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Influence of Cooling Hole Geometry and Material Conductivity on the Thermal Response of Cooled Silicon Nitride Plate

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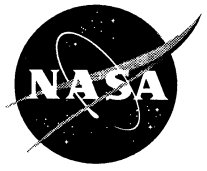
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Summary

To complement the effectiveness of ceramic materials and their applicability to turbine engine applications, a parametric study using the finite element method was carried out. This study conducted thorough analyses of a thermal-barrier-coated silicon nitride (Si_3N_4) plate specimen with cooling channels, where its thermal conductivity was varied in an attempt to minimize the thermal stresses and reach an optimal state of stress. The thermal stress profile was generated for specimens with circular and square cooling channels. Lower stresses were reported for a higher magnitude of thermal conductivity and in particular for the circular cooling channel arrangement. Contour plots for the stresses and the temperature are presented and results obtained are discussed.

Introduction

Lightweight, strong, tough high-temperature materials are required to complement efficiency improvements for next-generation gas turbine engines that can operate with minimum cooling. Because of their low density, high-temperature strength, and thermal conductivity, ceramic matrix composites are being investigated as potential materials for replacing nickel-base superalloys currently used for hot-section engine components. Ceramic structures can withstand higher operating temperatures and harsh combustion environments. In addition, their low densities relative to metals help to reduce component mass (refs. 1 and 2) and hence the engine weight and ultimately the fuel consumption.

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The general objectives of this research are to develop the manufacturing technology, the thermal and environmental barrier coating (TBC/EBC) system, and the analytical modeling capability to predict the thermomechanical stresses for testing minimally cooled silicon nitride burner rig specimens under simulated engine conditions. These stresses, resulting from the high temperatures in turbine engine environments, may affect the durability of engine components. To minimize the thermal stress, this report analyzes the effects of thermal conductivity (which varies with the temperature changes in these environments) and cooling channel geometry on the temperature distribution for coated silicon nitride in a burner rig environment.

Analytical Approach

Two-dimensional finite element analyses were performed in a parametric study in which heat transfer and stress analyses were conducted under steady-state conditions to demonstrate the feasibility of using cooled Si_3N_4 parts for turbine engine applications. The calculations were made under linear elastic conditions where the behavior of the material was defined by two material constants, Young's modulus and Poisson's ratio. The geometry of a silicon nitride plate with cooling channels used for the finite element analysis is shown in figure 1. Plate-shaped specimens were used in these analyses to simulate conditions and environmental behavior typically experienced by vanes in turbine engines. The test specimens consist of a square silicon nitride substrate with four coating layers arranged in the following order: a top layer of mullite, a second layer of combined mullite and 20 wt% barium strontium aluminosilicate (BSAS), a third layer of BSAS, and a fourth layer of zirconia. The first three layers each have an equal thickness of 0.0765 mm, and the zirconia layer has a thickness of 0.0254 mm. Figure 1 shows the test specimen with eight 2.03-mm-diameter cylindrical cooling channels spaced 1.02 mm apart. The specimen with the square cooling channels has edge dimensions equal to the diameter of the cylindrical channels in this specimen.

The analyses embraced a thermal model that closely simulated impingement heating applied on the plate by a burner rig flame generated during previous experiments (Dennis Fox, 2001, NASA Glenn Research Center, experimental work). The hot flame was pointed symmetrically at the center region with the gas temperature being linearly dissipated over the rest of the plate. Because of symmetry, only half the plate was modeled. The steady-state temperature distributions were generated. All the finite element calculations were conducted with ANSYS 5.7 code (ref. 3).

Finite Element Analysis

Mesh Generation

Stress and steady-state heat transfer analyses were conducted to simulate a burner rig experimental setup that included internal cooling by air. The finite element model was generated with MSC/PATRAN graphics (ref. 4). Figures 2 and 3 represent the two-dimensional finite element models for the square and the circular channel test specimen configurations, respectively. The models consist of 10 216 eight-node quad elements and 31 475 nodes for the circular-channeled specimens and 9740 eight-node quad elements and 30 145 nodes for the square-channeled specimens. The specimen was constrained along the line of symmetry by restraining all the nodes from moving along

the X-direction, and another node was constrained along the Y-direction to suppress rigid body motion (see fig. 3).

