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STRUCTURAL ANALYSES OF ENGINE WALL COOLING CONCEPTS AND MATERIALS

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ABSTRACT

The severe thermal environments under which hypersonic aircraft such as the National AeroSpace Plane (NASP) will operate require cooling of the engine walls, especially in the combustor. The NASA Lewis Research Center is undertaking an extensive in-house effort to investigate composite materials and cooling concepts for their applicability to NASP engine walls. In this study a preliminary assessment is made of some candidate materials based on structural analyses for a number of convective cooling configurations. Three materials are currently under consideration; graphite/copper (Gr/Cu) and tungsten/copper (W/Cu) composite alloys with 50 percent fiber volume fractions and a wrought cobalt-base superalloy, Haynes 188. Anisotropic mechanical and thermal properties for the composites were obtained from a computer code developed at NASA Lewis. The code, called ICAN, determines the composite material properties from the individual properties of the fiber and matrix materials. The Haynes 188 material properties were obtained from an International Nickel Company brochure. The structural analyses were performed by using the MARC nonlinear finite-element code. The analyses were based on steady-state operation at an inlet ramp condition. Heat transfer analyses were conducted to calculate the metal temperature distributions. Elastic- plastic analyses were performed for the Haynes 188 and W/Cu materials. The Gr/Cu composite was treated as an elastic material because of the lack of adequate material property information. The analyses demonstrate the applicability of nonlinear structural analysis technology to complex real-world problems.

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ANALYTICAL INPUT CONDITIONS

A preliminary assessment is made of some candidate materials based on heat transfer and structural analyses for several cooling configurations. Three materials were considered: Gr/C and W/Cu composite alloys with 50 percent fiber volume fractions and a wrought cobalt-base superalloy, Haynes 188. Anisotropic mechanical and thermal properties for the composites were obtained from the ICAN computer code developed at NASA Lewis. The heat transfer analyses were based on the gas and coolant temperatures and pressures shown below. The heat flux was 500 Btu/ft^2 sec, which would be characteristic of the engine inlet region.

CONFIGURATIONS

- RECTANGULAR PASSAGES
- CURVED (D-SHAPED) PASSAGES
- CIRCULAR PASSAGES

MATERIALS

- HAYNES 188
- Gr/Cu
- W/Cu

CONDITIONS

- GAS TEMPERATURE, 4000 °F; GAS PRESSURE, 50 psi
  COOLANT TEMPERATURE, 100 °F; COOLANT PRESSURE, 1200 psi
- HEAT FLUX, 500 Btu/ft^2 sec

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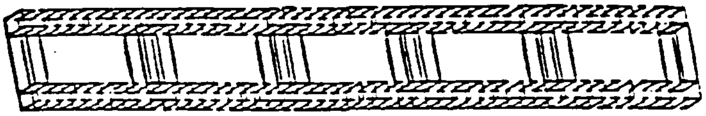
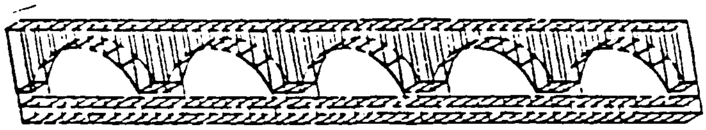
FINITE-ELEMENT MODELS

Finite-element models were created for cooling configurations involving rectangular, curved (D-shaped), and circular passages. The configurations had wall and fin thicknesses of 0.015 in. Passage spacings were 0.150 in. for the rectangular and curved geometries and 0.075 in. for the circular geometry. The models were constructed of 110 twenty-node, three-dimensional elements. The three-dimensional elements were needed to impose the directional properties of the composite materials. Five passages were modeled for each configuration in order to avoid temperature and stress distortions from the boundary conditions applied at the end surfaces. The shape of the structures was maintained by applying the boundary conditions so that all nodes on the end surfaces were tied together and had the same displacements perpendicular to the initial position of these faces. Only the central passages were considered in evaluating the analytical results. Elastic-plastic analyses were performed for the Haynes 188 and W/Cu materials by using the MARC nonlinear finite-element code. Only elastic analyses were performed for the Gr/Cu material because of the lack of inelastic stress-strain properties.

