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OBTAINING THE SENSED TEMPERATURES FROM A DETAILED MODEL OF A WELDED THERMOCOUPLE

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ABSTRACT

When imbedded in dissimilar materials subject to large temperature gradients, thermocouples are known to yield erroneous (bias) temperature measurements. It has been established that the bias error may be accounted for with an appropriate computational model and the measured temperatures may be corrected with an appropriate kernel function. In this work, a thermocouple with a welded bead is considered. Early two-dimensional models considered the thermocouple to be a single wire with effective thermal properties. The model in the current investigation is three-dimensional and represents the sensor as two wires, each with unique thermal properties. The welded bead is represented as a separate entity with properties distinct from those of the wires.

The problem of determining what location in the three-dimensional model corresponds to the measured temperature is considered. Earlier models have considered the sensed temperature to be the temperature at the tip of the two-dimensional thermocouple or, in three-dimensional models, the temperature at the center of the volume of the welded bead. In the current work, a theory is set forth for identifying the location at which the temperature is sensed by a thermocouple. This theory is in line with traditional thermoelectric theory and is supported with experimental evaluation with thermal imaging as well as examination of thermocouples by scanning electron microscopy and energy dispersive X-ray analysis. The significance of accurate modeling of the sensed temperatures is demonstrated with a numerical experiment.

INTRODUCTION

Imbedding thermocouples in solid material is a common approach to obtaining experimental temperature histories for inputs to the inverse heat conduction problem. It is well established that imbedded thermocouples in high temperature gradients are subject to significant bias error,[1-5] particularly when the sensor is imbedded in a material with much different thermal properties. A common approach to accounting for such bias is to use a computational heat transfer model.

The simplest and most common approach to representing a thermocouple is to use an axisymmetric model. Such a modeling effort requires that the thermocouple be treated as a single wire with effective thermal properties. An example of a simple axisymmetric thermocouple model is shown in Figure 1. The axisymmetric approach can yield very good results. However, there is very little documentation available regarding three dimensional modeling of a thermocouple and, thus, there is a need to investigate its value.

In its simplest form, a thermocouple has three volumes of interest: the two wires and the weld. An axisymmetric model lumps these three volumes into one cylindrical body. In addition, a cylindrical volume may be placed around the effective thermocouple wire to represent insulation. When employing a three dimensional model, however, all of these volumes may be represented as separate entities with unique thermal properties.

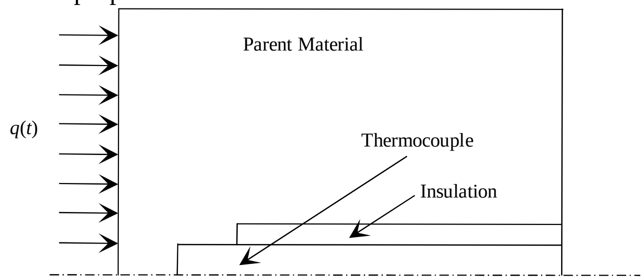

Figure 1. An axisymmetric thermocouple model

Using a computational model, one can estimate the temperature which would be measured by a thermocouple during transient heating or cooling conditions and the undisturbed temperature some large distance away.[1,2] An interesting issue arises at this point in the endeavor: what exactly is the location at which the temperature is sensed by a thermocouple? For a simple axisymmetric model, options for choosing the "sensed" temperature are pretty limited. One could select the geometric center of the tip surface or, perhaps, the entire tip surface. For a three-dimensional representation of a thermocouple, the issue is significantly less trivial.

In this paper, we seek the location at which the temperature is sensed within a thermocouple. Scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX) is employed to explore the composition of various regions of the wire. An infrared camera is used to obtain thermal images of the temperature changes of a thermocouple during transient heating and cooling. A numerical experiment is conducted with a computational model of a thermocouple to demonstrate the significance of accurate representation of the sensed temperature. Finally, a theory is set forth describing the actual location of the sensed temperature.

SEM ANALYSIS

An investigation was conducted to assess the composition of a welded thermocouple. A thermocouple was analyzed by scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX). Elemental mapping of the overall composition of the sensor as well as the composition at point locations were considered.

The sample considered was a pre-fabricated, "off the shelf" 24 AWG type K thermocouple. The thermocouple lead wires were trimmed so that only a short length near the weld remained. The sample was mounted for SEM-EDX analysis. Material was removed from the mounted sample for viewing the plane which passes approximately through the axes of the wires and through the center of the welded bead.

