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Contact Thermocouple Methodology and Evaluation for Temperature Measurement in the Laboratory

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Abstract

Laboratory testing of advanced aerospace components very often requires highly accurate temperature measurement and control devices, as well as methods to precisely analyze and predict the performance of such components. Analysis of test articles depends on accurate measurements of temperature across the specimen. Where possible, this task is accomplished using many thermocouples welded directly to the test specimen, which can produce results with great precision. However, it is known that thermocouple spot welds can initiate deleterious cracks in some materials, prohibiting the use of welded thermocouples. Such is the case for the nickel-based superalloy MarM-247, which is used in the high temperature, high pressure heater heads for the Advanced Stirling Converter component of the Advanced Stirling Radioisotope Generator space power system. To overcome this limitation, a method was developed that uses small diameter contact thermocouples to measure the temperature of heater head test articles with the same level of accuracy as welded thermocouples. This paper includes a brief introduction and a background describing the circumstances that compelled the development of the contact thermocouple measurement method. Next, the paper describes studies performed on contact thermocouple readings to determine the accuracy of results. It continues on to describe in detail the developed measurement method and the evaluation of results produced. A further study that evaluates the performance of different measurement output devices is also described. Finally, a brief conclusion and summary of results is provided.

1.0 Introduction

The Mechanics and Life Prediction Branch of the Structures and Materials Division at the National Aeronautics and Space Administration's Glenn Research Center (GRC) developed a method using contact thermocouples for temperature measurement in a high-temperature laboratory setting. This procedure used 0.025 mm (0.001 in.) diameter, platinum–rhodium/platinum type-R beaded contact thermocouples to take readings at laser-designated locations in order to accurately measure the temperature across the surface of a test article. Performed as described in the following sections, results produced were as accurate as traditional welded chromel–alumel type-K thermocouple readings. This method was developed to enable benchmark creep testing of the heater head for the Advanced Stirling Converter (ASC) component of the Advanced Stirling Radioisotope Generator space power system (Refs. 1 to 3). The heater head is composed of the nickel-based superalloy MarM-247, which is highly susceptible to crack initiation at welds; therefore the use of welded thermocouples was prohibited. Welded thermocouples were also not desirable because their presence created false readings of test article geometry from in-situ optical measurements using laser micrometers.

2.0 Background

In order to accurately characterize creep strain, precise temperature readings were required at various points axially and circumferentially on the variable wall thickness heater head test article (Refs. 4 to 7). For past heater head test articles fabricated from other alloys, multiple welded thermocouples were used to collect this data (Fig. 1). However, two problems were evident during initial use of welded thermocouples. First, the thermocouple wires and their insulating sleeves interfered with laser micrometer scan readings. The laser units measured diameters along the specimen's longitudinal axis; this data was used to calculate the in-situ experimental diametral strains. The interference likely occurred due to thermal expansion, which caused the thermocouples wires and their insulation to enter the laser path and to produce false readings (Fig. 2). In turn, this led to misinterpretation of data and automated shutdown of the test apparatus, due to exceeding the programmed maximum allowable diameter value. Secondly, cracks were initiated at thermocouple weld locations on heater head test articles fabricated from the nickel-based superalloy MarM-247. When under test pressure and subsequent high stress, the cracks rapidly propagated (Fig. 3). The cracking was first observed in a specimen labeled "SN18" and caused the premature termination of creep testing. Because of these problems, it was concluded that the method of multiple welded thermocouples was not acceptable for MarM-247 heater head creep testing. An alternative method that did not rely on welded thermocouples was needed to monitor the temperature of test articles. A study was performed to determine if accurate temperature readings could be obtained using contact thermocouples, and a description of that study and its results follows.

Figure 1.—Thermal standard test article: Type-K thermocouples were welded on this specimen, which was used for furnace development and temperature testing.

