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METHODS AND PROCEDURES FOR EVALUATING, FORMING, AND INSTALLING SMALL-DIAMETER SHEATHED THERMOCOUPLE WIRE AND SHEATHED THERMOCOUPLES

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16. Abstract

A discussion of the methods and procedures required for evaluating, forming, and installing reliable and durable small-diameter sheathed thermocouples is presented. The sheath diameters of interest are 0.025 and 0.050 cm. Topics discussed are limitations and problem areas, test characteristics and test procedures required, and some current installation methods, including laser-welding and flame-spraying. Results indicate that these methods and procedures can successfully reduce the failure rate of sheathed thermocouples from approximately 50 percent after 5 hours and 4 thermal cycles of testing to less than 20 percent after 40 hours and 12 thermal cycles of testing.

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METHODS AND PROCEDURES FOR EVALUATING, FORMING, AND INSTALLING SMALL-DIAMETER SHEATHED THERMOCOUPLE WIRE AND SHEATHED THERMOCOUPLES

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SUMMARY

Evaluation methods and procedures which are required to form a reliable and durable small-diameter sheathed thermocouple are discussed. The thermocouple sheath diameters of interest are 0.025 and 0.050 centimeter. These evaluation methods and procedures were developed for air-cooled turbine vanes and blades; however, these methods and procedures are generally applicable for small-sheath-diameter thermocouples. The general topics discussed are the limitations and problem areas associated with small sheath diameters, the significant test characteristics and test procedures required, and some current methods of installing the sheathed thermocouple, including laser-welding and flame-spraying. Results indicate that a reliable and durable product can be obtained by application of these methods and procedures. Thermocouple failure rates, during experimental testing, have been reduced from 50 percent after 5 hours and 4 thermal cycles to less than 20 percent after 40 hours and 12 thermal cycles.

INTRODUCTION

Methods were developed for the evaluation of commercially available small-diameter sheathed thermocouple wire and for the evaluation of the fabricated thermocouples and their installation into thin-walled air-cooled turbine blades and vanes in a manner that resulted in improved life under test conditions.

Sheathed thermocouple wire normally purchased from commercial sources was not of consistently reproducible, high quality to tolerate the high temperature levels and thermal cycling required for turbine heat-transfer testing. Before the evaluation methods presented in this report were established, thermocouple failure rates were as high as 50 percent after exposure to moderate gas temperature levels (up to 1100 K) and 3 or 4 thermal cycles. These failures were manifested as secondary hot junctions, grounding of the thermoelement to the sheath, and open circuits (such as broken thermoelements). The sheathed thermocouple wire sizes (outside diameter of the sheath) discussed in this report are 0.025 and 0.050 centimeter (10 and 20 mils). The strength of the assembly and the spacing of the insulation become quite critical for these small sizes.

A check list for the evaluation of thermocouple parameters such as spurious electromotive force (emf), insulation resistance between components, and the resistance of the thermoelement were developed from information contained in references 1 to 3. This report combines the information of these references with the procedures and techniques developed by trial and error and discusses their application to producing a reliable and durable thermocouple. Reference 1 was used to establish the definition of terms used in this report. Table I gives three of these definitions.

SHEATHED-THERMOCOUPLE PROBLEMS

The materials specifically considered herein were Chromel-Alumel thermoelements, crushed magnesium oxide insulation, and Inconel 600 stainless steel tubing as the sheath. Some of the problem areas that may be encountered are noted in this section; however, it should be understood that this discussion does not cover all possible problem areas. Also, other combinations of materials may present other problems. The sheathed thermocouple wire considered is usually delivered in a fully annealed state, but unless care is exercised in handling, the thermocouple wire can quickly become work-hardened and a calibration shift may result. If the ends of the sheathed thermocouple wire are exposed to the atmosphere, the hygroscopic property of the crushed magnesium oxide insulation can quickly lead to entrapment of moisture, and, when the ends of the sheath are subsequently sealed, the sheath will burst on exposure to high temperature. The life of the sheathed material is limited because of grain growth in the sheath wall with the resultant failure of the sheath material and exposure of the insulation and thermoelements to the test environment.