The thermoelements for a type K thermocouple are chromel and alumel. The nominal composition of chromel is 90% Ni, 10% Cr and the nominal composition of alumel is 94% Ni, 3% Mn, 2% Al, 1% Si. The primary components are analyzed separately with images (Figure 2-Figure 4) obtained by SEM-EDX analysis. The component of interest in each image is indicated by white areas. Brighter white areas indicate a higher concentration of the component of interest. In each image, the chromel wire is positioned at the top and the alumel is at the bottom of the image. For clarification, the approximate layout of the thermocouple is represented in Figure 5.

In Figure 4, distinct regions of chromium concentration really stand out. Specifically, the bright chromel wire at the top left, the dark alumel wire at the bottom left, and the welded bead all contrast with one another. The chromium content is high enough in the chromel wire (9-10% Cr) that it significantly contrasts with the alumel wire (~0% Cr). Both wires contribute to the composition of the weld, and it can be viewed as an approximate average of the compositions of each constituent. This is supported by the line scan analysis.

Figure 2. Elemental mapping from SEM-EDX analysis of chromium content in a type K thermocouple

The nickel concentration is shown in Figure 2. As both chromel and alumel are nickel-based alloys, high nickel concentrations are detected throughout the sensor. As expected, a higher nickel concentration is observed in the alumel wire than in the chromel wire.

For elemental components with low concentrations, only slight contrast can be expected. This can be seen in Figure 3 for manganese. The average manganese content in the alumel lead was found by SEM-EDX to be less than 2%. So the only elements that are present in a concentration high enough to possibly exhibit a contrast adequate for a meaningful analysis are nickel and chromium.

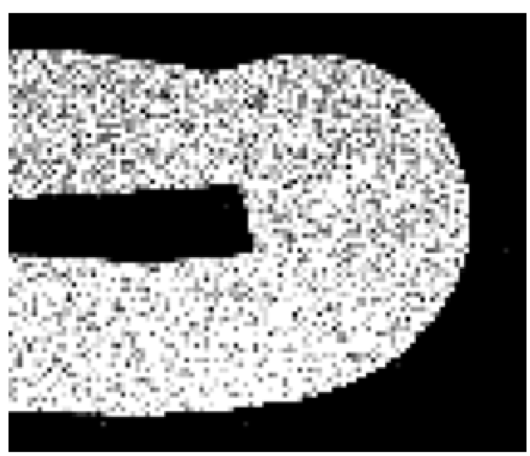

Figure 3. Elemental mapping from SEM-EDX analysis of nickel content in a type K thermocouple

Figure 4. Elemental mapping from SEM-EDX analysis of manganese content in a type K thermocouple

Line scans of the thermocouple composition were performed starting in each wire and passing over the wire/weld interface. The approximate locations of each line scan are illustrated in Figure 5. Line Scan 1 started in the chromel wire material and, scanning from left to right, crossed into the weld material. The compositions obtained from Line Scan 1 are shown in Figure 6. Line Scan 2 was initiated in the alumel wire material and passed from left to right over the wire/weld interface. The Line Scan 2 compositions are shown in Figure 7.