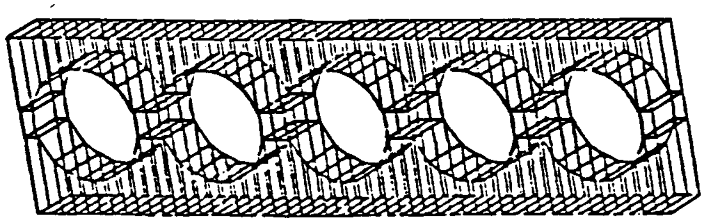
RECTANGULAR PASSAGES



CURVED PASSAGES



CIRCULAR PASSAGES



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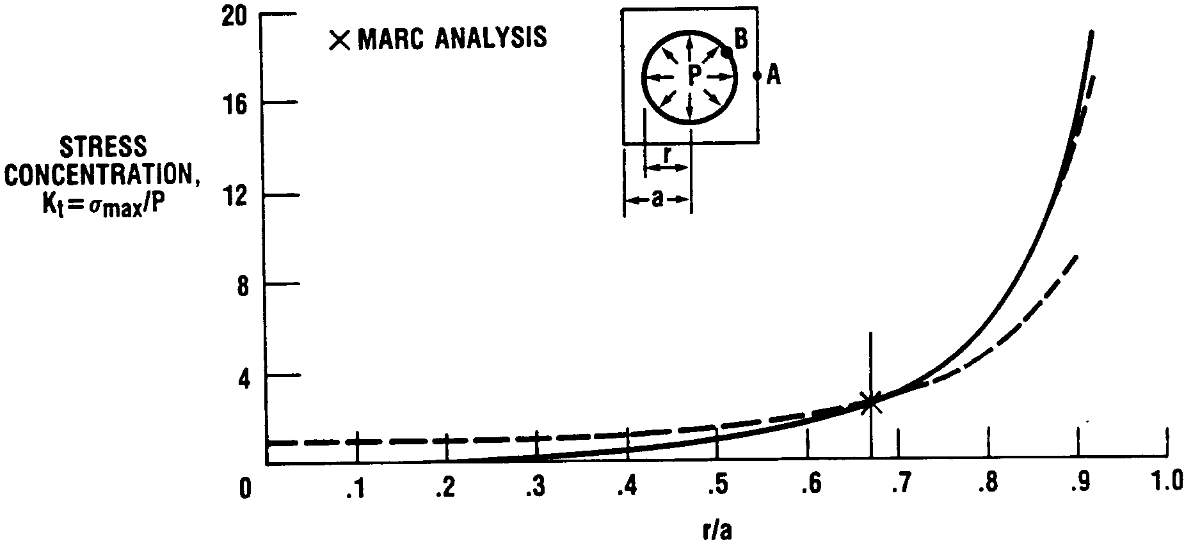
VERIFICATION OF STRUCTURAL ANALYSIS ACCURACY

So that the accuracy of the structural analyses could be verified with finite-element models, an isolated circular passage was analyzed as a flat plate with a central hole. Internal pressure loading was applied around the rim of the hole. Calculated stresses at the horizontal and vertical diametral points were compared with photoelastically determined elastic stress concentration factors from Peterson (1974). Agreement between the analytical and experimental results was within 4 percent.