Heat Transfer Analysis

The thermal boundary conditions applied were fundamental in evaluating the thermal profile predicted by the analyses. Several assumptions were made to model the heat transfer phenomena experienced by the test specimen. Furthermore, convective boundary conditions were applied, and the corresponding heat transfer coefficients were obtained from reference 5. Convective flame impingement was imposed over the top of the plate, while convective cooling was applied to the bottom of the plate and inside the cooling channels, as shown in figure 2. Also note in figure 2 that the convective heat transfer coefficient was linearly varied from the center to the edge, simulating a decaying flame. At the center, impingement heating conditions were imposed, and the forced-convection state between the flame and the plate surface had a convective coefficient value of 883 W/m^2 °C associated with a gas temperature of 1982 °C. This value of heat transfer coefficient corresponds well with values of heat transfer coefficients for superheated steam or air under forced convection (ref. 5), which are highly representative of data used for an impingement heating environment. At the edge, a convective heat transfer coefficient of 6 W/m^2 °C was applied, representing the free-convection state considered in the analysis. The gas temperature was linearly tapered off across the plate from a high of 1982 °C until it reached a low of 700 °C.

The cooling channels and the specimen bottom were modeled with a convective heat transfer coefficient of 114 W/m^2 °C, a typical value for water cooling in a forced-convection state (ref. 5) and a gas temperature of 700 °C. Air is the cooling medium assumed in these analyses.

A symmetry boundary condition was imposed at the specimen midregion because only half the specimen was considered for the analyses. All the coating layers were included in the analyses; layers of elements representing the coatings in the order described in figure 1 were generated. More details pertaining to the thermal modeling can be found in reference 1. The material properties for the coatings and the silicon nitride are listed in table I.

Discussion of Results

Contour plots showing the silicon nitride thermal and structural response are shown in figures 4 to 7. The temperature and the axial stress as a function of the thermal conductivity for the circular and square cooling channel configurations are also shown in figures 8 and 9. The temperature and the stress results presented were generated under cooling conditions.

Figures 4 and 5 represent the contour plots of the temperature distribution at a silicon nitride thermal conductivity of 100 W/m °C. They indicate that the maximum temperature is at the center section of the plate as expected. Additionally, the influence of the cooling channel configuration is clearly exhibited by the temperature distribution between the two channel layouts. A hotter region is recognized for the square configuration. Figures 4 and 5 show the silicon nitride temperature predicted by the analysis. Furthermore, temperature effects of the material properties reported in Table I

were all incorporated into the analyses. Such implementation has enabled accounting for all the thermal conductivity variations due to material properties changes with temperature. Figures 6 and 7 illustrate the axial stresses as a result of the thermal loading conditions applied. Similar stress distribution trends for both cooling channel shapes are clearly indicated. However, the stresses were lower, close to 50 percent, for the circular cooling channel plate compared with that of the square channels. High stress concentrations are seen at the square corners and specifically near the flame area (see fig. 6). The plate with the circular cooling channels experienced high stresses at the top section of the channels along the 90° angle (see fig. 7); however, no stress concentrations were noted. Thus, a circular cooling channel configuration seems to be more suitable for intended turbine engine applications.

The data presented in figures 8 and 9 show the effects of both the shape of the cooling channels and the thermal conductivity simultaneously. For instance, figure 8 illustrates the variation of the temperature under cooling conditions as the thermal conductivity of the silicon nitride is increased from 2 to 100 W/m °C. This variation range was randomly chosen in an attempt to evaluate a broader spectrum of material conductivity data. It is obvious that the temperature is decreased as the thermal conductivity increases. Note also that the specimens with the square and the circular cooling channels were at nearly the same temperature over the conductivity range considered. This is attributed to the similarity in the boundary conditions applied.