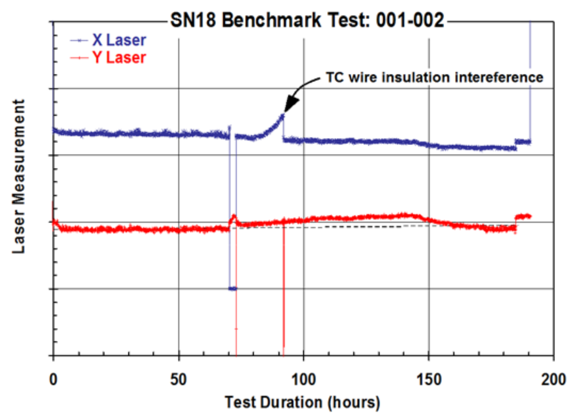

Figure 2.—Laser data from heater head SN18 Testing: Welded thermocouples eventually interfered with the continuous X laser micrometer signal as seen here.

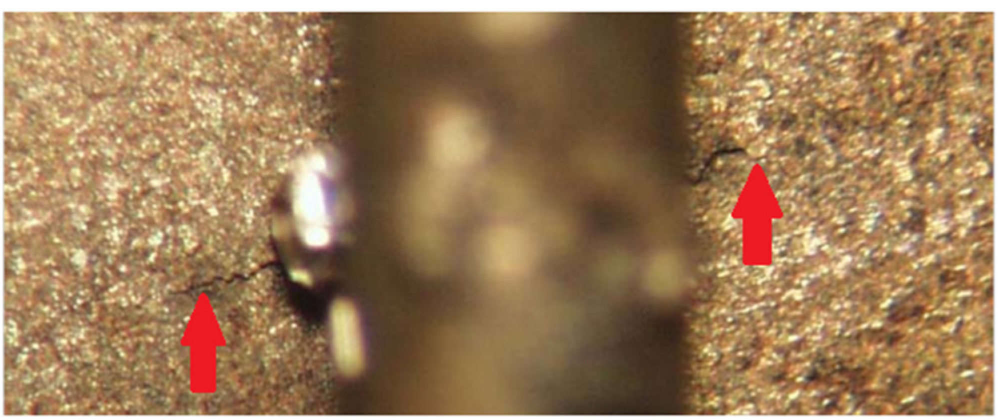

Figure 3.—Crack initiation at thermocouple weld: Crack growth at a type-K thermocouple weld was evident; the through-cracks caused gas leakage and resulted in the termination of the creep test.

3.0 Verification Study

Before contact thermocouple measurement methodology could be used to produce data for ASC heater head benchmark creep testing, a study was required to verify the accuracy of those readings. To accomplish this task, over one-thousand high temperature contact thermocouple measurements were taken at the locations of welded thermocouples on an existing heater head test article.

The first variable investigated was the thermocouple wire diameter. Many wire diameters were tested, ranging from 0.25 mm (0.010 in.) diameter wire to 0.025 mm (0.001 in.) diameter wire. It was observed that all contact readings were slightly lower than the control temperature, but the 0.025 mm (0.001 in.) diameter beaded thermocouples resulted in readings nearest to the welded thermocouple values (partial data shown in Fig. 4). This diameter also produced readings in the shortest time; it is believed that the larger diameter wires transferred heat by conduction more quickly, which lowered the local temperature at the measurement location. Smaller diameter wires allowed less heat loss and thus higher, more accurate readings.

Because the optimal thermocouples had very small diameter wires, they were prone to breaking after repeated use. The planned heater head creep tests were expected to last many weeks and require many repeated temperature measurements, so a single beaded thermocouple was not expected to last the entire test duration. Therefore, measurement differences between different beaded thermocouples of the same type were tested against a constant temperature reading from a welded thermocouple to ensure repeatability between thermocouples (Fig. 5). Results from this study indicated that thermocouple readings, though low, were repeatable. Therefore, temperature measurements could be made accurately even if contact thermocouple breaks occurred during the measurement process.