Reference 1 points out that several combinations of sheath, thermoelement, and insulator materials are available; however, some thought should be given to the intended application, the compatibility of the materials composing the assembly, and the compatibility of the materials and the test environment. The thermal expansion of the thermoelements and the sheath must be considered for high-temperature application, since differential growth rates could cause the thermocouple element to break while in use. Magnesium oxide insulation is generally used for small-diameter sheathed thermocouple wire. Other types of insulators appear to cut or nick the thermoelements and/or migrate into the thermoelements. These phenomena can have detrimental effects on the function of the thermocouple.

The result of entrapped water or possible voids in the insulation due to the hygroscopic property is graphically shown in figure 1. Two samples of a sheath are shown which ruptured when a length of thermocouple wire was heated to 1100 K in a furnace. The ends of the sheathed thermocouple wire should be sealed against moisture at all times to prevent this type of failure. Also associated with this problem is the integrity of the sheath material. Cracks, holes, or porous areas may also allow the entrapment of water in the magnesium oxide.

Three other types of failures which commonly occurred were secondary junctions, open circuits, and grounds at points along the sheath. The secondary junctions occurred when voids in the insulation or the dielectric breakdown of the insulation allowed the thermoelements to short circuit. Because of the small sheath diameters, the spacing of the thermoelements is quite critical, and deviation from the nominal value (given in this section) can lead to faulty operation of the thermocouple. With a dielectric breakdown of the insulation, a circuit can also be formed with properly separated thermoelements.

The open circuits occurred when the thermoelements had been work-hardened or otherwise damaged. Damage to the thermoelements can also occur at the time the hot junction is formed for a grounded type junction. The welding process can create a tensile stress on the thermoelements and cause them to elongate and work-harden and thereby lose strength.

The voids in the magnesium oxide, as mentioned previously, may also allow the thermocouple elements to become grounded to the sheath and create another junction, which will result in faulty operation of the thermocouple.

Formulas for the determination of the ideal spacing of sheathed thermocouple components are presented in reference 1. These formulas are based on the outside diameter D of the sheath and give the following values:

Nominal thermoelement diameter, d_n 0.19D
Nominal sheath wall thickness, t_n 0.16D
Nominal spacing, S_n 0.1D

TEST CHARACTERISTICS

Various test characteristics applicable to sheathed thermocouple wire are listed in table XXXI of reference 1. The general categories of these tests are (1) physical and metallurgical parameters, (2) isothermal electrical properties, and (3) thermoelectric properties. Four test characteristics were selected from these categories as significant parameters for indicating the quality of the commercially supplied sheathed thermocouple wire and the sheathed thermocouple formed from the supplied wire. These characteristics are as follows:

(1) Sheath integrity

(2) Insulation resistance

(3) Thermoelement homogeneity or spurious emf

(4) Junction integrity

Tests of these characteristics are described in ASTM standard E235-67, reference 3.

Sheath Integrity

The sheath integrity can be tested by a helium leak-check method. This method consists of placing a sample of sheathed thermocouple wire, with both ends sealed, in a pressure vessel and pressurizing with helium to approximately 50 atmospheres. The possible traces of helium which may have entered a defective sheath can be grossly checked by then placing the sample in an alcohol bath and examining the bath for bubbles. A more precise method of checking would consist of placing the sample in a vacuum chamber and checking for helium with a mass spectrometer. The mass spectrometer may also be used without the vacuum chamber to detect traces of helium that have entered the sheath through defects.