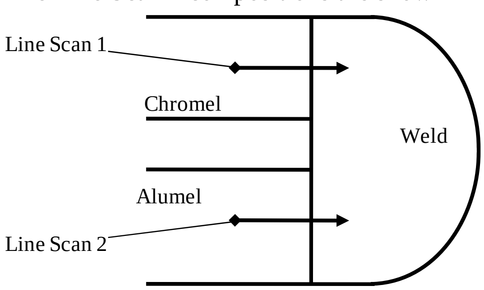

Figure 5. Schematic of locations of compositional line scans

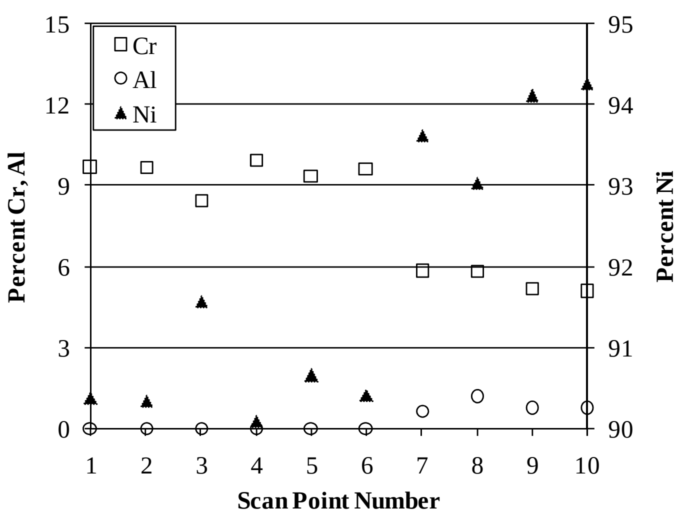

Figure 6. Compositions from Line Scan 1

In Figure 6, the transition from wire material to weld material can be identified by the increase in Ni, the decrease in Cr, and the appearance of Al from point 6 to point 7. Similarly, in Figure 7, the Ni and Al concentrations drop and the Cr content increases at the wire/weld interface which appears to be between scan points 8 and 9. Some Mn content should be detected in the weld by both scans. However, no Mn appears. This may be a result of the Mn being masked by another element.

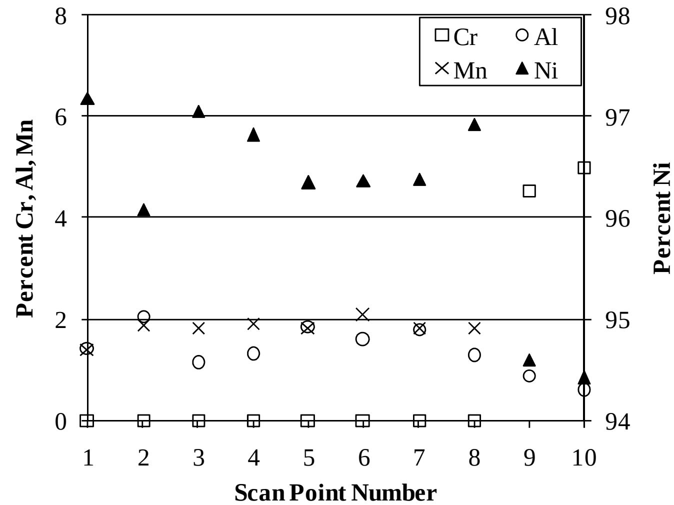

Figure 7. Compositions from Line Scan 2

EXPERIMENTAL TEMPERATURE ANALYSIS

In an attempt to determine the location at which the temperature of a thermocouple is sensed, an experiment was conducted which involved two approaches to acquiring temperature data from a thermocouple during transient heating and cooling. The first approach was traditional thermocouple measurement and was performed with a digital data acquisition system. The second approach was the use of an infrared (IR) camera which is used to obtained thermal images.

Experiments were conducted to investigate transient heating of a welded thermocouple bead. The thermocouple was comprised of 0.9 mm diameter wires and the welded bead was about 1.8 mm in width. Initially, the volume of the bead was nearly spherical in shape. Some of the mass of the thermocouple was ground away so that the bead was of approximately of uniform thickness. This was done in attempt to make the heat flow nearly two-dimensional. The thermocouple was painted flat black with high temperature paint to minimize reflectivity and increase the emissivity. The thermocouple was suspended in air at room temperature and then heated with a torch.

The temperature of the thermocouple was recorded with a digital data acquisition system (DAQ). The measured temperature histories of the thermocouple are recorded continuously throughout the duration of the experiment. The thermocouple is connected to a 16-bit input capable of 20,000 samples per second. The computer receives the temperature data via a SCXI device. One temperature is acquired every 0.5 second, and each temperature recorded is an average of 10 samples at a rate of 20 samples per second.

Transient thermal images were obtained with an IR camera. A close focus lens was used to capture the images. These images can be processed with software to extract the temperature data from user-specified points or areas. The temperatures of the surface of the thermocouple were recorded with an infrared camera. The reference emissivity for the thermal imaging was set to 0.9 and the reference background temperature was set to 22°C.

The thermocouple was heated by a flame from a propane torch. Heat was applied to the tip so that a temperature gradient would be present across the weld. Images taken about 3.5 seconds and about 6 seconds after heat was applied to the thermocouple are shown in Figure 8 and Figure 9, respectively. The temperature gradient can be observed in these images. The tip of the bead is at a higher temperature than the area opposite of the tip.

