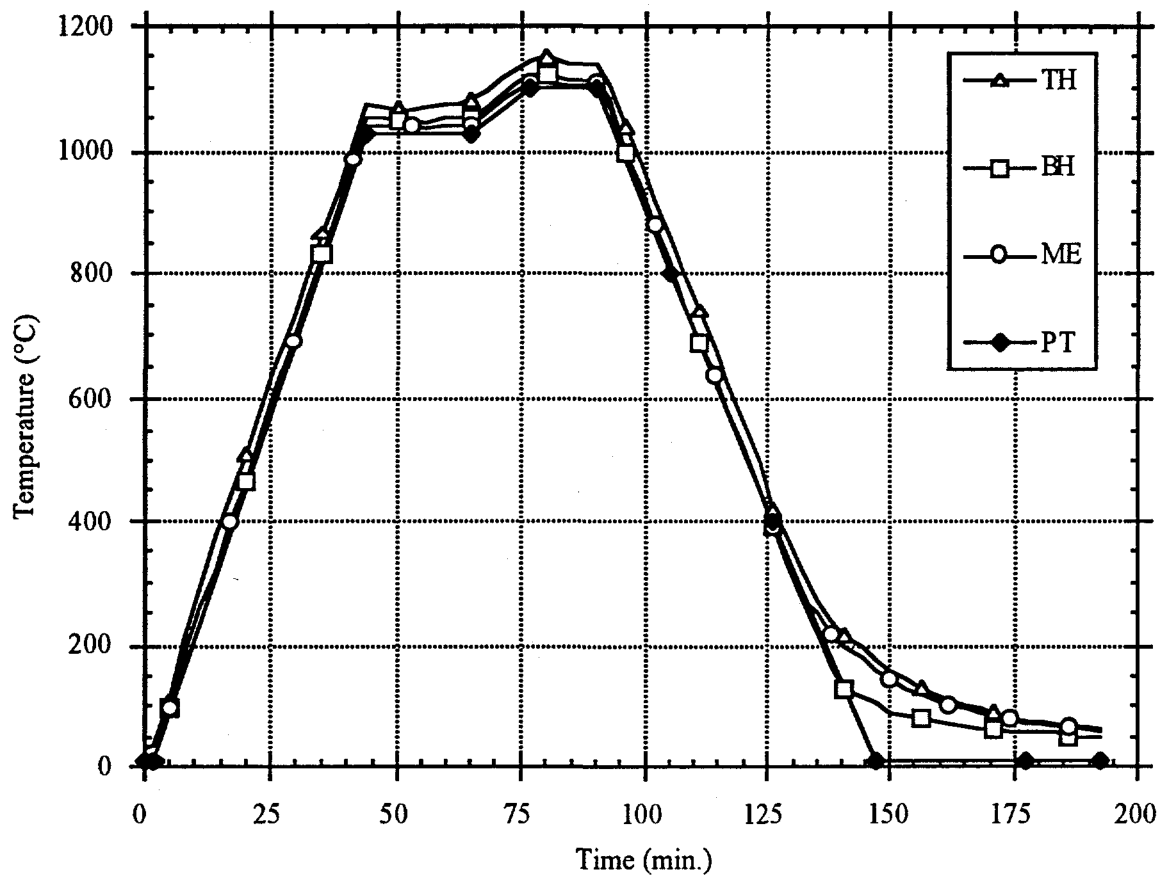

Figure 4: Temperature profiles for a 100Cu furnace survey (TH - top heater, BH - bottom heater, ME - main element control temperatures; PT - programmed temperature).

Although the bottom and main control temperatures converged to the set soak and peak temperatures within a 5-10°C range, the top zone was generally hotter than the main programmed temperature by 40-60°C. These values suggest that temperature uniformity is an issue in the furnace, particularly for parts loaded in different locations on the work rack. For example, parts placed on the bottom shelf might not braze as well as parts processed on the third shelf, due to axial nonisothermal heating within the furnace and potential conductivity differences between the work shelf and loaded materials. Loading density can also influence the furnace's thermal response. Accurately predicting these transient physical and thermal changes, therefore, can be very difficult to accomplish. A computational error of 5%, usually acceptable when analyzing experimental data, could result in a 50°C offset at 1000°C. This deviation might yield useful information about trends in the brazing process, but the results cannot be used to predict or control joint level responses. The validation experiments described in this paper have attempted to narrow the gap between the predicted and actual temperature profiles by identifying and resolving uncertainties in the model, such as incorrect materials properties or the physical and thermal boundary conditions of the loaded furnace.