Insulation Resistance

The insulation resistance between the thermoelements and between the elements and the sheath can be measured with a megohm meter. An arbitrary minimum value of 100 megohms per 30 centimeters of wire length (at ambient temperature) for an applied voltage of 5.0 volts direct current on a 0.050-centimeter-diameter sheath (see ref. 1) is being used for thermocouples installed in turbine heat-transfer test facilities. Since the magnesium oxide is hygroscopic, as mentioned previously, the resistance will drop several orders of magnitude within a few minutes unless the exposed ends are sealed against moisture.

Spurious Electromotive Force

The homogeneity of the thermoelements as reflected by the measured spurious emf, is another critical test for developing a quality thermocouple. A spurious emf can be generated by applying a steep temperature gradient to a small section of either or both thermoelements of a thermocouple at points other than the hot junction. A typical circuit setup required to obtain a spurious emf is shown in figure 2. The emf produced is a function of the applied temperature level, the size of the temperature gradient, and the inhomogeneity of the thermoelements. For the test procedure discussed in this report, a temperature of about 900 K over a length of about 2.5 centimeters produced maximum levels of spurious emf.

A test for spurious emf is shown in progress in figure 3. A sheathed thermocouple is held above a natural gas flame which, in turn, is slowly traversed the length of the sheath. The traversing velocity of the flame along the sheath is the critical parameter in order to achieve the desired temperature and gradient and was established as 60 centimeters per minute for the 0.025-centimeter sheath and 30 centimeters per minute for the 0.050-centimeter sheath. The emf produced is then amplified and read out on the chart recorder shown. Values of emf greater than ±50 microvolts for the 0.050-centimeter-diameter sheath and ±100 microvolts for the 0.025-centimeter-diameter sheath (see ref. 1) were judged sufficient to reject the sample tested.

Junction Integrity

The integrity of the hot junction is also an important parameter associated with the thermocouple forming and installation. The welding process, by which the grounded hot junction is formed, may elongate (reduce thermoelement diameter) and work-harden the thermoelements. These elements are then easily broken by thermal stresses. As an indication of this potential failure, a mechanical junction is formed initially, and the resistance of the thermocouple element is precisely measured. The welded junction is then formed, and the resistance again precisely measured. If the second value of resistance exceeds the initial value and indicates a reduction in the cross-sectional area of the thermoelements, the thermocouple is rejected; a new junction is formed and the test is repeated.

TEST PROCEDURES

The spurious emf and insulation resistance can be quantitatively defined in purchase specifications. Thermocouple wire which meets the limits established in the section TEST CHARACTERISTICS will give more reliable service. These characteristics of the sheathed thermocouple wire are also checked when the wire is delivered. When a sheathed thermocouple is formed, and before installation, the characteristics are checked again and this time the four tests discussed previously are included.

Acceptance Tests

Before a spool of sheathed thermocouple wire is accepted, a spurious emf test is made on the full length of the wire. If the entire spool of wire does not meet the ±50- and ±100-microvolt limits for the 0.050- and 0.025-centimeter-diameter sheaths, respectively, the spool is rejected. Many times, however, only sections of thermocouple wire on the spool may not meet the specifications, and just these sections are rejected.

The insulation resistance is also checked at this time. The sheathed thermocouple wire is rejected if the resistance does not equal or better an ambient temperature value of 100 megohms per 30 centimeters of wire length.

Tests During Thermocouple Fabrication

A procedure was developed by Leonard A. Wilhelmi of the Lewis Research Center to ensure that a quality sheathed thermocouple would result from the forming process. This procedure is generally described as follows:

(1) After the desired lengths of sheathed wire are cut, the ends are sealed against moisture with a liquid plastic sealant.

(2) The sheath integrity is checked by either of the two methods described previously:

(a) Helium bubble check made in an alcohol bath

(b) Precise measurement of helium leak rate by a mass spectrometer

(3) The sheaths are heated to approximately 1100 K in a furnace either to remove entrapped water or to cause the sheath to rupture as shown in figure 1.