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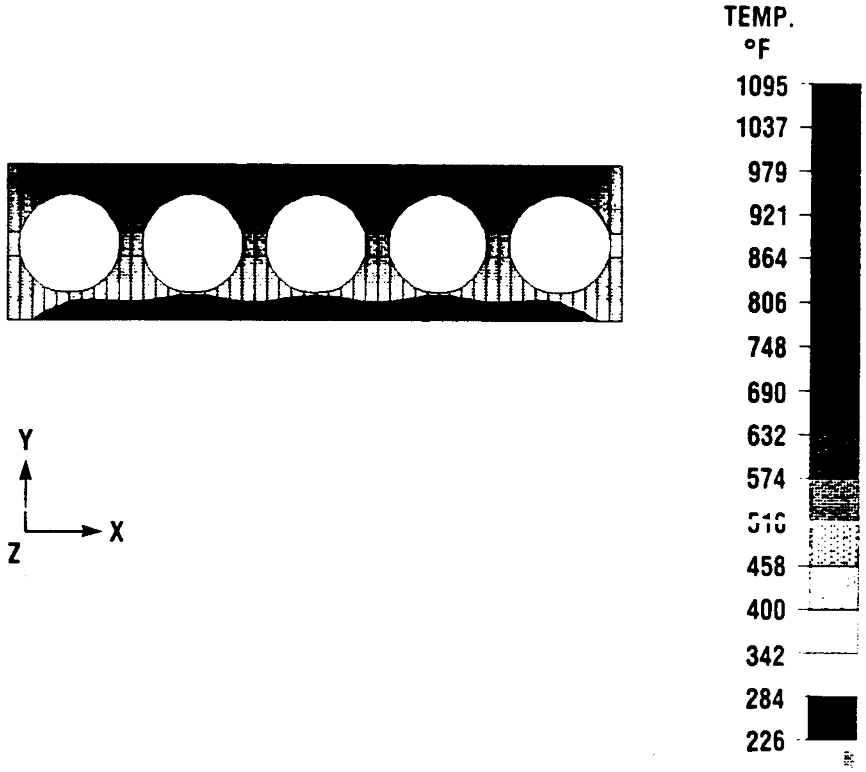
TEMPERATURE DISTRIBUTION IN HAYNES 188 CIRCULAR CONFIGURATION

The temperature distribution in a Haynes 188 circular configuration is shown. The maximum metal temperature was above 1000 °F, in contrast to about 900 and 1300 °F for the rectangular and curved configurations, respectively.



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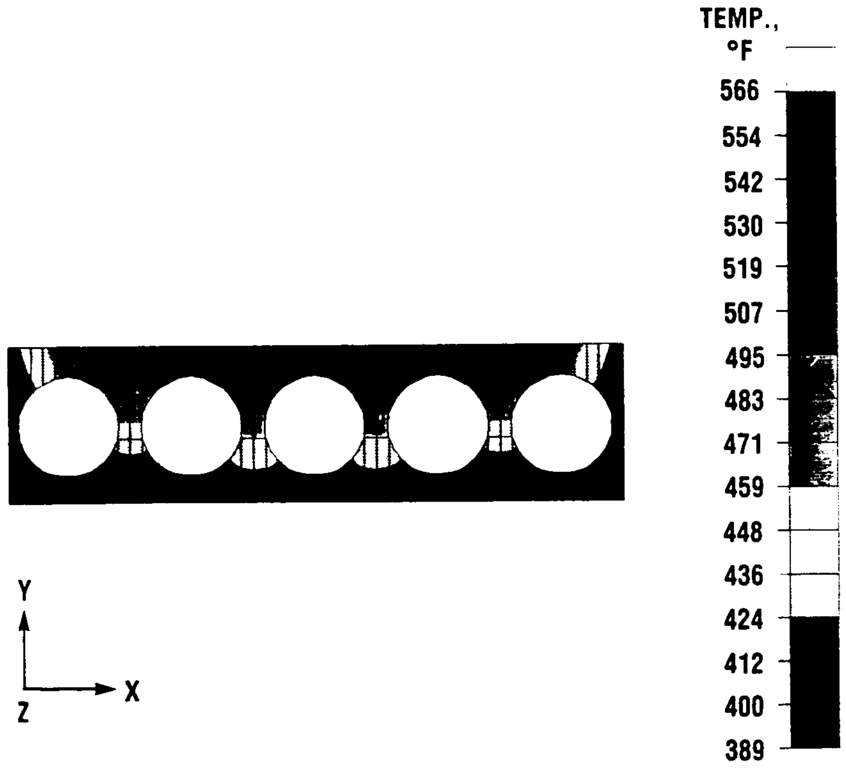
TEMPERATURE DISTRIBUTION IN W/Cu CIRCULAR CONFIGURATION

The temperature distribution for a W/Cu circular configuration is shown. The maximum metal temperatures were about 600 °F. The metal temperatures in the composite material structures were lower than those for Haynes 188 structures because their thermal conductivities were much higher. The maximum temperatures for the composite structures were not significantly affected by the passage geometry. This figure illustrates the temperature nonuniformity due to the end boundary conditions and shows why the analyses had to be conducted for a number of passages.