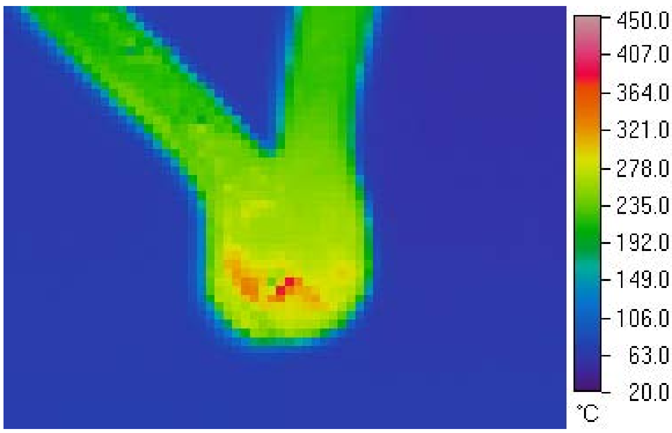

Figure 8. Thermal image of a thermocouple 3.5 seconds after application of heat

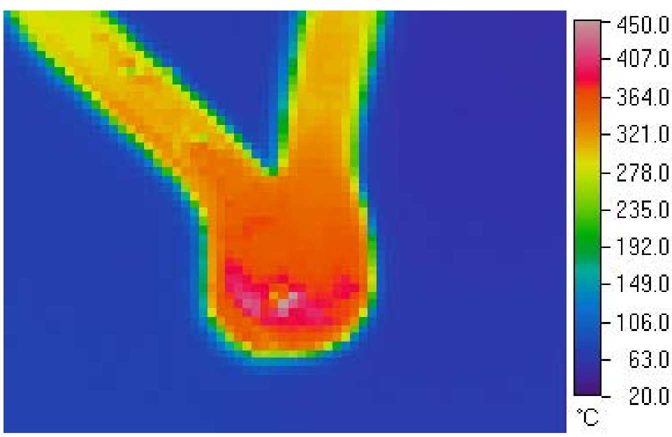

Figure 9. Thermal image of a thermocouple 6 seconds after application of heat

Four regions of the sensor were investigated. These regions are shown in Figure 10. Region 1 is the area of the weld at which the two wires are closest to each other. Region 2 approximately represents the interface between the weld and the wires at which the composition distinctly changes as illustrated by the chromium analysis in Figure 4. Region 3 is the area at the center of the weld surface. Region 4 is the area at the tip of the welded bead. The temperature recorded from regions 1, 3, and 4 are the average temperatures over the specified areas. The temperature recorded by region 2 is the average temperature over the line. Temperatures recorded from these regions during 20 seconds of transient heating and cooling are plotted with the temperature histories recorded by the DAQ.

From Figure 11 - Figure 14, it can be seen that the temperature history obtained from region 2 is the closest to the DAQ temperature history. The two temperature histories in Figure 12 are extremely close during heating. However, the temperature of region 2 does not cool as quickly as the DAQ. The temperature history of region 1 (Figure 11) is also quite close to the DAQ, particularly during heating.

The temperature histories at the center of the weld (region 3, Figure 13) and at the tip (region 4, Figure 14) do not follow the DAQ history as closely. Both the center and the tip increase in temperature earlier than the DAQ. The tip cools more rapidly as indicated by the larger temperature drop.