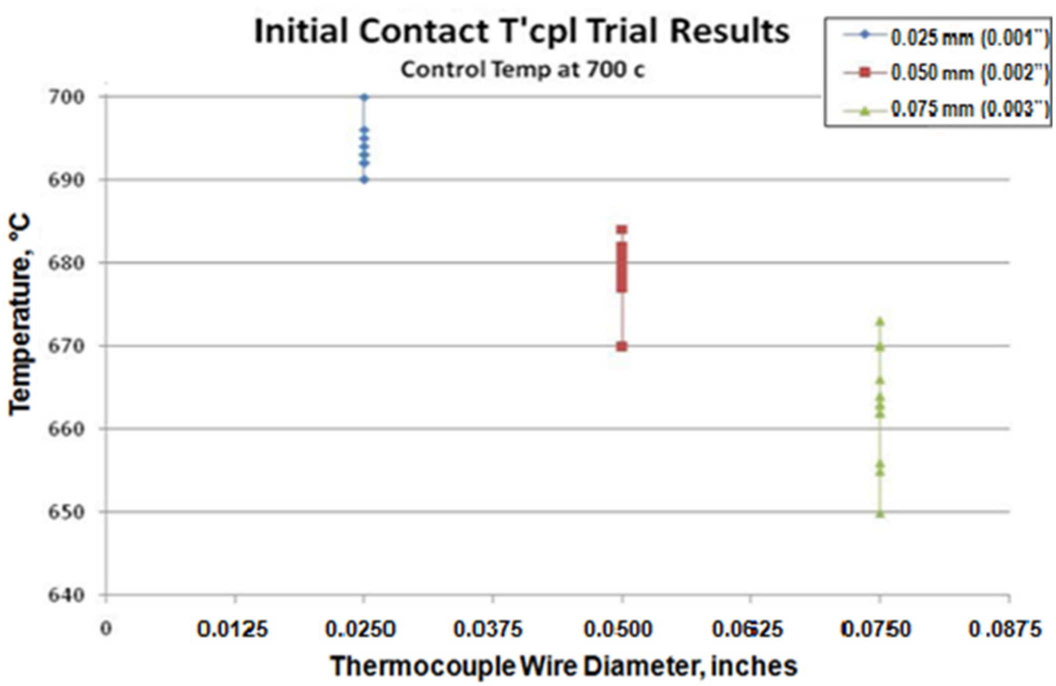

Figure 4.—Wire diameter investigation: Readings from three different diameter contact thermocouples were compared to welded thermocouple readings.

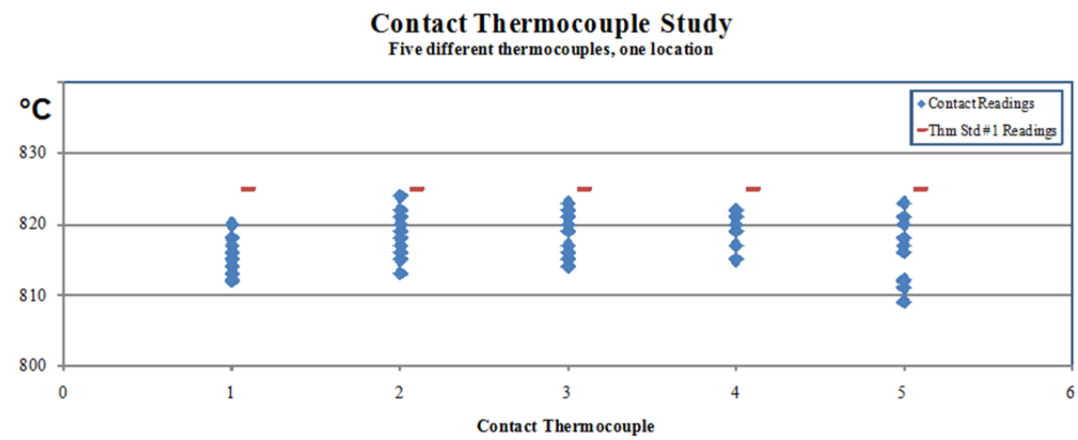

Figure 5.—Different thermocouples of the same diameter and type: It was determined that no significant measurement differences existed between nominally identical thermocouples.