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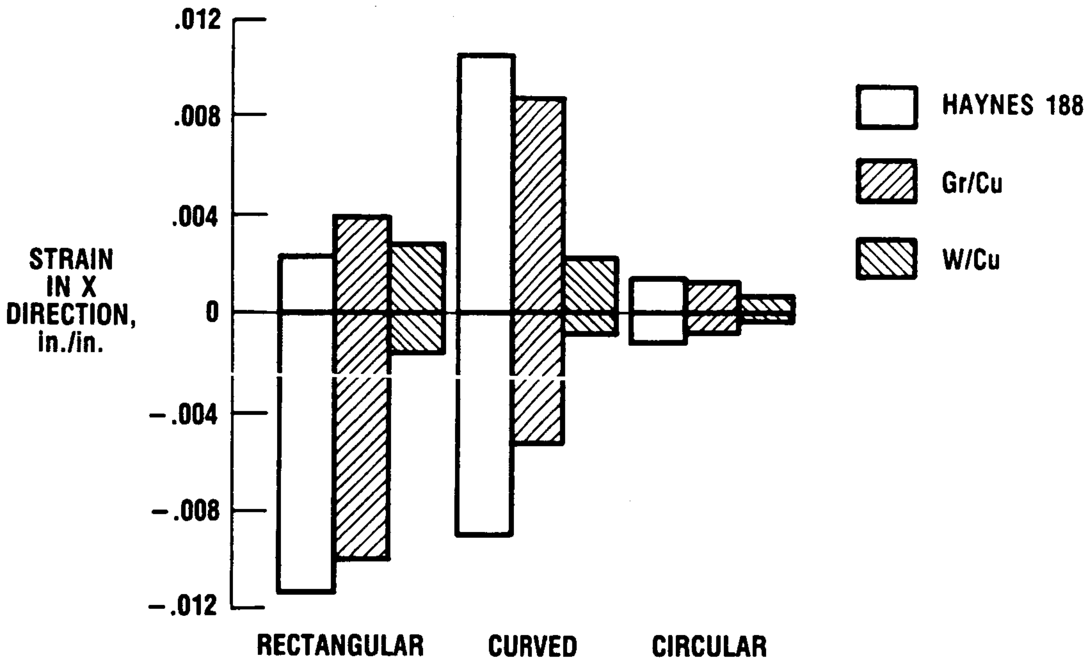
PEAK STRAINS IN COOLING CONFIGURATIONS

The bar graph shows the peak tensile and compressive strains for each material for the three passage geometries. The Haynes 188 alloy had the largest strains because it has the highest temperatures and thermal gradients; the W/Cu composite had the smallest strains because it has the lowest temperatures and thermal gradients. Of the three cooling configurations the curved geometry was the worst and the circular geometry the best in terms of the maximum strain levels.



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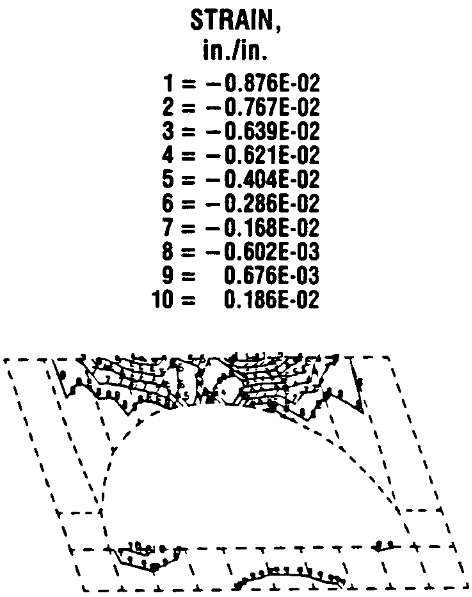
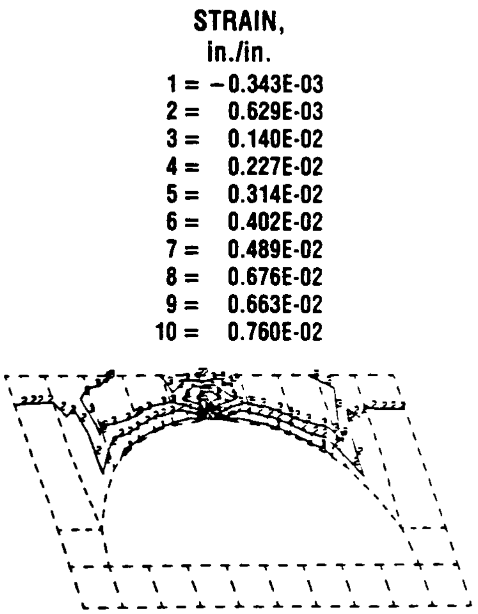
INELASTIC STRAINS IN HAYNES 188 CURVED CONFIGURATION