(4) The spurious emf is measured by the method discussed and recorded.

(5) Each sheath length is checked for short circuits between the thermoelements and between each thermoelement, and the sheath and the resistance values are recorded.

(6) The hot junction is formed, and the following tests are made:

(a) The junction integrity is checked by the method of resistance measurements discussed previously.

(b) The sheathed thermocouple element is checked for continuity, and a record is made of the resistance of the thermocouple element and of the resistance between each wire of the element and the sheath.

(c) The sheath integrity is checked again by either of the two methods discussed previously.

(d) The sheathed thermocouples are heat cycled in a furnace from ambient to 1100 K five times in approximately 5 hours, and the continuity check is again made.

INSTALLATION OF THERMOCOUPLES

The installation of the sheathed thermocouple is a critical factor in obtaining a reliable temperature reading. Many methods of installation of these sheathed thermocouples are possible. Three methods of installation are discussed in this report and are referred to as a commonly used current method and other currently available methods; the latter methods include sheathed and bare-wire thermocouple installation. The methods discussed are for application on turbine vane and blade airfoils.

Current Methods

A relatively simple method of installing sheathed thermocouples is shown by the sketch in figure 4. A square cross-sectional slot is cut in the airfoil surface to the point where the temperature is to be measured. The thermocouple is laid in the slot and the junction is peened into position by a contoured tool which has the effect of locating the temperature measuring junction approximately 0.008 centimeter from the bottom of the slot (the approximate thickness of a 0.050-cm-diam sheath). Locating the measuring junction in a turbine vane airfoil is of particular importance, since for some high-heat-flux conditions, a change of 0.008 centimeter in location can represent a difference in temperature of up to 20 K. Figure 5 is a photograph of a 0.050-centimeter-diameter thermocouple installed by this method. (Note the tapered shape at the end of the sheath.) The remainder of the sheath is held in place by spot-welding small wires to the vane airfoil only (see end view of fig. 4). This retains the sheath while allowing room for thermal expansion or contraction. The remaining void in the slot can be filled with a ceramic cement or by a ceramic or metallic filler flame-sprayed over the area. Also, an Inconel or stainless steel sheet can be spot-welded in place over the thermocouple. The final step consists of grinding the covering back to the original airfoil contour.

Other Methods Currently Available

Some methods of thermocouple installation which show promise make use of laser-welding and flame-spraying.

Laser welding. - A pulsed ruby laser has been used for forming thermocouple junctions, welding the thermocouple in place, and a variety of other welding problems which require precise control in a small area. The pulsed ruby laser has a maximum output of 10 joules at a 0.05-centimeter-diameter spot size. The pulse time can be varied from 1 to 5 milliseconds. An optical system enables the user to focus the laser beam to within 0.0008 centimeter of the desired location. Wire sizes as small as 0.0025-centimeter-diameter can be welded to form a thermocouple junction. Also, the thermocouple junction can be welded in place after the peening operation described previously. The welded length should be restricted to approximately 25 sheath diameters, so that the remaining sheath is free for thermal expansion or contraction.

Flame-spraying. - Another technique which could be used to reduce the overall size of the thermocouple assembly involves a flame-spraying procedure. A schematic representation of the technique is shown in figure 6. The procedure utilized is to flame-spray 0.005 centimeter of insulation on the bottom of a shallow slot. For purposes of discussion this slot is assumed to be 0.02 centimeter deep. Two 0.010-centimeter wires are then laid in the slot and the hot junction is laser-welded to the airfoil. More insulation is then sprayed over the area to fill in the slot. This filler is then ground back to the original airfoil contour.

