Transient Surface Temperature
Measurements Using Nanmac Eroding Thermocouples

Abstract

In this study, the eroding thermocouple is tested for accuracy and precision in making transient temperature measurements. The eroding thermocouple is a product of Nanmac Corporation.

The experiments involve transient surface temperature measurements of two identical specimens. Twelve eroding thermocouples with different design parameters are used. More than sixty experiments are performed and the measurements produced by the eroding thermocouples are in good agreement with the expected values.

The functional relationship between the measured surface temperatures of the specimens and several design parameters of eroding thermocouples are investigated using statistical F-test method. Comparisons between the response of the eroding thermocouples are made and important design parameters are determined.

Some numerical solutions of eroding thermocouple models are obtained using the finite difference technique. From these solutions, error analyses regarding the design characteristics of eroding thermocouples are made.

1.3 Literature Review

There have been numerous studies on the subject of thermocouple errors but, since the eroding thermocouples are fairly new, theoretical and experimental studies regarding the errors associated with them are not available. However, the same kinds of thermal considerations as for other types of thermocouple installation methods apply to the eroding thermocouples.

One common method of transient surface temperature measurement is obtained by using an intrinsic thermocouple. An intrinsic thermocouple is composed of one or two wires attached to the surface of an electrically conductive material (called the substrate). The substrate forms part of the thermocouple circuit [5.) Heat is transferred from the substrate to the wire(s) due to temperature increase of the substrate. The heat transfer between the substrate and the intrinsic thermocouple can alter the local temperature distributions of the interface and in so doing introduces errors in temperature of heat flux measurements. Burnett [2], Henning and Parker [3], Shewan [4], Keltner [5], Keltner and Beck [6], Litkouhi [7], and several others have investigated this problem experimentally and/or theoretically.

Keltner [5] considered the classical node of an ideal intrinsic thermocouple (see Figure 1.1a) and developed a method for its response to a step change in substrate temperature. His studies using the finite difference technique and various analytical methods indicate that “at early times, there are very large temperature gradients near” the corners of the interface between the intrinsic thermocouple and the substrate. Litkouhi [7] further considered this case, which is important at early times. His results, which are in good agreement with Shewan [4] and Keltner [5], indicate that for a particular case of chromel substrate and an alumel wire the difference between the center line and the corner of the interface at early times may be in excess of ten percent of the total step temperature rise of the substrate. Keltner and Beck [6] have shown that “the difference between the undisturbed temperature and the thermocouple temperature” is maximum at zero time and decreases to zero at large times. The magnitude of the zero time error and the dimensionless time of the significant error are both dependent on the thermophysical properties of the wire and the substrate.

Transient and steady-state temperature disturbances may result when beaded thermocouples are mounted on the surface of the substrate (refer to Figure 1.1 Ib). The difference between the beaded thermocouples and intrinsic thermocouples is that the effective junction is displaced from the surface by the thickness of the bead [6].

The errors are the result of the thermal inertia of the bead and imperfect contact between the bead and the substrate [6, 8-10].

The effect of thermal inertia of the bead is a delay in the response of the thermocouple to the input heat flux at zero time and, in [6], "an increase in the error for all times but very late times." The effect of imperfect contact between the bead and the substrate is a slowing of the response at early times and a shift in steady-state temperature measurements [6, 10].

A direct transient surface temperature measurement is often difficult. Such as, when the surface is exposed to a very high heat flux or when the surface is in contact with a moving object. In these cases, measurements are performed by installing the thermocouples inside a cavity which is drilled in the substrate (see Figure 1.1c) and temperature or heat flux histories of the surface are found by indirect methods. Therefore, it is important that the temperature measurements by an interior sensor by accurate. The errors are results of the very existence of the thermocouple and the substrate.

Beck [11, 12] and Chen [13-15] have found that the errors are inversely proportional to the ratios of the thermal conductivities and the heat capacities of the substrate to the thermocouple wire. If these ratios are less than one, then the errors are positive, which indicates overheating; errors are negative when these ratios are larger than one and the errors are maximum when the thermocouple is installed normal to the heated surface [11]. The presence of the cavity in the substrate would result in a hot spot at the heated surface of the substrate [12] and references [13] through [15] studied extensively the optimum cavity size and depth of the thermocouple installation from the heated surface to minimize these errors.

Nanmac eroding thermocouples are designed to minimize the number of errors resulting from the application of thermocouples in temperature measurements, such as:

I. Thermal disturbances due to thermophysical properties of the thermocouple assembly.
2. Errors due to thermal inertia of the junction, and
3. Errors resulting from the unknown location of the junction.

The thermocouple assembly of an eroding thermocouple (thermowell) can be made from the same material as the substrate. This feature of eroding thermocouple eliminates the first error; however, temperature disturbances may occur as the result of the imperfect contact between the pins and the cone of the thermowell assembly and the taper of the pins (see Figure 2.4). The analyses regarding these errors are given in Chapter Four.

The junction of an eroding thermocouple is effectively massless (see Section 2-3) and the junction is made flush with the heated surface of the substrate. When an eroding thermocouple is used to measure an interior location of a substrate, the cavity in which the thermowell is placed is eliminated by the use of the thermowell assembly. Also, in this case the desired location of the thermocouple junction can be achieved within an accuracy of $\pm$ 0.001 of an inch or better [1]. This is much more accurate than placing a thermocouple within a cavity such as those described in references [11] through [15]

Conclusion

The experimental results and analyses do not show any large systematic errors produced by the thermowell components of the Nanmac eroding thermocouples.