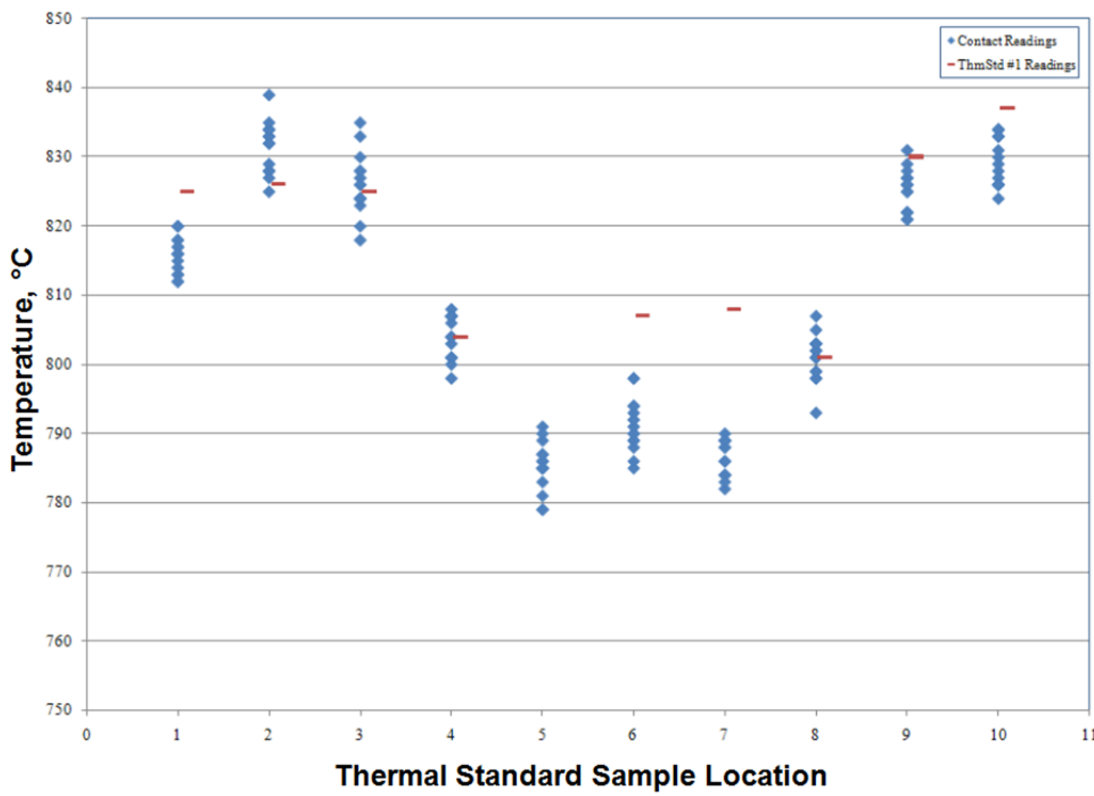

Figure 6.—Contact readings on the thermal standard: The data showed that in standard laboratory practice, type-R contact thermocouple readings correlated well with welded type-K thermocouple measurements.

Next, the repeatability of the contact thermocouple method in actual laboratory practice was evaluated using the thermal standard heater head. The thermal standard was heated to a number of the expected test temperatures. Several welded thermocouples at various axial and circumferential locations were selected, and multiple contact readings were taken at each of these points. The contact readings were then compared to those from the welded thermocouples (Fig. 6). Some of the contact readings were difficult to take due to location, apparatus interference, and imprecise contact placement. This resulted in temperature data with slightly greater scatter. To in placing the contact location, the laser extensometers were used to illuminate precise axial positions at which readings were to be taken. After refining the

