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ABSTRACT
Ceramic matrix composites (CMC) are being developed for use as enabling materials for advanced aeropropulsion engine and High Speed Civil Transport applications. The characterization and testing of these advanced materials in hostile, high-temperature environments require accurate measurement of the material temperatures. Commonly used wire thermocouples (TC) can not be attached to this ceramic based material via conventional spot-welding techniques. Attachment of wire TCs with commercially available ceramic cements fail to provide sufficient adhesion at high temperatures. While advanced thin film TC technology provides minimally intrusive surface temperature measurement and has good adhesion on the CMC, its fabrication requires sophisticated and expensive facilities and is very time consuming. In addition, the durability of lead wire attachments to both thin film TCs and the substrate materials requires further improvement. This paper presents a newly developed attachment technique for installation of free filament wire TCs with a unique convoluted design on ceramic based materials such as CMCs. Three CMCs (SiC/SiC CMC and alumina/alumina CMC) instrumented with type K, R or S wire TCs were tested in a Mach 0.3 burner rig. The CMC temperatures measured from these wire TCs were compared to that from the facility pyrometer and thin film TCs. There was no sign of TC delamination even after several hours exposure to 1200°C. The test results proved that this new technique can successfully attach wire TCs on CMCs and provide temperature data in hostile environments. The sensor fabrication process is less expensive and requires very little time compared to that of the thin film TCs. The same installation technique/process can also be applied to attach lead wires for thin film sensor systems.

INTRODUCTION
In order to meet the urgent needs in aeronautic and aerospace research where ceramic based materials are used for high temperature applications, sensors that can adhere to these ceramic based test articles and provide accurate temperature measurements in hostile environments are required. These sensors are often needed to evaluate and test advanced materials and components and to provide experimental verification of computational models. Wire thermocouples (TCs) have been widely used for temperature measurements on metallic components to very high temperatures. Installation of the wire TCs can be easily done by spot welding directly onto metallic test articles. The attachment of wire TCs on non-metallic components such as ceramics or ceramic matrix composites (CMC), however, is very difficult and has been a challenge for many researchers. Thin film TC (TFTC) technology has been advanced through several NASA contracts and grants and extended to ceramic and CMCs applications[1-5]. TFTCs can be tailored to have very good adhesion to CMCs. In addition, TFTCs add negligible mass to the surface and create minimal disturbance of the gas flow over the surface, therefore providing an advantage of minimally intrusive surface temperature measurement. Fabrication of the thin film sensors, however, often requires expensive and sophisticated clean room facilities, and the process is time-consuming. Also, poor adhesion of the lead wires, which bring the signal from thin film sensors out to the measurement devices, to both the test articles and the thin films often prevents successful transmission of the signals.

This paper presents a newly developed installation technique for attaching wire TCs with a unique design for high temperature measurements on ceramic based materials. The preparation and installation techniques using various combination of ceramic cements and flame-spraying coatings will be presented. The characteristics of these TCs of various types and various sizes tested in a Mach 0.3 burner rig to 1200°C will be discussed. A comparison to pyrometers and type R thin film TCs will also be presented This new gaging technique is simple and takes little time. Unlike thin film TCs, it requires no pre-oxidation, no post annealing, and no surface treatment of the CMC substrate materials. It can therefore save time and cost for sensor fabrication and installation. The same installation technique can also be applied to attach lead wires for thin film sensor systems when minimally intrusive measurements are required.

SENSOR DESIGN AND INSTALLATION TECHNIQUES

The thermocouples tested were made of wires of various sizes: 75, 125 and 250 μm (3, 5, and 10 mil) in diameter, and various types: type K (Nickel-Chromium vs. Nickel-Aluminum), type R (Platinum-13% Rhodium vs. Platinum) and type S (Platinum-10% Rhodium vs. Platinum). The TC wires have a unique convoluted design as shown in Figure 1a to provide thermal stress relief. Large differences in thermal expansion between metal thermocouples and low expansion material, such as CMC, normally generate large stresses in the wire and cause straight wires to detach. Convoluted wires, bonded with strips of coating, allow bending in the unbonded portion to relieve expansion stresses. Three CMC specimens of two types: SiC reinforced SiC matrix composite for combustion applications, and aluminum oxide (alumina) reinforced alumina matrix composite for nozzle applications were instrumented and tested. The TCs were installed on these CMCs with combinations of ceramic cements (SC* and WC16*) and flame-spray rokide coating as listed in Table I. SC is a SiC based cement, WC16 is an alumina based cement, and rokide is an alumina based rod used for flame-spraying. A thin layer of basecoat of SC cement or flame sprayed coating of about 25 - 75 μm thick was first applied to the surface where the TC was to be installed, followed by a layer of electrically insulating precoat of WC16 cement or rokide flame sprayed coating of about 25 - 75 μm thick. The TC wires were taped in place using 1 mm wide strips of Teflon fiberglass tape with 1 to 2 mm wide spacing between tape bars. The exposed area between tape bars was then bonded by rokide flame spraying or cementing with125 to 200 μm thick WC16 cement. The tapes were removed to complete the installation. The exposed wire was left uncovered so the unbonded wire could be free to bend, Figure 1b.