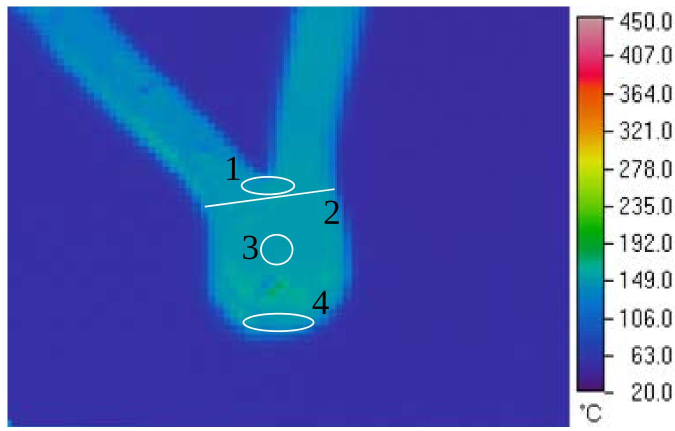

Figure 10. Locations of investigated regions

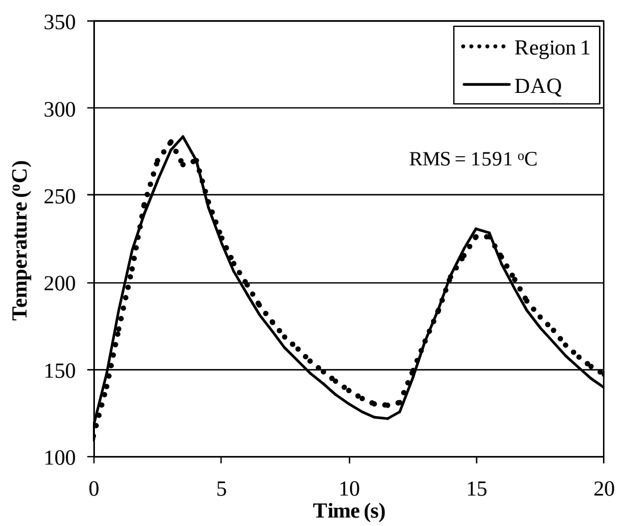

Figure 11. Temperature histories and RMS from region 1 of the thermal image and the data acquisition system (DAQ)

By comparing the time derivatives of the temperature histories, the rate of heating and cooling for each region and for the DAQ histories can be evaluated. During cooling, the time derivatives for each region are all very nearly identical to that of the DAQ. The time derivatives during the first five seconds of the experiment (Figure 15), however, reveal that only the rate change of region 2 compares closely to that of the DAQ.

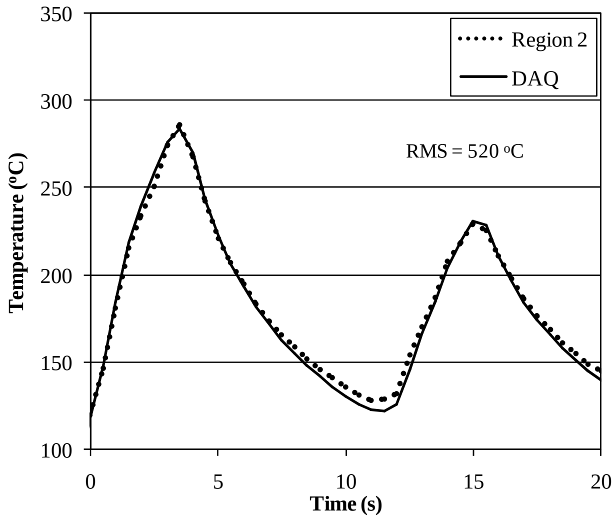

Figure 12. Temperature histories and RMS from region 2 of the thermal image and the data acquisition system (DAQ)

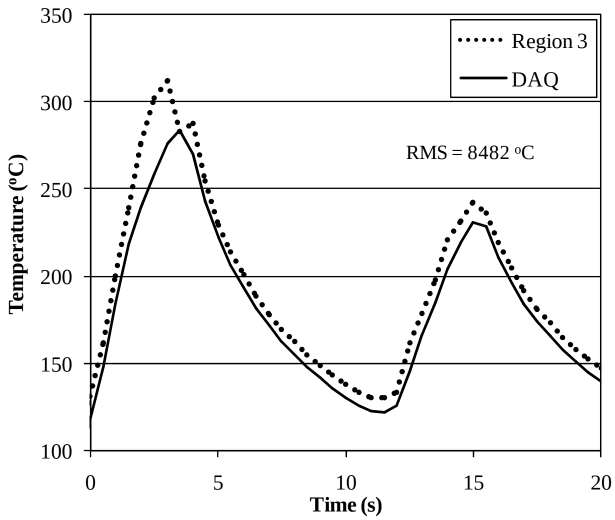

Figure 13. Temperature histories and RMS from region 3 of the thermal image and the data acquisition system (DAQ)