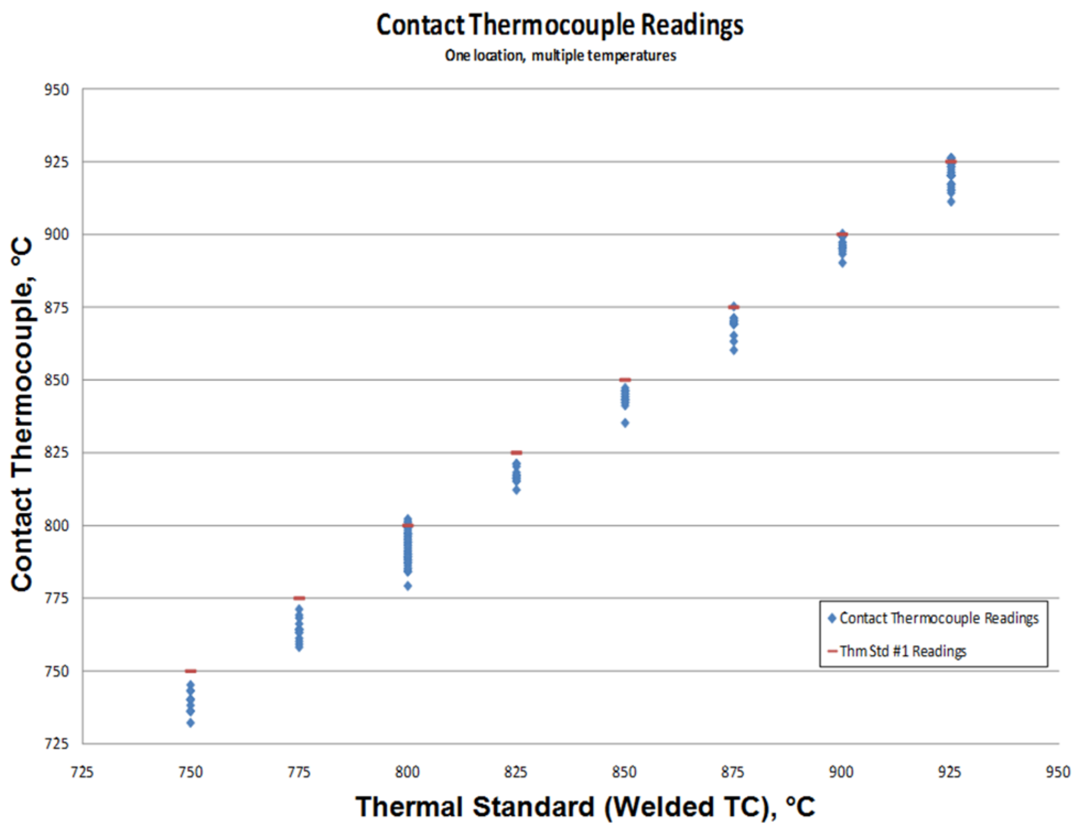

Figure 7.—Readings at varying temperatures: A single location set at various temperatures was used for these temperature measurements; measurement error was not dependent on temperature value.

contact procedure, the measurement data showed that contact thermocouple readings provided acceptable temperature measurement for the creep testing application, when an offset to the reading was made to adjust the mean value.

Finally, because the temperature of the test article was designed to vary with axial position, an investigation was performed to assure that the accuracy of the contact readings was not dependent on its value within a temperature range. To accomplish this, the test article temperature at one selected welded thermocouple was held constant at several different distinct temperature levels. Multiple contact readings were taken adjacent to this welded thermocouple at each temperature level. These were then compared to the controlled welded thermocouple temperature (Fig. 7). From these results, it was determined that the accuracy of the thermocouple readings was not related to the temperature measured, when the mean offset adjustment was made.

From this study, a technique for temperature measurement with contact thermocouples was developed. In addition, data to perform a valid comparison of the performance of contact thermocouples and welded thermocouples was collected. These are further described in the next section.

4.0 Methodology and Evaluation of Results

To generate accurate temperature measurements, the following describes the developed methods for taking contact thermocouple readings and evaluating the results. The most important factor for making accurate contact readings was properly contacting the thermocouple to the test article (Fig. 8). Initially the thermocouple bead alone made contact with the test article. Then the thermocouple was pressed more firmly, so that the wire on either side of the bead also contacted the test article. This likely minimized heat loss at the bead and created the highest temperature reading. If a contact was made such that the bead slid