IMPROVEMENT OF THERMOCOUPLE LIFE AS RESULT OF EVALUATION PROCEDURES

Two sets of two turbine vanes each have been instrumented and tested in a cascade using thermocouples formed by the techniques discussed. The first installation method discussed herein was utilized for both sets of vanes tested. The airfoil thicknesses of these two vanes were nominally about 0.15 and 0.25 centimeter. These vanes were tested at gas temperatures ranging from 811 to 1645 K. The airfoil temperatures for these gas temperatures varied up to a maximum value of about 1250 K. The thermocouple failure rate for the first set of vanes was between 10 and 15 percent after

40 hours and approximately 12 thermal cycles of testing. The failure rate for the second set of vanes was less than 10 percent after 25 hours and 10 thermal cycles of testing. These results are quite favorable when compared with the failure rates of 50 percent after 5 hours and 4 thermal cycles of testing which were commonly experienced before the adoption of the techniques and quality control procedures previously discussed.

CONCLUDING REMARKS

A reliable and durable sheathed thermocouple of small diameter can be obtained by following a comprehensive evaluation procedure. The procedures discussed in this report were developed because of a high failure rate for the thermocouples made by previous techniques and are based partly on the results of a trial and error investigation and partly on information contained in the literature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 6, 1971,
764-74.

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3. Committee E-20 on Temperature Measurement: Thermocouples, Sheathed, Type K, for Nuclear or for Other High-Reliability Applications. E-235-67, 1970 Annual Standards, Part 30, General Test Methods, ASTM, 1970.

TABLE I. - DEFINITION OF SOME COMMON TERMS

[From ref. 1.]

Term	Definition
Sheathed thermocouple	A thermocouple having its thermoelements, and sometimes its measuring junction, embedded in ceramic insulation compacted within a metal protecting tube
Sheathed thermocouple wire	One or more pairs of thermoelements (without measuring junction(s)) embedded in ceramic insulation compacted within a metal protecting tube
Thermoelement	One of the two dissimilar electrical conductors composing a thermocouple

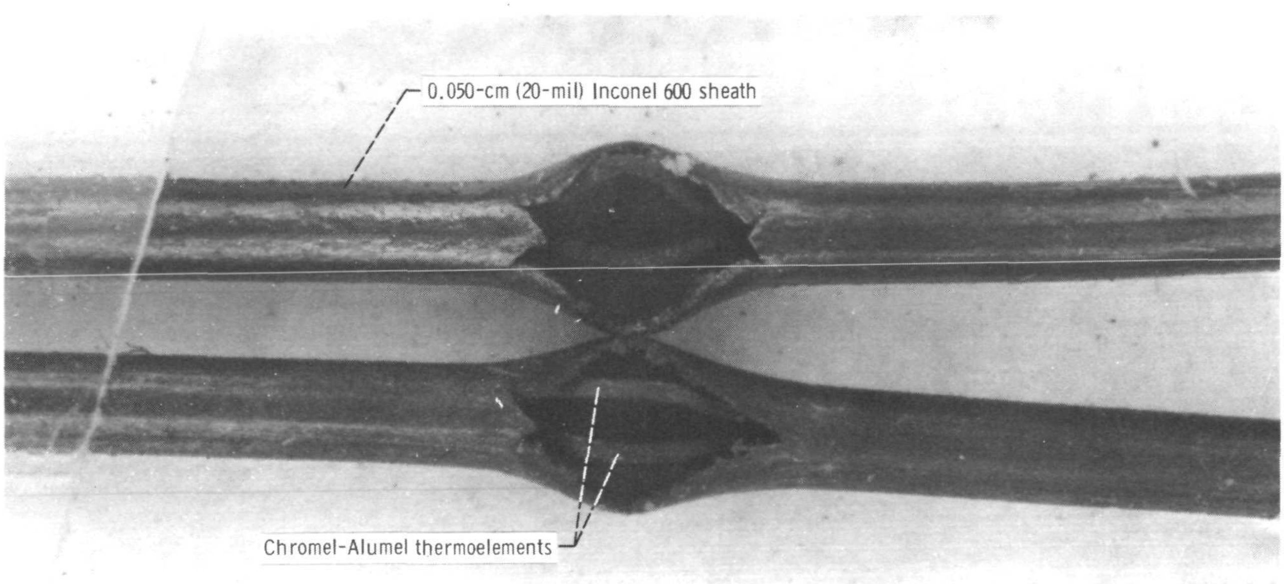

Figure 1. - Enlarged view of rupture area of Inconel 600 thermocouple sheath. Rupture occurred during heat cycle check.