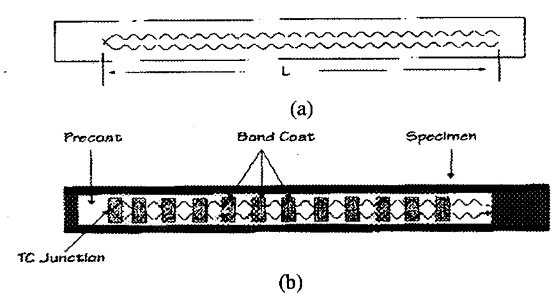


Fig. 1 (a). Construction of free filament convoluted thermocouples, and (b) free filament thermocouples installed.

Table I lists the material, size and shape of the three CMC specimens tested, and the size, type and installation technique/materials of the TCs on the specimens. Note that specimen #1 is a curved piece, and on specimen #3, there were two thin film TCs fabricated beside the wire TCs for comparison. Fabrication of the thin film sensors was completed using sputter-deposition techniques in a clean room to minimize possible contamination. The fabrication process of thin film sensor systems on a particular substrate material needs to be tailored to ensure good adhesion and no chemical interaction between the sensor and the substrate material[6]. In the case of electrically insulating materials such as alumina/alumina CMC, the sensor can be fabricated directly onto its surface. The details of the fabrication

* Trade name, available from Hitec Products Inc., Ayer MA.

* Trade name, also available from Hitec Products Inc.

process of thin film sensors can be found in reference 6. The lead wires were attached to the thin films via a parallel gap welding technique[7] and then secured on the specimen with WC16 cement.

Table I. Specimens Description

SPECIMEN	#1	#2	#3
Material	SiC/SiC CMC	SiC/SiC CMC	Alumina/ alumina CMC
Size	10 x 10 x 0.1 cm curved plate	6 x 6 x 0.1 cm flat plate	5 x 12 x 0.1 cm flat plate
TC type & #	4 type S	2 type K and 2 type R	5 type R
TC size and installation technique & materials	#1: 125 μm, rokide flame-spraying. #2: 125 μm, SC cement basecoat, rokide precoat and bondcoat. #3: 75 μm, SC cement basecoat, WC16 precoat and bondcoat. #4: 75 μm , NiCrAl basecoat, rokide precoat and bondcoat.	All TCs were 75 μm wires with SC cement basecoat: #1, type K, WC16 cement. #2, type K, rokide flame- spraying. #3, type R, WC16 cement #4, type R, rokide flame-spraying	All wire TCs were installed with rokide flame-spraying: #1, thin film, 5 μm #2, wire 75 μm #3, wire, 125 μm #4, wire, 250 μm #5, thin film, 5 μm
Purpose of the test	Determine the best installation technique/material for type S	Determine the best installation technique for type R and K. Compare wire TCs with pyrometer.	Determine the size effect on adhesion. Compare wire TCs with thin film TCs.

EXPERIMENTAL CONDITIONS

The gaged CMC specimens were tested in a Mach 0.3 burner rig whose configuration is shown in Figure 2. The combustor burns jet fuel and air in controlled ratios. It's combustion produces flame with a Mach 0.3 velocity from the exhaust nozzle and impinges on the test specimen. Figure 3 shows the burner rig facility during testing of CMC specimen #2. Note that the facility is equipped with a two-color pyrometer for an independent measurement of temperature. The test conditions and procedures for three CMC specimens are listed in Table II. Specimens #1 and 3 were tested in an air furnace to 1100°C for 20 & 10 hours, respectively, before the burner rig test. All the TC installations survived the air furnace high temperature exposure with no sign of delamination or interactions.