The inelastic strain distributions in the central passage region for the curved configuration are shown for the Haynes 188 alloy. Compressive plastic strains of almost 1 percent occurred at the hot upper surface. Smaller tensile plastic strains are evident adjacent to the passage corners and on the cold bottom surface. The creep strain distribution after 2500 seconds of dwell time is also shown. An equivalent creep strain (which is always positive) of 0.75 percent was reached at the hot upper surface.



PLASTIC STRAIN



EQUIVALENT CREEP STRAIN
(2500 SEC)

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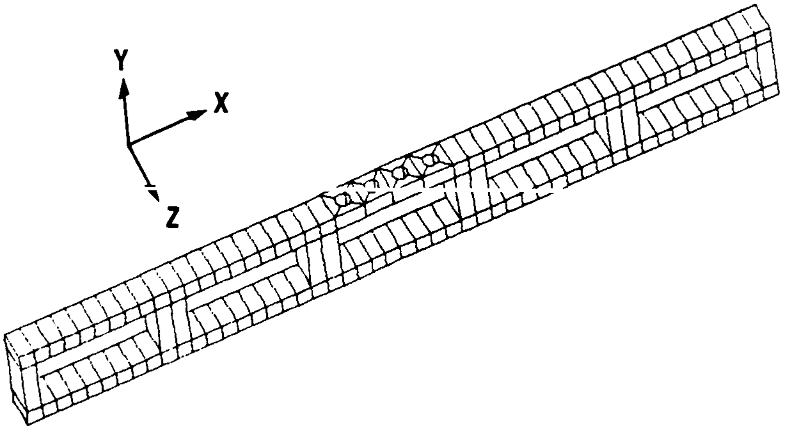
FINITE-ELEMENT MODEL OF SIMULATED FILM-COOLING CONFIGURATION

Film cooling was studied by modeling cooling holes in the upper surface of the rectangular central passage region, as shown in the finite-element model below. This increased the number of 20-node, three-dimensional elements to 118. The effects of film cooling on the upper surface were simulated by reducing the gas-side heat transfer coefficient by 10 percent. This decreased the maximum temperatures by several hundred degrees. The simulated film cooling reduced the maximum metal temperature in the central passage region from 900 °F to about 300 °F.



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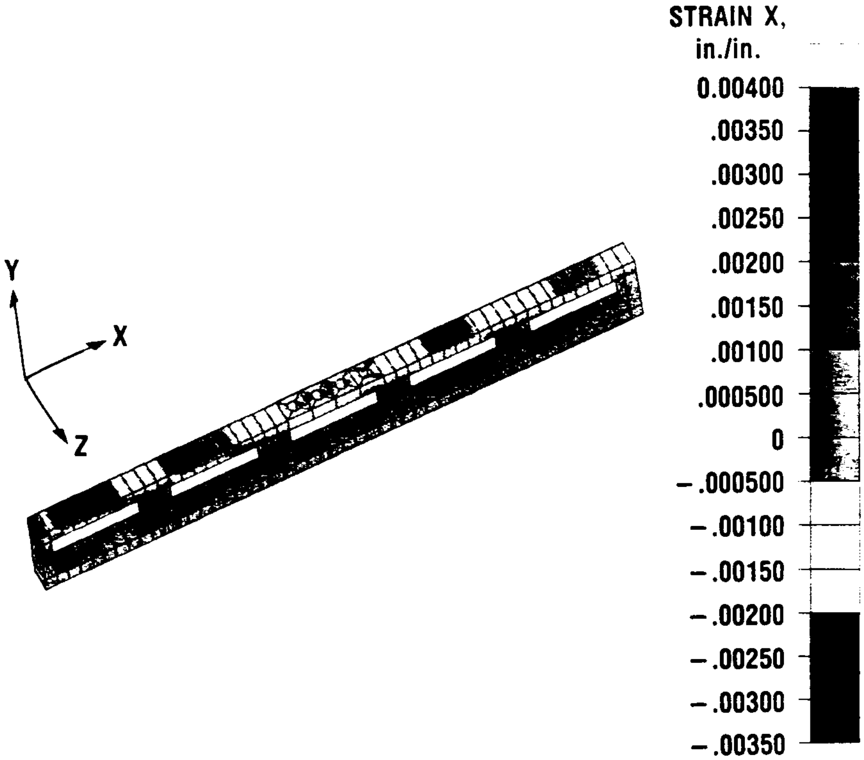
STRAIN DISTRIBUTION IN HAYNES 188 FILM-COOLING CONFIGURATION