The measured (WT) and predicted (ST) temperature responses of the molybdenum test piece for the two brazing cycles are compared in Figures 5 and 6. The plots include the measured main element temperature profile and the temperature difference, ΔT = (ST-WT), between the predicted and measured data. Each WT value represents the average of six thermocouple measurements.

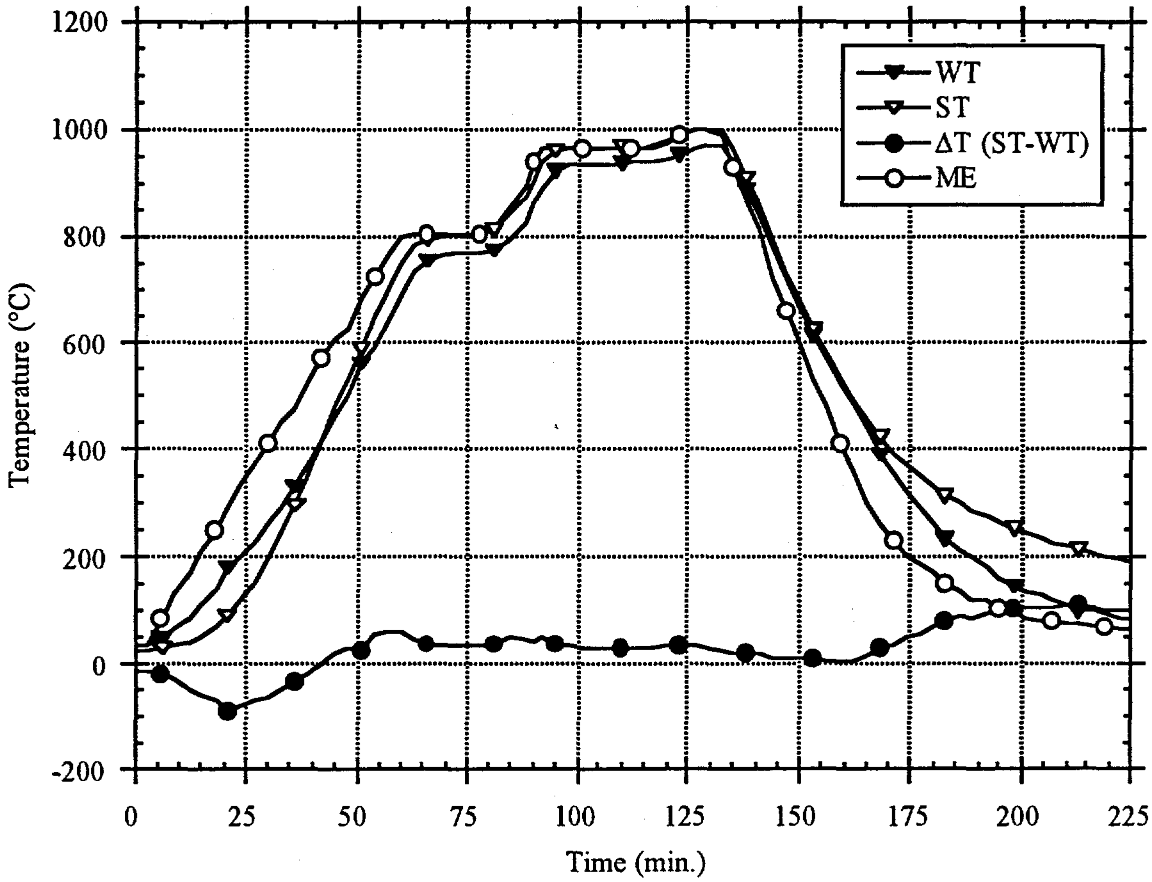

Figure 5: Temperature profiles for a 50Au-50Cu furnace run (WT - average work temperature (measured), ST - simulation temperature, ΔT (ST-WT) - difference between predicted and measured work temperatures, and ME - main element control temperature).