In figure 9 the maximum axial stress of the silicon nitride as a function of the thermal conductivity decreases as the thermal conductivity increases. Furthermore, the reduction of the stresses relative to the change in the thermal conductivity magnitude as it varied from 2 to 100 W/m °C is about 18 percent. This leads to the conclusion that at higher thermal conductivity the stresses become lower. However, the extent to which this decrease in stress, resulting from the thermal conductivity variation, affects the material's durability may be difficult to predict. Other factors like the coating materials and the thermal boundary conditions may have contributed to the outcome of these analyses and affected the conductivity influence of the ceramic on the stress response.

Conclusions

A parametric study using the finite element method was conducted to investigate the effects of varying the thermal conductivity and the cooling channel geometry on the thermomechanical response of a prototype coated silicon nitride (Si_3N_4) cooling-plate panel specimen. The analyses showed a decrease of about 18 percent in the stresses of the silicon nitride when the thermal conductivity was increased from 2 to 100 W/m °C. The plate specimen with circular cooling channels showed no stress concentration; in comparison, the specimen with the square cooling channels experienced stress risers at the channel corners. Layers of coating, as well as other factors such as boundary conditions, may have affected the changes reported as resulting from thermal conductivity variations. The current study offers a preliminary baseline assessment of the effects of the thermal conductivity on the thermomechanical response of the silicon nitride; however, more work is warranted under more realistic boundary conditions to reach a more conclusive statement relative to gains and benefits achieved with respect to durability. Efforts are in progress to study the effects of other key parameters such as material surface roughness, the thermal and environmental barrier coating (TBC/EBC) system, and the coolant pressure differential as expressed with more representative thermal boundary conditions.

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TABLE I.—MECHANICAL AND THERMAL PROPERTIES OF MATERIALS

Material	Temperature, °C	Elastic modulus, GPa	Poisson's ratio	Coefficient of thermal expansion, 10^{-6}/°C	Thermal conductivity, W/m °C
Silicon nitride[a]	25	300	0.22	8.380	30.0
	1386	250	.19	8.380	12.0
BSAS[a, b]	25	95	-----	23.96	2.0
	1386	95	-----	23.96	.50
Mullite[c]	25	145	.20	13.46	5.86
	1386	145	.20	13.46	3.87
BSAS-mullite mixture[a]	25	120	-----	18.71	2.0
	1386	120	-----	18.71	.24
Porous zirconia[d]	25	0.0025	.25	28.75	2.0
	1386	0.0025	.25	28.75	.50

[a]Ref. 6.
[b]BSAS is barium strontium aluminosilicate.
[c]Ref. 7.
[d]Ref. 8.

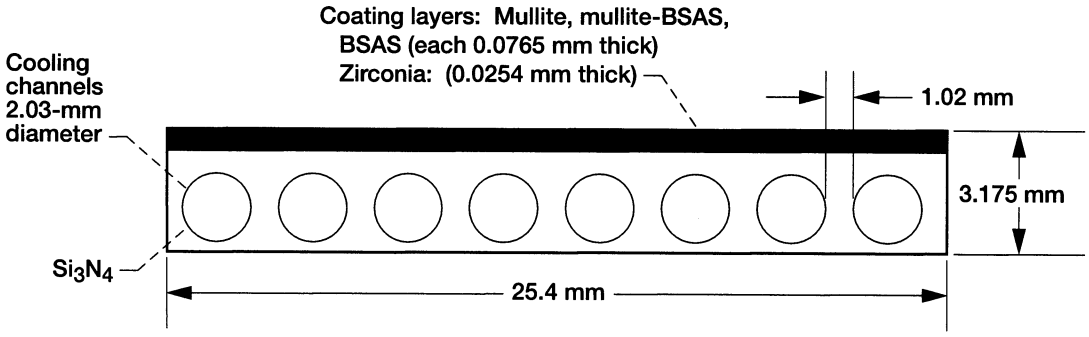


Figure 1.—Monolithic silicon nitride (Si_3N_4) circular-channeled cooling panel cross section. BSAS is barium strontium aluminosilicate.