The strain distribution is shown for the Haynes 188 film-cooling configuration. High local strains are evident near the end surfaces. In the central passage region the highest strains occurred adjacent to the passage corners. There was a significant reduction in the maximum compressive strain at the hot upper surface, from 0.0050 in the rectangular geometry to 0.0025 in the film-cooling geometry. Also, the plastic flow previously encountered at the upper surface was eliminated because of the lower metal temperatures, improved material properties, and decreased strain levels.



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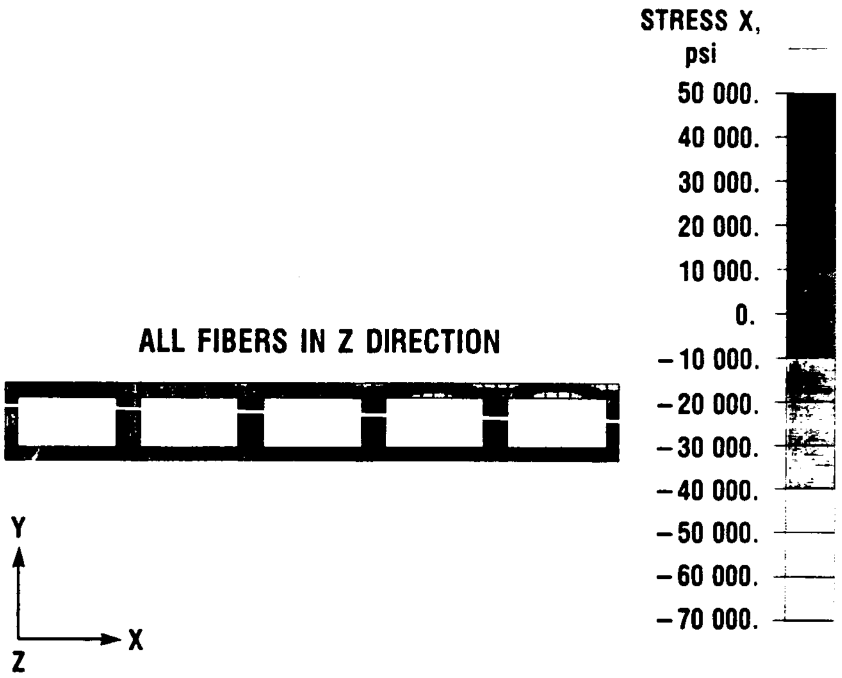
STRESS DISTRIBUTION IN W/Cu CONFIGURATION - ALL FIBERS IN Z DIRECTION

The W/Cu structures were initially analyzed for fibers oriented parallel with the direction of the fins (z direction). This orientation would be required in the thin-fin region and would be most convenient for the whole structure from a fabrication standpoint. However, it places the weak transverse properties in the x direction, where the stresses are the most severe. Small plastic strains (under 0.1 percent) were induced at the hot upper surface.