For the 50Au-50Cu braze run (Fig. 5), the predicted values initially lagged the actual part temperature. Once above 400°C, however, this trend was reversed. The ΔT between the two values also decreased and began to converge during the hold at peak temperature. On cooling, the ΔT again increased, particularly below 400°C, with the measured temperature leading the calculated values. The average ΔT above 800°C was 33°C ± 8, with a convergence to 20°C ± 7, at and immediately following the set peak temperature. This corresponded to a 4 to 2% computational error, respectively. The error values were much higher on heating and cooling below 400°C.

Similar trends were observed during the 100Cu braze run (Fig. 6). The predicted values initially lagged the actual part temperature. Once again, the ΔT values were much higher at the lower ends of the process during heating and cooling. The 100Cu computed and measured data were closer in value above 400°C than the data obtained using the 50Au-50Cu test conditions. The average ΔT for the higher temperature brazing cycle was 21°C ± 8 above 1000°C, with a convergence to 12°C ± 6, at and immediately following the set peak temperature. This corresponded to a 2 to 1% computational error, respectively, a significant improvement over the 50Au-50Cu model validation results. The higher temperature furnace profile appears to yield better temperature uniformity in the furnace and agreement with the modeled inputs.

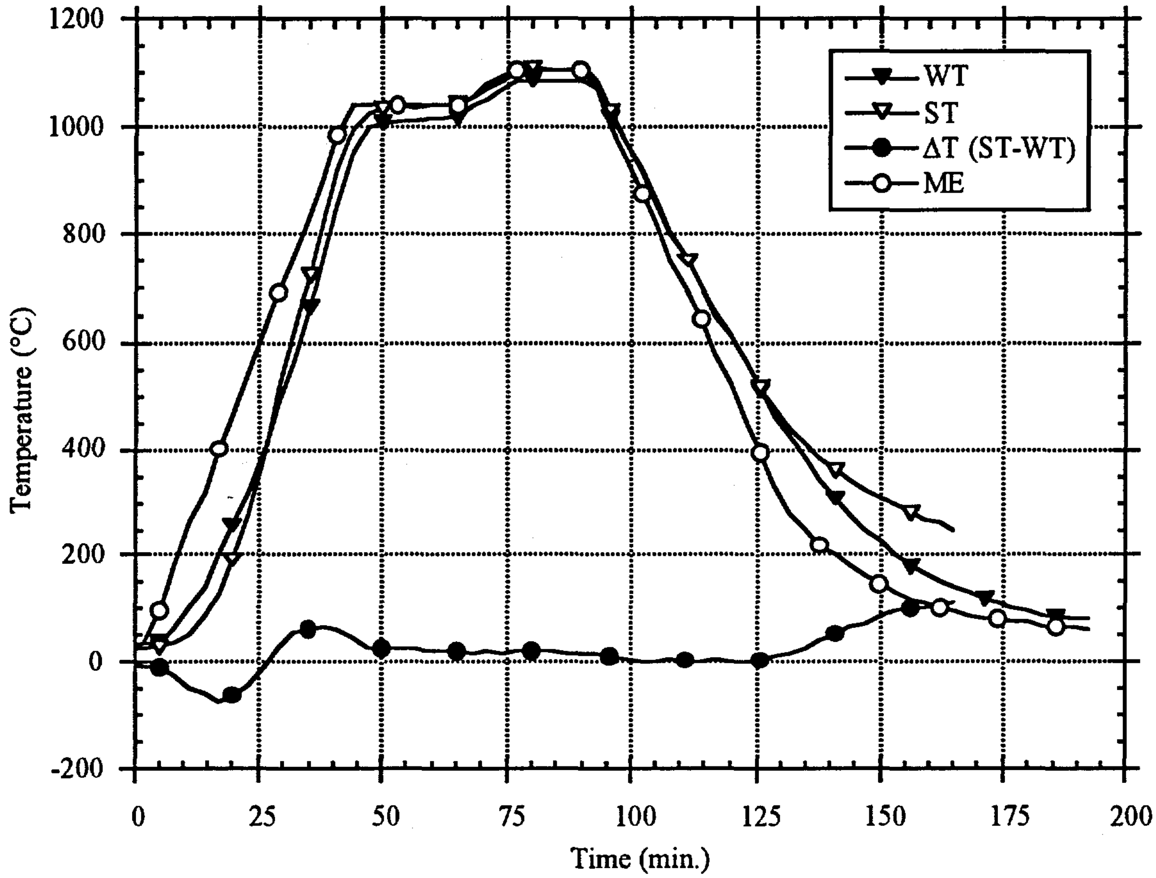

Figure 6: Temperature profiles for a 100Cu furnace run (WT - average work temperature (measured), ST - simulation temperature, ΔT (ST-WT) - difference between predicted and measured work temperatures, and ME - main element control temperature).

Although the resulting experimental and computational thermal profiles tracked reasonably well at the programmed brazing temperatures, significant differences in the data occurred for the lower transient thermal conditions. The work temperature, both predicted and measured, was consistently lower than the control temperature. The results provide useful information on the furnace's boundary conditions and potential computational uncertainties in the model. Early in the transient thermal event, the predicted temperatures lagged the measured data. This suggests that the thermal capacitance (i.e., density x specific heat) was over-estimated. As the brazing cycle proceeded, the predicted temperatures were greater than the measured values. This implies that the specific heat data above 400°C that was inputted into the model was too low. Since density is nominally constant with temperature, the assumed temperature-dependent values of specific heat could be slightly off. The same holds true for the other inputted thermal properties, such as thermal conductivity. Better temperature-dependent materials data would improve the transient accuracy of the model. At the high end of the thermal cycle, the ΔT value also appears to be affected by the thermal