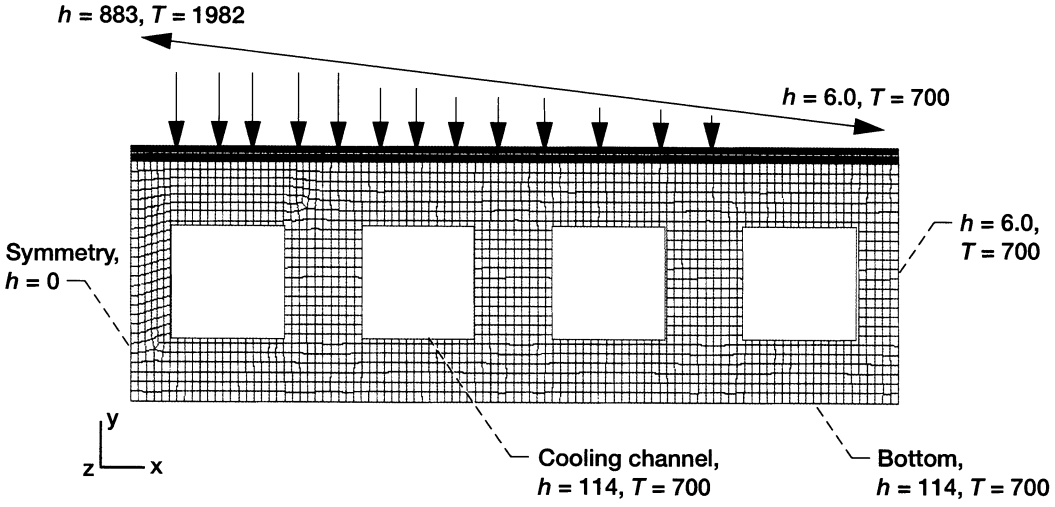


Figure 2.—Two-dimensional finite element model of square configuration (9740 eight-node quad elements, 30 145 nodes) and thermal boundary conditions showing applied gas temperature, T (°C) and heat transfer coefficients, h (W/m^2 °C).

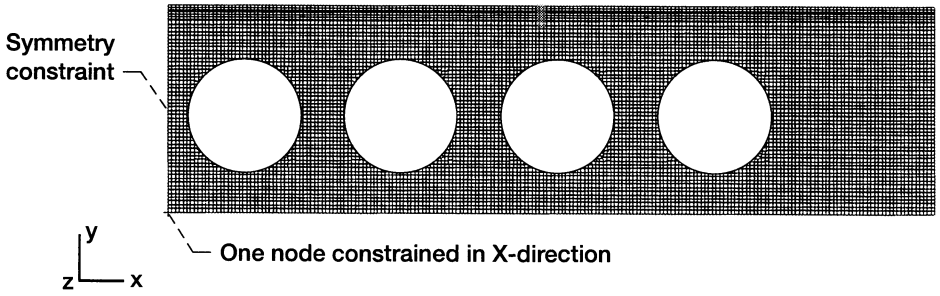


Figure 3.—Circular configuration finite element model (10 216 eight-node quad elements, 31 475 nodes) and boundary conditions applied.