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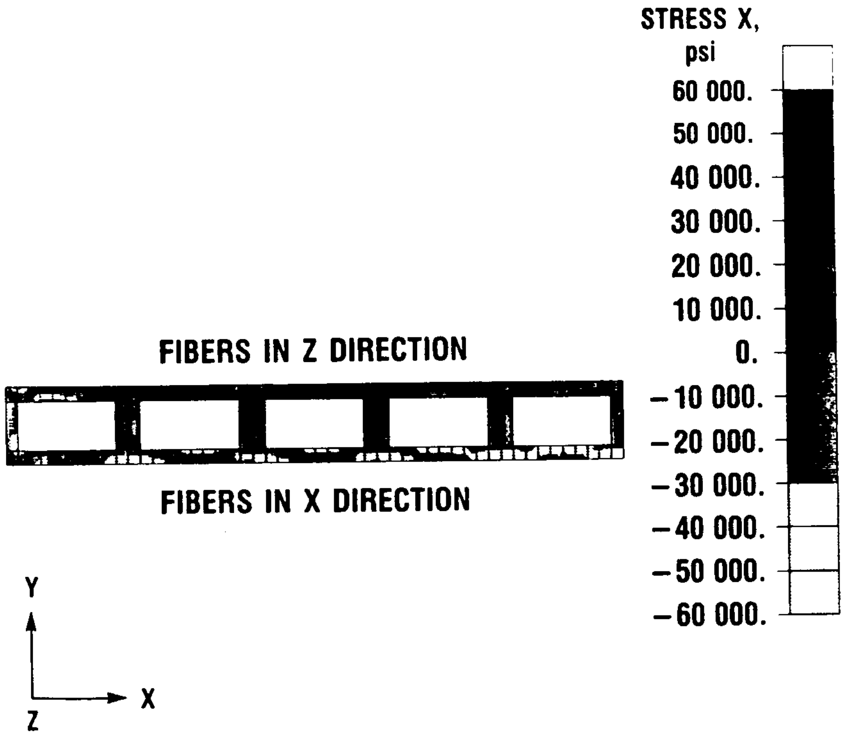
STRESS DISTRIBUTION IN W/Cu CONFIGURATION - FIBERS IN X AND Z DIRECTIONS

The fiber orientation was changed analytically so that the fibers were in the x direction, transverse to the fins, in the bottom or cold wall. The fibers at the top wall remained in the z direction. In doing this, essentially two different materials were being joined because of the significant differences in material properties between the longitudinal and transverse directions in the material. These differences are even greater in the Gr/Cu composite. From a structural analysis standpoint the stress-free temperature is that at which the structure is cured. The curing temperature of the W/Cu composite was assumed to be 1800 °F. This assumption resulted in reversing the signs of the stresses in the walls so that tensile stresses were induced in the hot upper wall and compressive stresses in the cold bottom wall.



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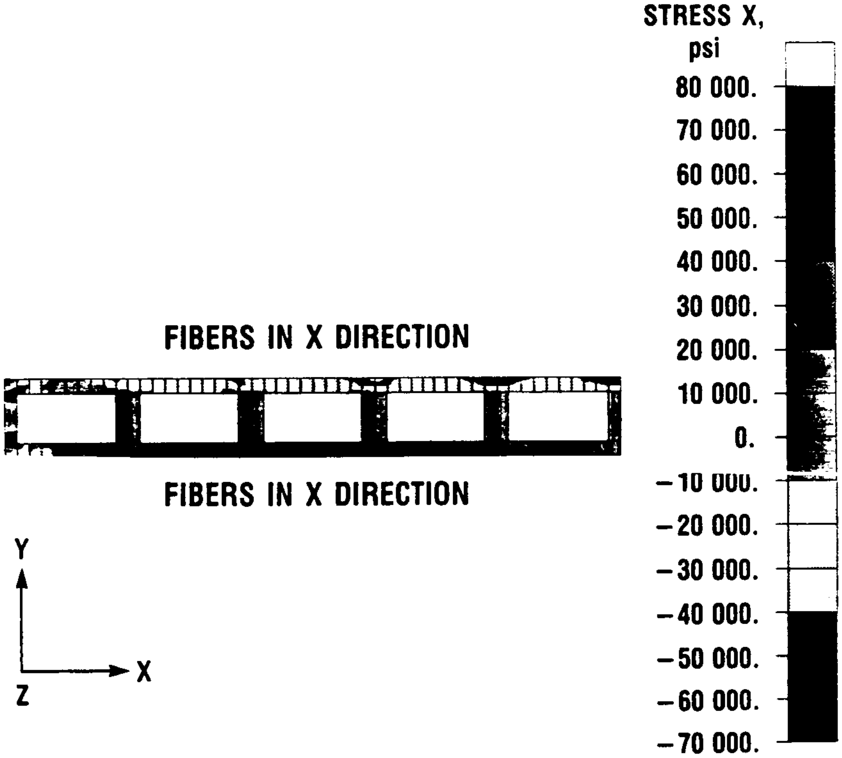
STRESS DISTRIBUTION IN W/Cu CONFIGURATION - ALL FIBERS IN X DIRECTION