and materials-dependent emissivity of the furnace structure and loaded parts. Changing surface conditions, caused by thermal, chemical, and physical reactions, can make it difficult to obtain "good" emissivity numbers. All of the above factors contribute to the model's computational errors. Thermal predictions can be improved by resolving these materials and processing uncertainties. Better control of the furnace's temperature uniformity (bottom, main, and top heater feedback loop control) and a more detailed mapping of the furnace's thermal boundary conditions should further enhance model accuracy.

A second series of furnace simulations and experimental validations were conducted to predict the thermal response to more complex loading configurations. The investigation utilized different loading density, work zone location, and test materials conditions. The loaded samples consisted of 94% alumina, molybdenum, and Kovar™ (Fe-29Ni-17Co, wt. %) cylindrical test pieces, with machined holes for thermocouple placement. Transient thermal responses of the loaded assemblies were measured and predicted as a function of the global location within the furnace and the axial position in the part. Resolution of uncertainties from the initial baseline evaluations were used to reduce errors in the more complex furnace analyses. Initial test results have shown that the thermal response of the loaded components lags the programmed transient heating conditions of the furnace. This predicted lag increases with increasing loading density, although axial heating from the bottom to the top of the work rack is more uniform. These results suggest that axial uniformity within the furnace increases with increasing loading density. The size of the loaded components also affects furnace response. The results provide a useful range of thermal responses for bracketing the furnace brazing process.

Conclusion

A thermal model has been developed to predict the response of a hydrogen brazing furnace to different loading and processing conditions. Supporting experiments were conducted to validate brazing process simulations. Relatively small differences between the computed and measured test sample temperatures were observed above 800-1000°C. Larger ΔT values occurred at the lower ends of the investigated thermal cycles, typically below 400°C. The computational errors were attributed to materials and processing uncertainties in the baseline conditions. Resolving these uncertainties through more accurate temperature-dependent model inputs, including materials properties and furnace boundary conditions, should yield improved brazing simulations. Computational and experimental results have demonstrated the importance of loading density, work zone location, and materials properties in response to the furnace's thermal environment. Work is underway to investigate the local thermal and mechanical issues that determine joint-level braze properties.

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