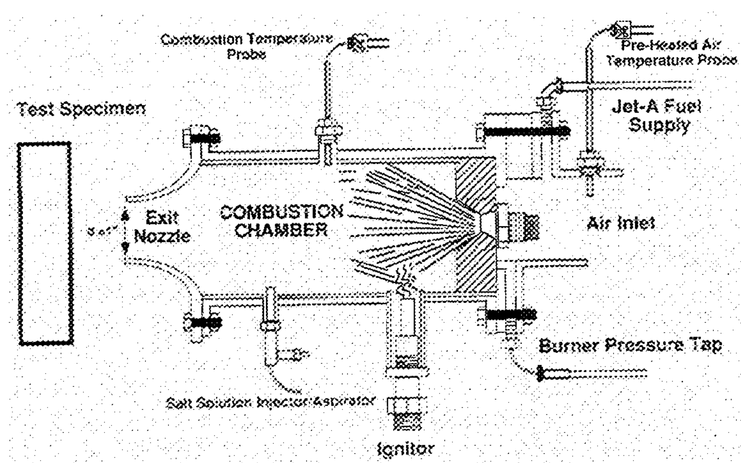


Fig. 2. Configuration of a Mach 0.3 burner rig at the NASA Lewis Research Center

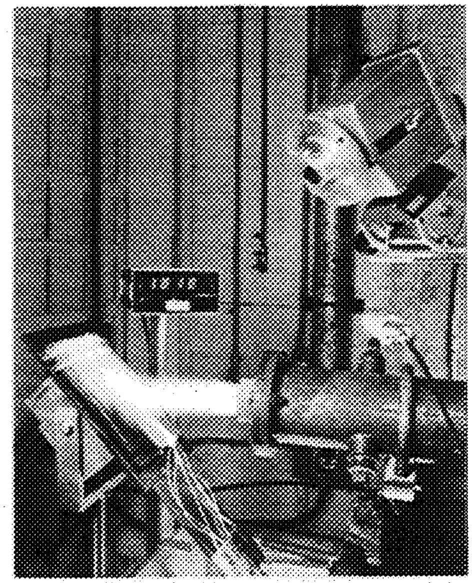


Fig. 3. Mach 0.3 burner rig facility during testing of CMC specimen

Table II: Test Sequences for three CMC specimens

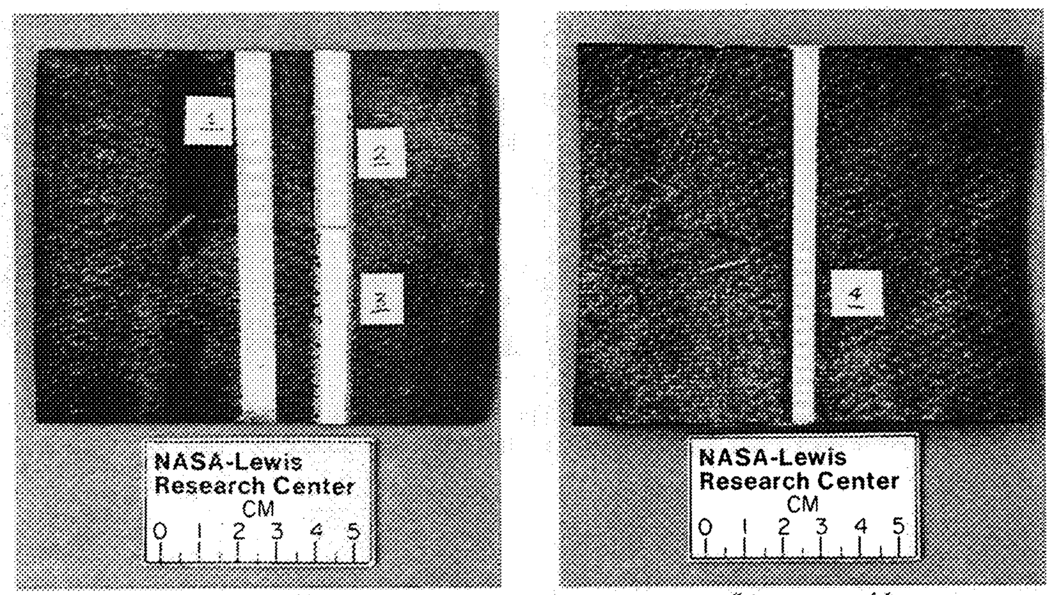
SPECIMEN	1	2	3
Air furnace	1100°C - 20 hours	N/A	1100°C - 10 hours
Burner rig	1200 °C - 1 hour	800°C - 1 hour 800°C - 2 hour 1000°C - 2 hour thermal cycle to 1000 °C thermal cycle to 1200 °C 1200 °C - 2 hour thermal cycle to 1200 °C	1200 °C - 2.5 hours