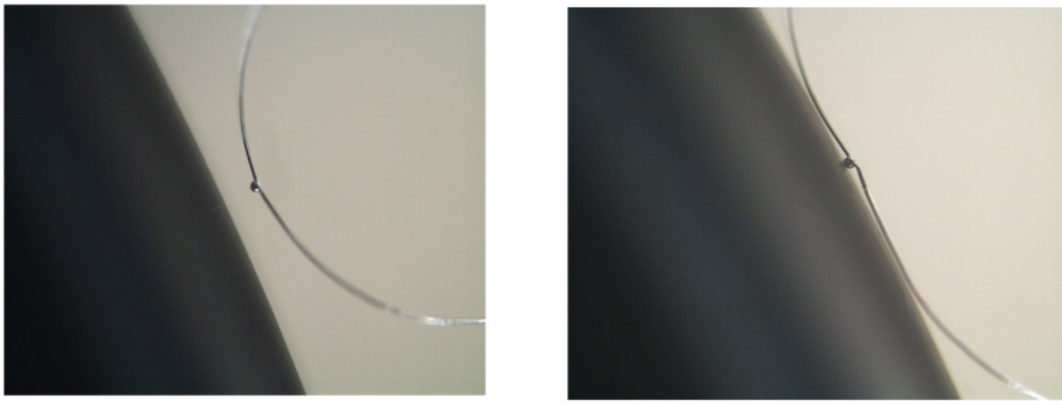

Figure 8.—Desired contacting method: The most desirable contact was determined to occur when the thermocouple bead and wires on both sides were touching the test article.

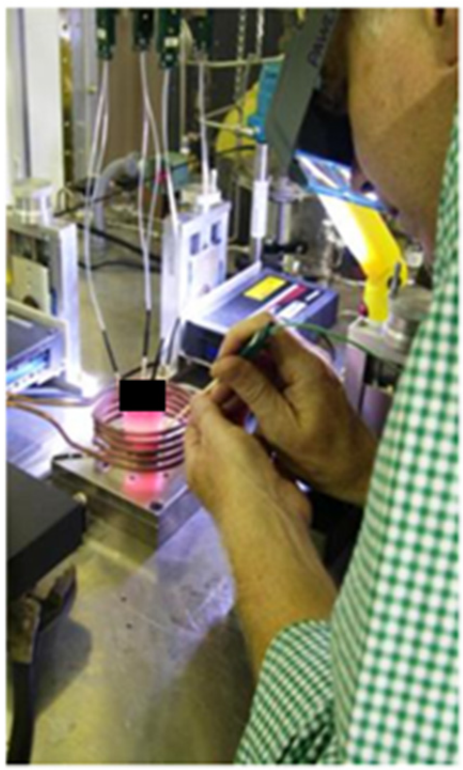

Figure 9.—Contact method: Lasers were used to illuminate measurement location.

or rolled along the test article, the reading was not recorded, and instead the measurement was performed again. To ease the task it was often necessary or helpful for the technician to wear magnifying eyewear and use high intensity local lighting (Fig. 9). This allowed a better view of the thermocouple wire and bead while performing the contact procedure. For accurate axial placement of the contacts, planar lasers on vertically translating stages were used; these marked the target level with laser light. Before each contact, it was necessary to re-shape the thermocouple wire loop. A properly shaped loop situates the bead at the apex of a well-rounded loop of wire. To re-shape the loop, a specially designed tool was used to avoid breaking the fragile thermocouple wire (Fig. 10). The thermocouple loop forming tool was made from PTFE rod that was tapered and smoothed on the forming end. The material and surface finish of the tool were selected to offer the least amount of friction, and therefore damage, to the delicate thermocouple wire.