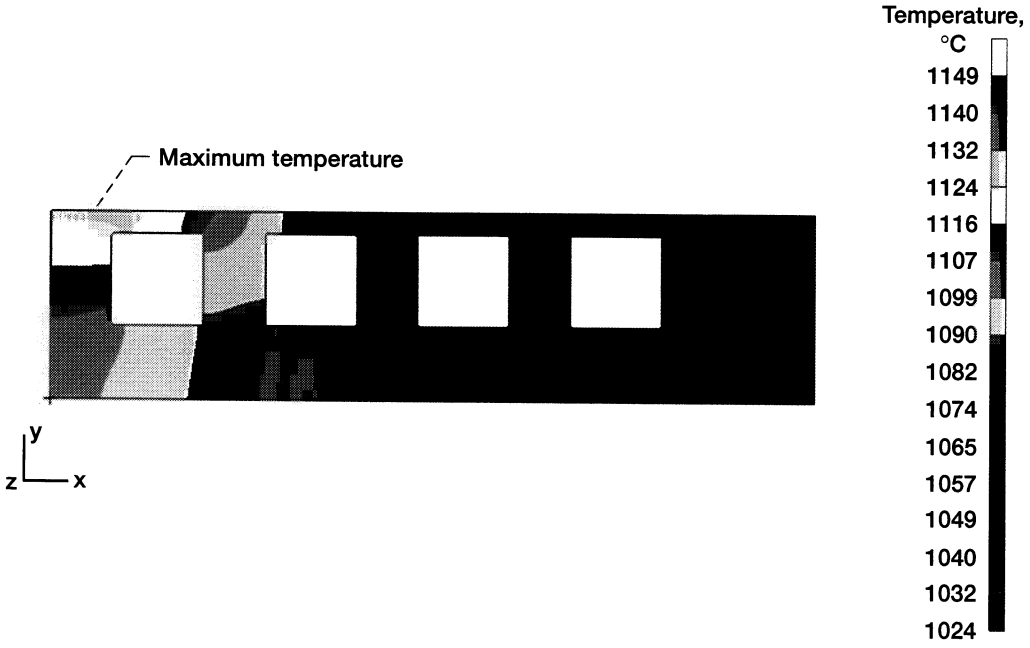


Figure 4.—Temperature distribution at thermal conductivity of 100 W/m °C for cooling with square channels.

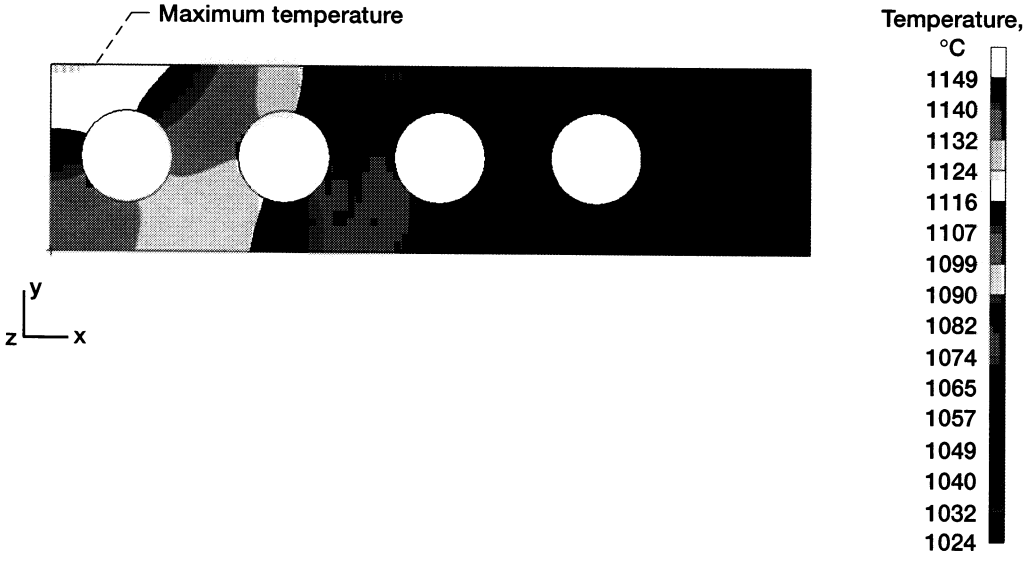


Figure 5.—Temperature distribution at thermal conductivity of 100 W/m °C for cooling with circular channels.