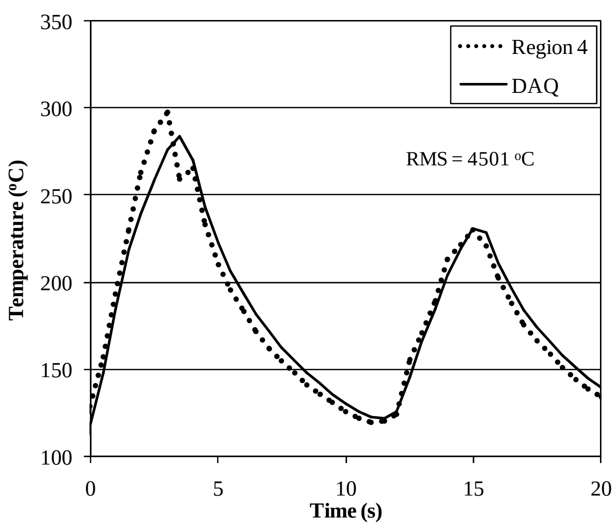

Figure 14. Temperature histories and RMS from region 4 of the thermal image and the data acquisition system (DAQ)

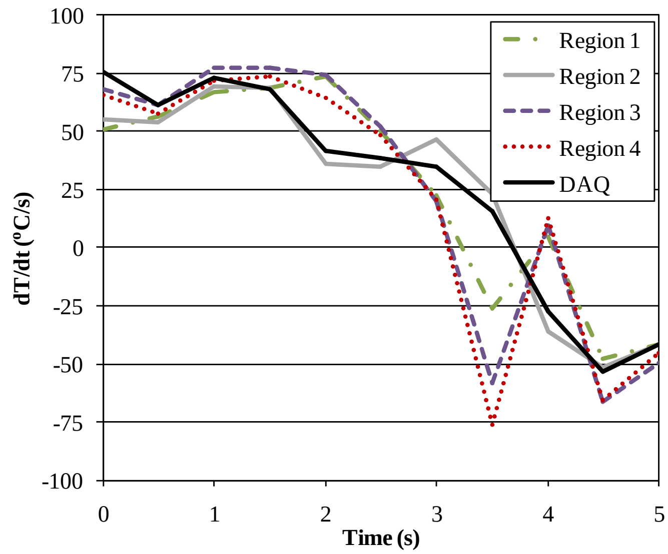

Figure 15. Time derivatives of the temperature histories of the DAQ and regions 1 - 4 during heating

The root mean squared (RMS) values were taken to compare the temperatures from each region of the thermal imaging analysis to temperatures obtained with the DAQ. The RMS values reveal that the temperature histories from region 2 relate best to the DAQ temperature data. The RMS value for regions 1, 2, 3, and 4 are 1590°C, 520°C, 8482°C, and 4501°C.

THERMOCOUPLE MODEL

A detailed three-dimensional thermocouple model was employed in this investigation to estimate the temperature difference across the weld. Each of the three compositional volumes was represented in the model. The wires were represented by cylindrical volumes and the bead was represented by an ellipsoidal volume. The sensor was configured such that the axes of the cylindrical wires were perpendicular to the heated surface. The system under investigation is a bare (no insulation) thermocouple imbedded in a resin-bonded sand mold. The boundary condition was representative of a heat flux that might occur at the interface of a mold filled with molten aluminum.

The sensor considered (Figure 16) is a 24 AWG (American Wire Gauge) type K (chromel-alumel) thermocouple. The wire radius, r_w, is 0.25 mm. The dimensions of the welded bead of a 24 AWG type K thermocouple were measured with calipers. The geometry of the bead is approximated in the model as an ellipsoid with a major axis radius, r_{maj}, of 0.625 mm and a minor axis radius, r_{min}, of 0.42 mm. The tip of the thermocouple is a distance $E = 2\sqrt{2r_w^2}$ from the heated surface.

The thermal properties used in the model were considered as constant for this work. The individual thermocouple wires were modeled with distinct thermal properties. The thermoelements for a type K thermocouple are chromel (k = 19.25 W/m-K, ρc_p = 3.91E+06 J/m^3-K) and alumel (k = 29.71 W/m-K, ρc_p = 4.50E+06 J/m^3-K). The thermocouple bead is formed by welding the two wires together, and thus the properties are an average of the properties of the constituent materials (k = 24.48 W/m-K, ρc_p = 4.20E+06 J/m^3-K). The properties for used for the sand mold are k = 1 W/m-K and ρc_p ≈ 1.60E+06 J/m^3-K.

The model was used with commercial CFD software to simulate and evaluate the temperatures within the system. The temperature histories shown in Figure 17 were extracted from four point locations within the system. Three of these four points were located within the bead: at the tip of the bead, at the volumetric center of the bead, and near the junction of the bead. The temperature that represents the "junction temperature" was taken at a point location on the bead between the two wires and directly opposite of the tip. The fourth point was some very large distance away from the modeled sensor so that it is not affected by the temperature field disturbance which occurs due to the presence of the thermocouple.