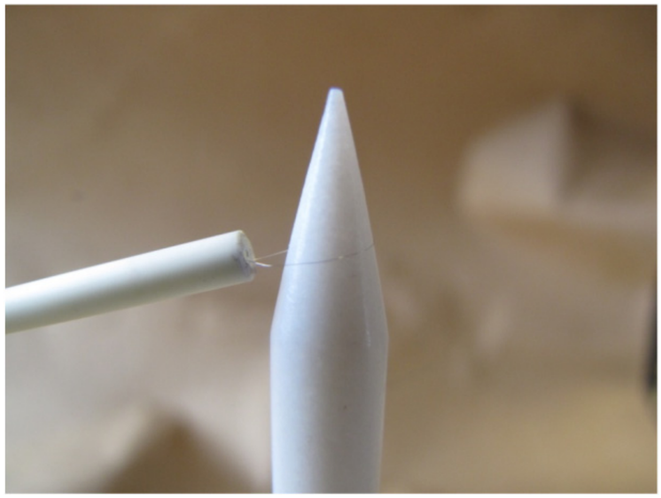

Figure 10.—Thermocouple loop preparation: Use of this tool allowed proper shaping of the thermocouple loop.

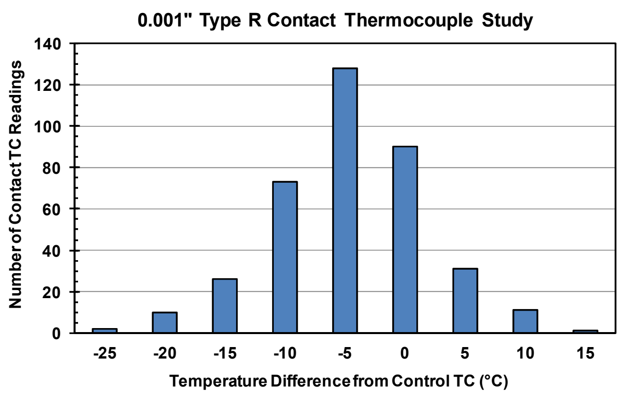

Figure 11.—Contact reading offset: Type-R contact measurements on average were 6.7 °C (12 °F) lower than the welded type-K thermocouple readings.

To enable accurate temperature measurements, it was necessary to take repeated contact readings at a given location and consider the resulting values as normally distributed. Statistical analysis determined that a sample of five individual contact readings at a location produced the same average as an extremely large sample size at that location with 95 percent confidence; thus, only a small number of repeated contact readings were required. Based on an analysis of the contact readings in the relevant temperature range of 750 to 925 °C, the contact readings' average was 6.7 °C lower than the welded thermocouple control values, with no significant dependence on temperature value (Fig. 11). Therefore, to calculate an accurate temperature measurement, 6.7 °C was added to the average of the five readings at any one location.

It proved difficult to maintain precise thermocouple contact, and therefore, it was helpful to employ two technicians—one to observe and record readings, and one to perform the thermocouple contact. The observing technician noted only the peak value displayed by the output device, because as previously described, the thermocouple wire and bead dissipated heat, reducing local temperature of the test article slightly. Using the highest displayed temperature produced a value closest to the welded thermocouple value. Another study was performed to investigate if there were significant differences in temperature readings when different thermocouple conditioning devices were used, or when peak readings were recorded automatically by the device, rather than manually by the technician. Two different devices were analyzed: a Fluke 714 meter and a Fluke 54II meter. The 54II included a peak reading capture function. First, several contacts were performed and technician-observed peaks were recorded with the Fluke 714 meter at a laser-determined location on the test article. Next, the Fluke 54II meter was used in the same manner to record technician-observed peaks, with the device's peak-capture display obscured. Finally, contacts were performed utilizing the peak-capture feature of the 54II meter. Results showed no significant difference between the devices or methods used (Fig. 12).

In summary, the contact thermocouple method required five temperature readings per location. To the average of these five readings, 6.7 °C (12 °F) was added. The result was an accurate temperature measurement for that location. This data was then used for creep deformation predictions, test records, and test article temperature profile maintenance.

Note that for continuous real time monitoring and feed-back temperature control, welded thermocouples were positioned at four innocuous, non-stressed locations for the ASC heater head test articles (Fig. 13). The first test article to fully utilize this test method was designated "C08" (Ref. 8). That testing proved that the contact thermocouple method was both applicable and accurate. Only four welded thermocouples were used to monitor temperatures and control induction heating, while the periodic contact thermocouple measurements ensured that the required test temperature axial profiles were maintained.