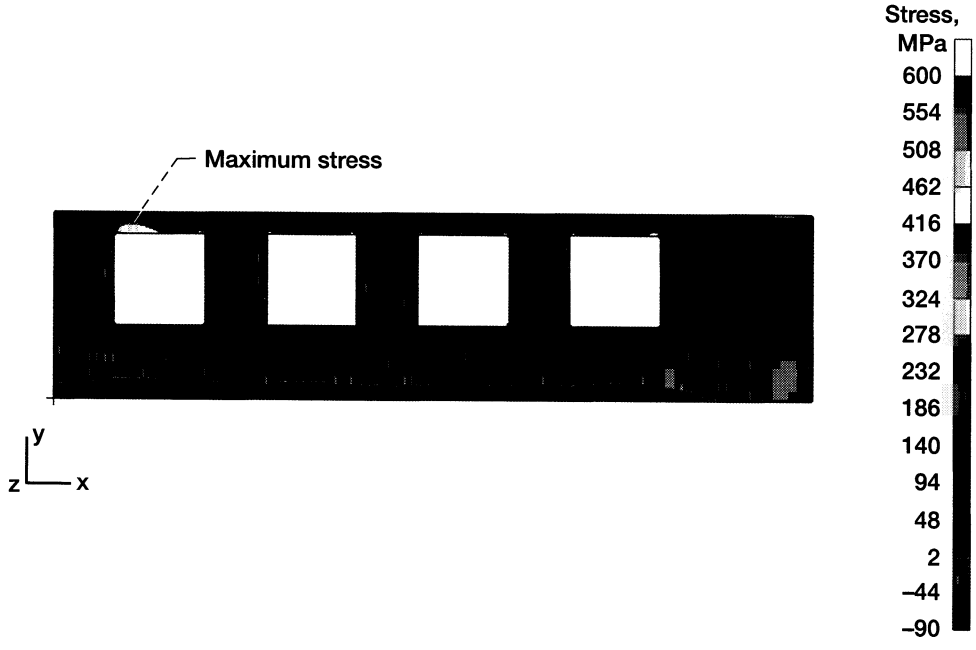


Figure 6.—Axial stress distribution at thermal conductivity of 100 W/m °C for cooling with square channels.

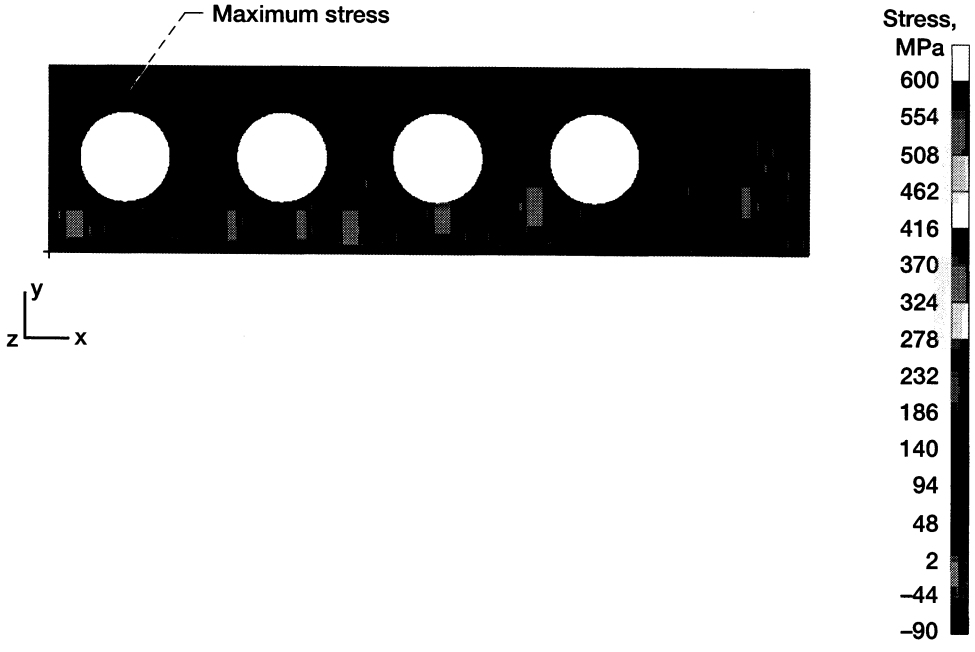


Figure 7.—Axial stress distribution at thermal conductivity of 100 W/m °C for cooling with circular channels.