In this configuration the fibers were oriented in the x direction everywhere except in the fin region. This gave the structure the strongest properties in the most severe direction and temperature region. No plastic straining occurred with this orientation.



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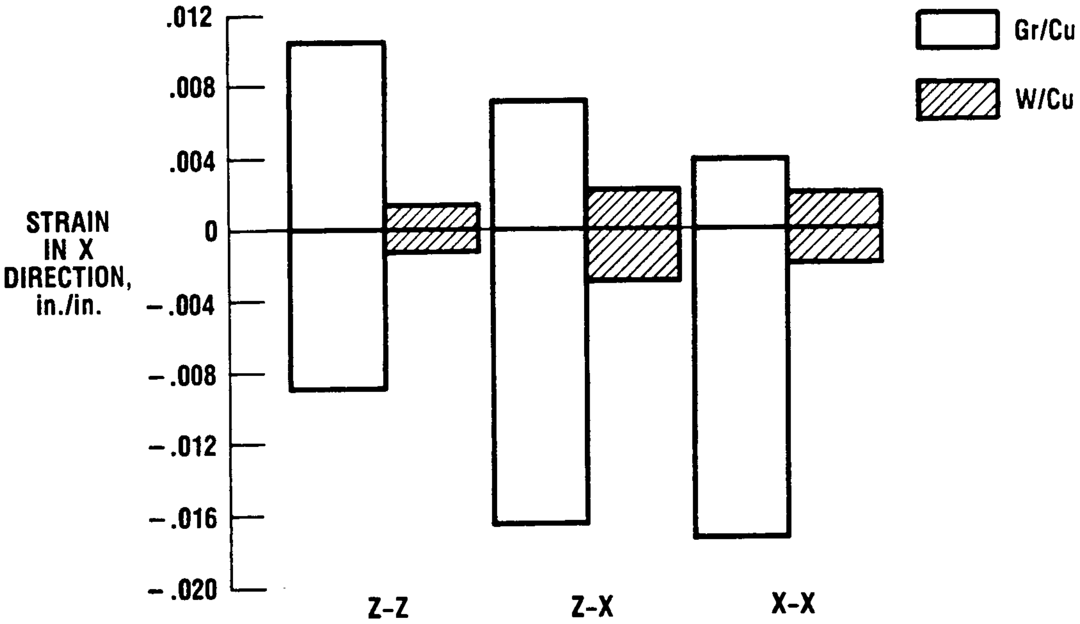
EFFECT OF FIBER ORIENTATION ON STRAINS IN W/Cu CONFIGURATION

This bargraph summarizes the effects of fiber orientation on the strain levels. For the Gr/Cu composite the effect of changing the fiber orientation to the x direction was to reduce the tensile strain and increase the compressive strain. The W/Cu configuration with both the fin and transverse fiber orientations exhibited the smallest strains of the three candidate materials.



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CONCLUSIONS

- HIGHEST STRESS COMPONENT WAS IN TRANSVERSE DIRECTION TO FINS
- CIRCULAR PASSAGES GAVE LOWEST AND CURVED PASSAGES HIGHEST STRAINS
- W/Cu WITH TRANSVERSE FIBERS GAVE LOW TEMPERATURES AND STRAINS WITHOUT PLASTIC FLOW
- HAYNES 188 WAS ACCEPTABLE WITH CIRCULAR AND FILM-COOLED GEOMETRIES; HIGH CREEP STRAIN IN CURVED GEOMETRY

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REFERENCES

Peterson, R.E., 1974, "Stress Concentration Factors." John Wiley & Sons.