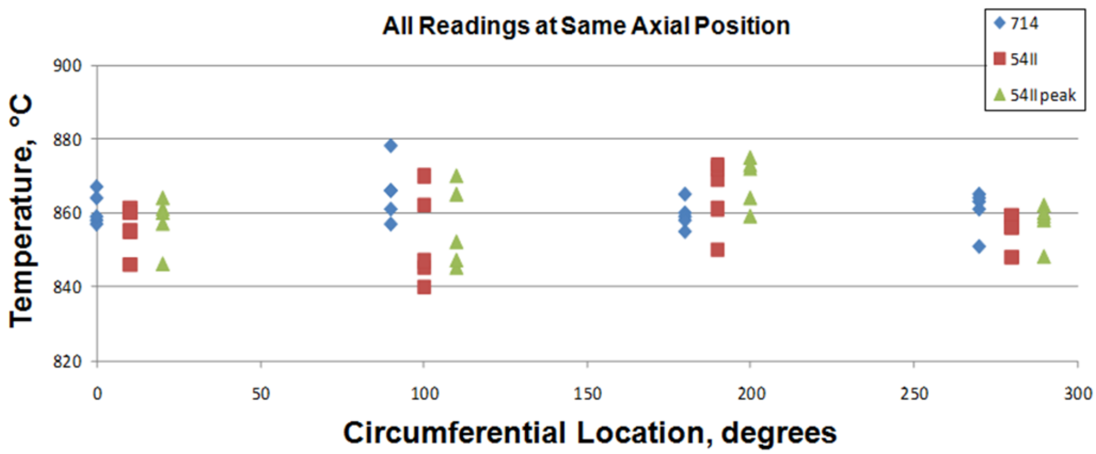

Figure 12.—Temperature measurements for different conditioning devices: No significant difference existed beween the two devices, nor between technician-read and intrument-captured signal peaks.

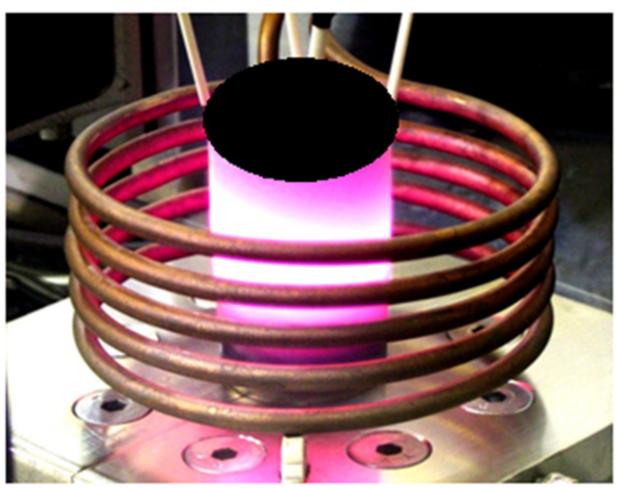

Figure 13.—C08 Test Article Setup: C08 was the first heater head test article using the contact thermocouple temperature measurement method; welded thermocouples in a non-stressed area were used for furnace control.

5.0 Conclusion

A highly accurate temperature measurement method using small diameter contact thermocouples was developed by the Mechanics and Life Prediction Branch of the Structures and Materials Division at NASA GRC. The approach resolved difficulties in temperature measurement of ASC heater head creep test articles arising from the use of traditional welded thermocouples: weld points initiated cracks in the nickel-based superalloy heater heads, and welded thermocouple wires and insulation interfered with test-specific optical measurements made using laser micrometers. For each temperature measurement site, the technique required five precise contact readings using a 0.025 mm (0.001 in.) diameter type-R beaded thermocouple, and the resulting calculated temperature was determined to be as accurate as the reading from a welded type-K thermocouple. The procedure was successfully implemented in subsequent structural benchmark creep testing of the ASC test articles. Further measurement testing and analyses are suggested to expand the use of this method to other laboratory settings and to other test specimens. The method has a wide range of potential applications in laboratory and field measurement of materials at high temperatures.

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