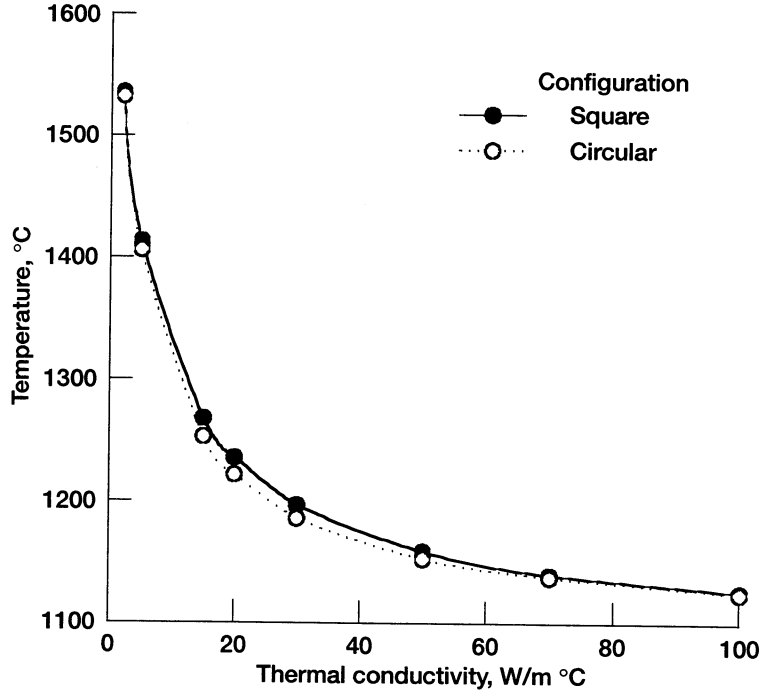


Figure 8.—Temperature of silicon nitride as function of thermal conductivity for two different cooling channel configurations.

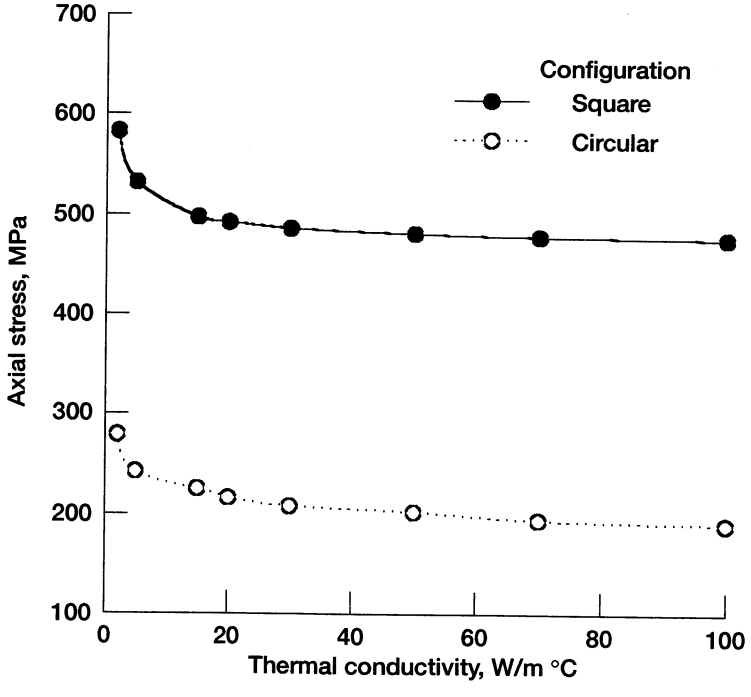


Figure 9.—Axial stress for silicon nitride in X-direction as function of thermal conductivity for two different cooling channel configurations.

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13. ABSTRACT ***(Maximum 200 words)***

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