RESULTS AND DISCUSSION

The test results for three CMC specimens are discussed separately as follows:

Specimen #1:

This curved SiC/SiC CMC specimen was instrumented with four type S convoluted TCs; three on the convex side and one on the concave side as shown in figure 4. The purpose of the test was to determine the adhesion of the installation techniques using various cements and flame-spraying coatings (Table I). The specimen was first heat treated in an air furnace for 20 hours at 1100 °C (2040°F) and then tested in the burner rig for 1 hour at 1175 °C (2175 °F). The resistance of the TCs was taken before and after the testing to ensure there were no open circuits. No temperature reading from the TCs were taken during the testing; the test temperatures were determined by the furnace controller thermocouple or the burner rig facility two-color pyrometer. All four TCs , two 75 μm and two 125 μm diameter wires, survived the tests with no sign of delamination, open circuits or interactions. SiC based cement (SC) appeared to provide very good adhesion between the CMC and the alumina based coating.



(a) convex side (b) concave side

Fig. 4. Curved SiC/SiC CMC instrumented with four type S convoluted TCs

Specimen #2:

The second specimen was instrumented with two type K and two type R TCs with installation techniques/materials as listed in table I. Temperature data were taken from these TCs during the burner rig testing and compared to that of the two-color pyrometer as shown in figure 5. Note that CMC temperature data obtained from all four wire TCs were very close to that of the facility pyrometers at temperatures below 1200 °C (2215 °F).

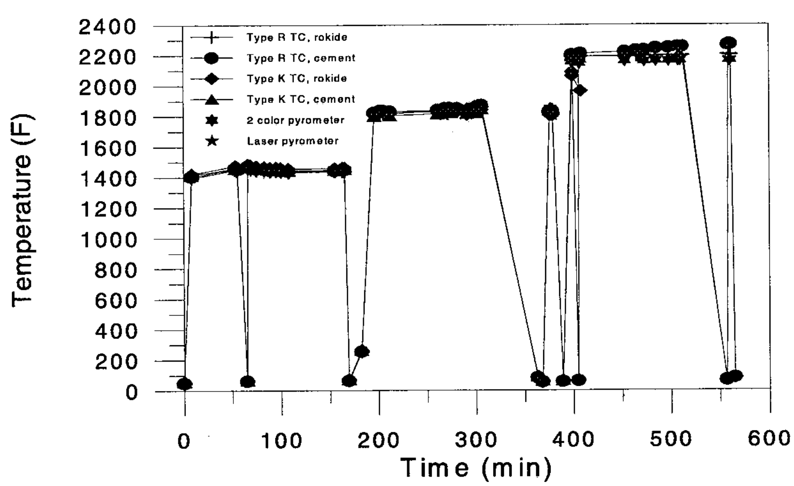


Fig. 5. Comparison between two type R and two type K TCs on a SiC/SiC CMC with pyrometers.

No data were obtained from type K TCs when the CMC specimen temperature reached 1200 °C (2215°F). This was due to the broken wire as revealed during the post test examination as shown in figure 6. Both type R TCs were still intact after the testing and the rokide installation appeared to have better stability at 1200 °C. The CMC temperature data measured by type R TCs matched that of the pyrometer to within 2% up to 1200 °C.

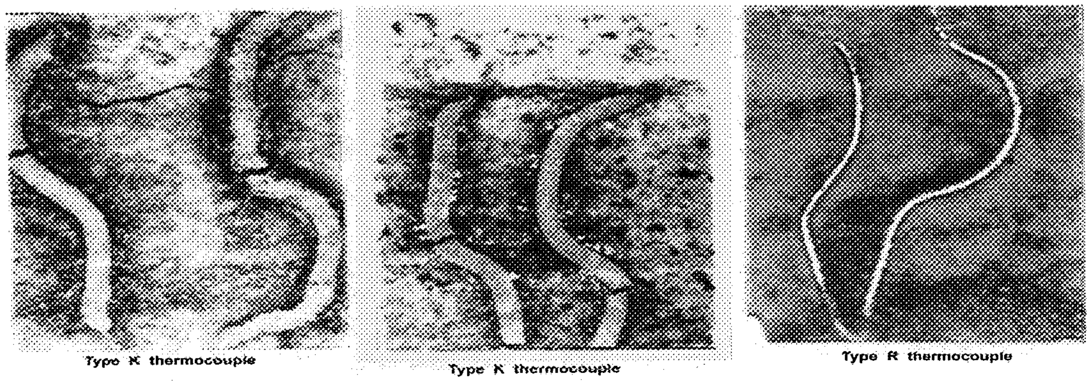


Figure 6. TCs on SiC/SiC CMC specimen #2 after burner rig testing to 1200 °C. Note that type K broke after the rig test while type R was still intact.