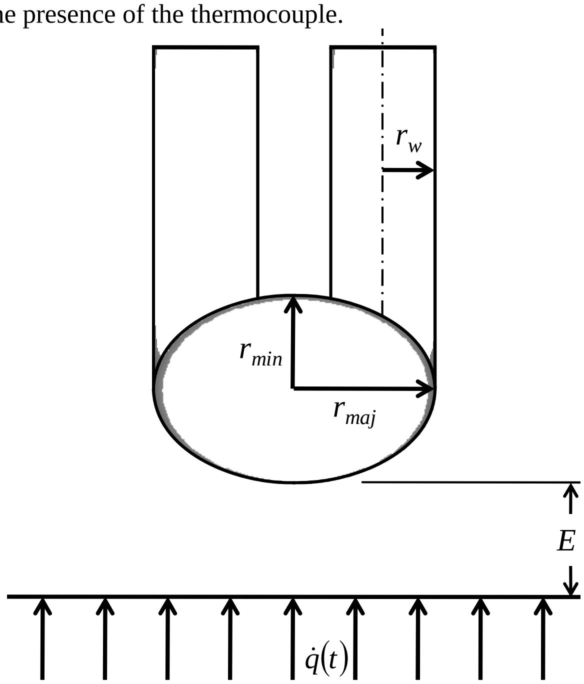

Figure 16. Model geometry of a thermocouple imbedded near a heated surface

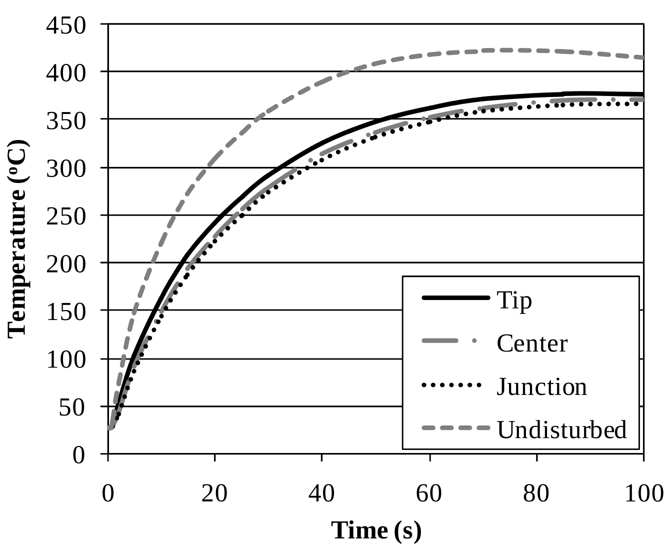

Figure 17. Simulated temperature histories

It can be seen from Figure 17 that the thermocouple acts a heat sink and thus must return biased measurements. The tip temperature is higher than both the center temperature and the junction temperature. The junction temperature is the most erroneous by comparison to the simulated undisturbed temperature. The temperature difference across the bead is shown in Figure 18. The maximum temperature difference across the bead is just over 20°C. The temperature depression at and around the thermocouple weld is illustrated in Figure 19.