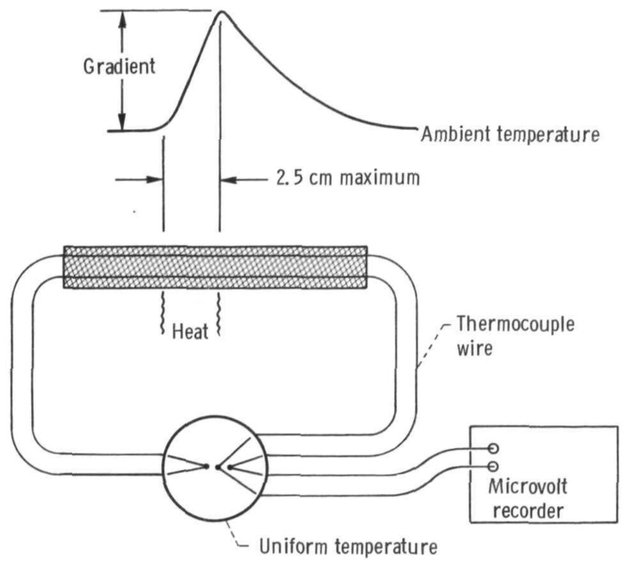

Figure 2. - Typical circuitry used to obtain spurious EMF measurement.

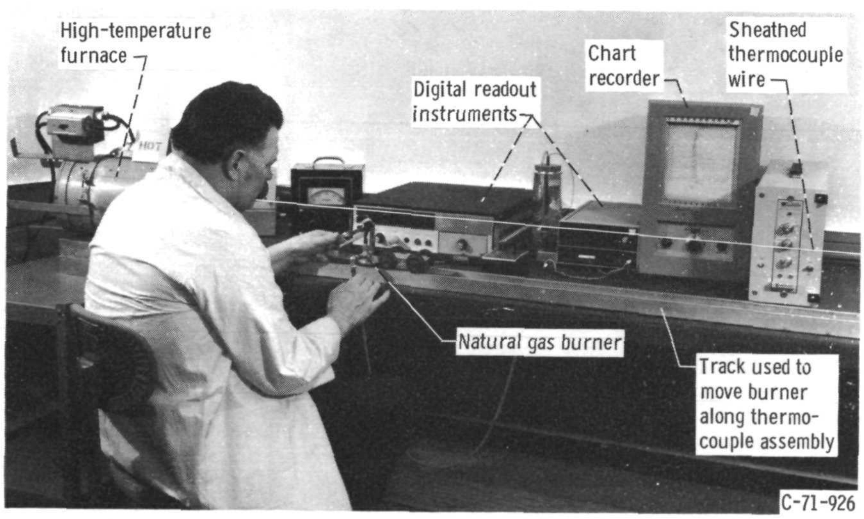

Figure 3. - Test for spurious emf during thermocouple checkout procedure.

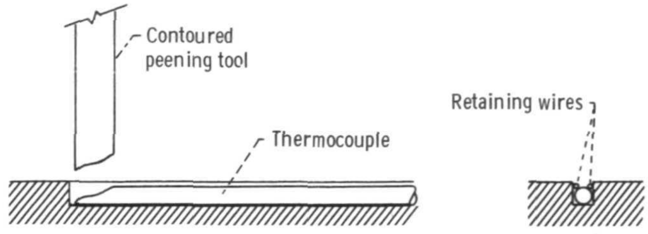

Figure 4. - Schematic representation of peening tool and thermocouple installation.