Specimen #3

This specimen was made of alumina fiber reinforced alumina matrix composite. On this specimen, there were three wire TCs together with two thin film TCs which were fabricated beside the wire TCs as shown in Figure 7. The sizes of the wire TCs were 75, 125 and 250 μm in diameter, and the thickness of the TFTCs was approximately 10 μm. The TFTCs were fabricated after the installation of the wire TC, and then annealed in an air furnace at 1100°C for 10 hours. It took approximately 8 days to fabricate the two TFTCs compared to two days needed for the three wire TCs. This specimen was tested in the burner rig to 1200°C for 2.5 hours. The temperature data were taken from all TCs during the testing and compared to that of a laser pyrometer. The two color facility pyrometer did not work with this transparent alumina/alumina CMC specimen. The laser pyrometer, which has a signal wavelength of 0.865μm, only worked to 1100 °C. Data obtained from all three wire TCs of various sizes were very close as shown in Figure 8. One of the thin film TCs also followed the wire TCs very closely, whereas the other one was slightly lower. This, however, may be due to the location of the TFTC which was off the center of the hot zone. No delamination of the three wire TCs or the TFTCs was observed after the testing.

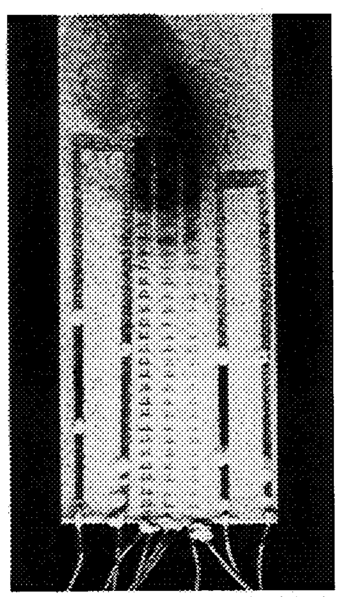


Fig. 7. An alumina/alumina CMC instrumented with three wire TCs (center) and two thin film TCs (sides) after burner rig testing

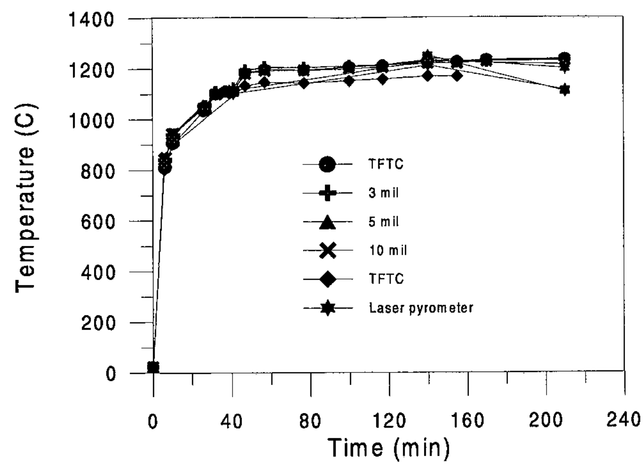


Fig. 8. Temperature measurements from three wire TCs, two thin film TCs and a laser pyrometer on an alumina/alumina CMC tested in a burner rig

SUMMARY AND FUTURE WORK

Temperature measurement of advanced materials such as CMCs in a hostile environment has been a difficult task due to the poor adhesion of the measurement systems. A new installation technique utilizing convoluted wire thermocouples (TCs) was developed and proven to have very good adhesion on CMCs even in a burner rig environment. Because of the unique convoluted design, TCs of various types and various sizes remain on the CMC specimens, flat or curved, even after testing in a Mach 0.3 burner rig to 1200°C for several thermal cycles and several hours at high temperatures. This new gaging technique, therefore, provides a mean for temperature measurement when minimally intrusive measurement is not required. Its fabrication process is much cheaper and takes less time compared to less intrusive thin film TC. Unlike thin film TCs, this new technique requires no pre-oxidation, no post annealing, and no surface treatment of the CMC substrate materials. It can therefore save time and cost for sensor fabrication and installation. The same installation technique can be applied to attach lead wires for the thin film sensors when minimally intrusive measurements are required. This technique should work for any low thermal expansion materials such as ceramics (alumina, sapphire, zirconia, silicon nitride) and other composite materials such as carbon /carbon composites.

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