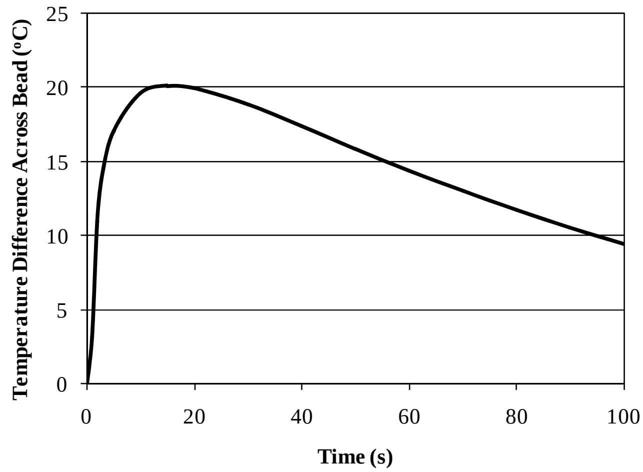

Figure 18. Difference between simulated tip and junction temperatures

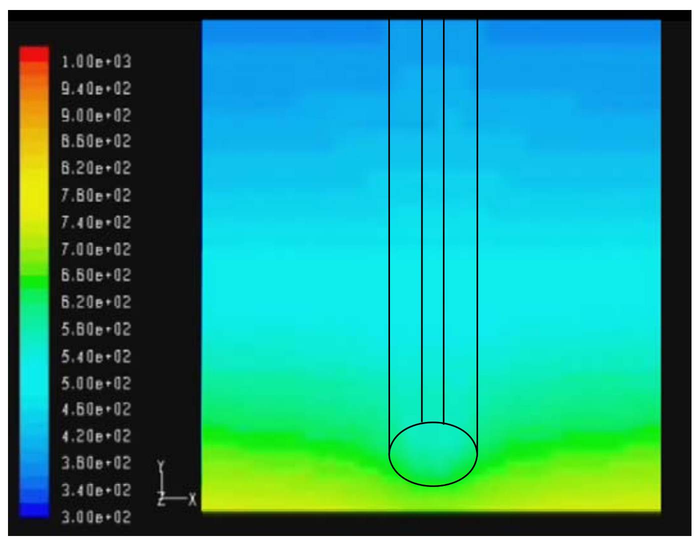

Figure 19. Simulated temperature disturbance (temperatures are in degrees Kelvin)

DISCUSSION OF RESULTS

From the analysis by scanning electron microscopy, three different compositional regions were observed in Figure 4. Two of the regions are the chromel and alumel wires and the third region is the weld. There is a distinct transition zone between each wire and the weld.

The law of intermediate metals of thermoelectric thermometry tells us that, for two wires of dissimilar metals joined to a metal of a third material, the electromotive force (EMF) registered by the thermocouple is the average of the EMF that would register by thermocouples if each junction could be considered without the presence or influence of the other. Based on the law of intermediate metals and the SEM-EDX analysis, it can be theorized that the temperature sensed by a thermocouple is the average temperature at the transition zones from wires to weld. This theory was supported by the thermal imaging analysis.

Of the four different regions of the thermocouple that were investigated, the line average near the wire/weld interface yielded temperature measurements which most closely matched the temperature history recorded by the data acquisition system. The temperatures obtained from the thermal imaging may be sensitive to the emissivity settings used in the analysis. However, the rates of temperature change with respect to time may be less sensitive to the emissivity settings. An evaluation of the time derivative of the temperature histories also reveals that results from the line average near the wire/weld interface most closely reflects the results from the DAQ.

A numerical experiment was conducted to investigate the temperature difference within a thermocouple bead. The difference between the tip temperature and the junction temperature reached over 20°C. That is more than a 12.5% difference in the temperature at that time.

Axisymmetric models have commonly been used in the past to demonstrate or estimate the measurement bias which results from a thermocouple having different thermophysical properties from a surrounding material.[3-5] It should be noted that the temperature difference across the bead cannot be accounted for with axisymmetric models. Furthermore, the unique properties for each material cannot be considered in an axisymmetric model. This could be significant since the thermal properties for alumel are so much higher for alumel than chromel. For instance, from published sources of temperature dependent properties, k for alumel is 50% to 90% higher, ρc_p is 2.5% to 15% higher, and α is 40% to 80% higher.[6-8]

CONCLUSIONS

In this paper, the location within a thermocouple at which the temperature is sensed is investigated. A theory is established which states that the temperature is sensed at the interface between the wire and weld. The wire/weld interface was illustrated in images obtained from SEM-EDX analysis. Thermal imaging analysis performed with an infrared camera yielded results to support the theory.

Based on the compositional analysis of the three regions of the thermocouple, it can be concluded that, as expected, the weld composition is approximately an average of the composition of the two wires. Also, the weld material is close enough to uniform that it can be approximated as uniform in a model. So it is reasonably to model the weld as a single material with properties that are averaged from the properties of chromel and alumel.

A numerical experiment was conducted to simulate the temperature change within a system containing a thermocouple imbedded in a sand mold. The results showed that the temperature difference across the weld can reach at least 12.5%.

It can be concluded from this work that, when modeling a thermocouple system in transient heating or cooling, it is important to use a high fidelity model which is capable of accurately representing the temperature which is sensed by the thermocouple. This is particularly true when high temperature gradients are involved, such as with quenching or solidification interfacial heat transfer problems.

ACKNOWLEDGEMENTS

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