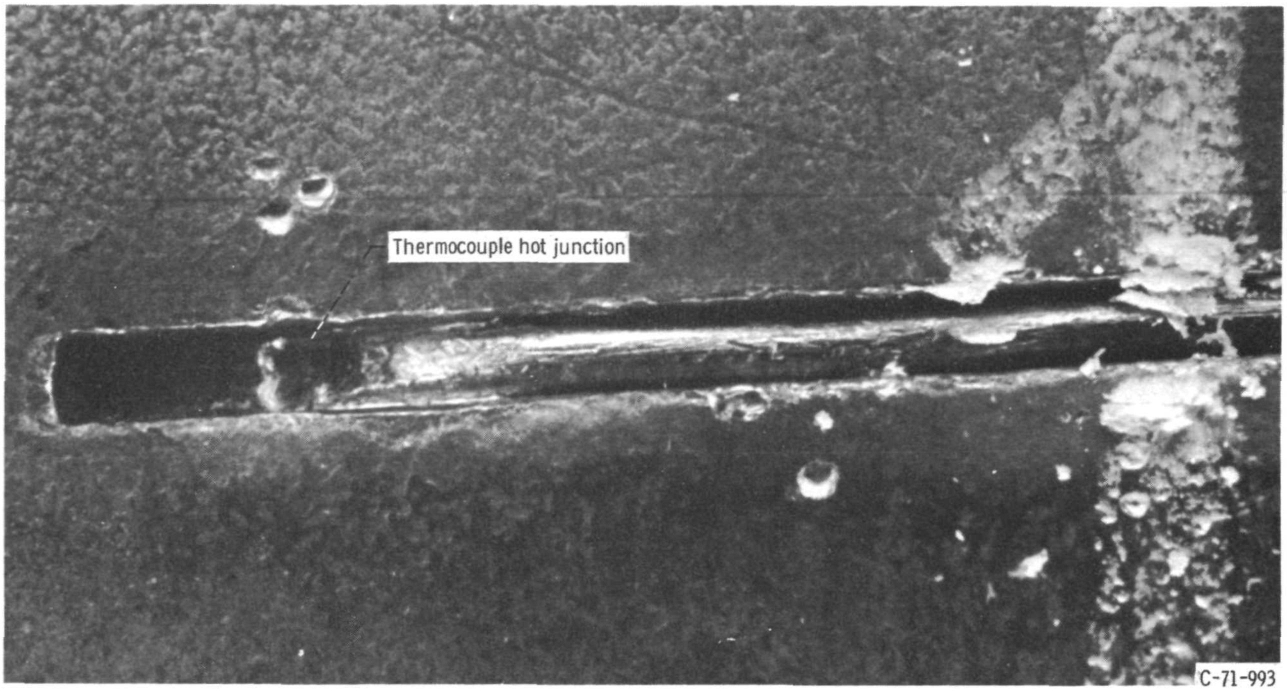

Figure 5. - View of 0.050-centimeter- (20-mil-) diameter thermocouple peened into slot using contoured tool.

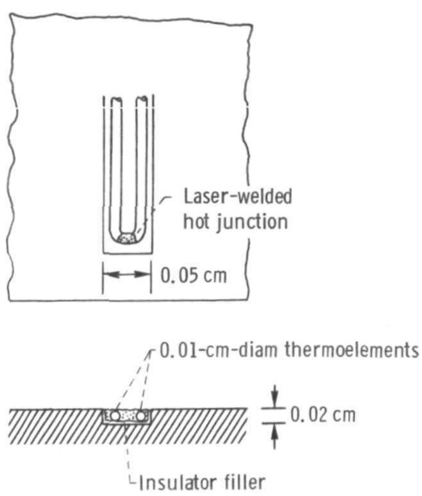

Figure 6. - Schematic representation of flame-sprayed thermocouple installation.

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