NASA/TM—2001-211305

Superalloy Foams for Aeroshell Applications

John Gayda and Santo Padula II
Glenn Research Center, Cleveland, Ohio

November 2001

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National Aeronautics and
Space Administration

Glenn Research Center

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SUPERALLOY FOAMS FOR AEROSHELL APPLICATIONS

John Gayda and Santo Padula II
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

INTRODUCTION

Current thermal protection systems for reentry from space, such as that employed on the space shuttle, rely on ceramic tiles with ultra-low conductivity. These materials provide excellent thermal protection but are extremely fragile, easily degraded by environmental attack, and carry no structural loads. Future thermal protection systems being proposed in NASA's MITAS Program will attempt to combine thermal protection with improved durability and structural capability without significant increases in vehicle weight. This may be accomplished by combining several materials in a layered structure to obtain the desired function for aeroshell applications. One class of materials being considered for inclusion in this concept are high temperature metal foams.

The objective of this paper was to fabricate low density, superalloy foams and conduct limited testing to evaluate their thermal and structural capabilities. Superalloys were chosen for evaluation as they possesses good strength and excellent environmental endurance over a wide range of temperatures. Utilizing superalloys as low density foams, with porosity contents greater than 90 percent, minimizes weight and thermal conductivity.

MATERIAL AND PROCEDURES

Two nickel-base superalloy compositions were selected for this study. The first, Alloy 10, is a high strength, γ' strengthened superalloy which can be used at temperatures up to 800 °C (ref. 1). The second, Haynes 230, is a solid solution strengthened superalloy which can be used at temperatures as high as 1000 °C. The compositions of both alloys are presented in table I. Foams of each composition were produced by Porvair Corporation of Hendersonville, North Carolina using a patented metal foam fabrication process. The process starts with fine metal powders of the desired composition. In this study the powders were supplied by Homogenous Metals Corporation and were produced by argon atomization. The powder is mixed with liquid binders and wetting agents to form a slurry with a tightly controlled rheology. The desired rheology is dependent on the porosity and structure of the foam. The slurry is then forced into an open cell plastic foam which acts as a "template" for the metal foam. The plastic foam is generally cut to the desired shape of the part. In this study, flat panels 16 by 16 by 1.7 cm were fabricated. After impregnating the plastic foam with the slurry it is dried in an oven. The dried foam is then transferred to a nitrogen atmosphere furnace where the plastic foam is burned-off at a relatively low temperature followed by a high temperature sintering cycle to "densify" the metal powder. The porosity, cell size (number of pores per unit length), and composition of each panel produced in this study are summarized in table II. Basically, two porosity levels and two cell sizes were produced for each composition using plastic foam templates with differing structures.

Structural and thermal characterization of the panels were performed on cylindrical coupons which were cut from the panels using an EDM process. For structural evaluation, cylinders measuring 2.5 cm in diameter and 1.7 cm long were employed. Compressive "crush" strength of these cylinders were measured at room temperature on a MTS 808 Material Test System. To prevent premature failure associated with excessive loading of a single ligament in the foam specimens, cardboard pads, about 1 mm thick, were placed on the top and bottom of the cylinders. A ram speed of 2.5 mm/sec was employed in these tests. Samples of metallic foam, 5.0 cm in diameter and 1.7 cm long, were also prepared and sent to TPRL Inc., for thermophysical property testing between room temperature and 1000 °C. Thermal diffusivity values (α) were measured using the step heating method on foam specimens while specific heat values (C_p) were determined using a scanning calorimeter on bulk samples of superalloy. Thermal conductivity values were then calculated as the product of $\alpha C_p d$, where d is the density of the foam. Metallographic sections of the superalloy foams were also prepared and evaluated using an optical microscope and a SEM.

RESULTS AND DISCUSSION

Visual examination of the superalloy foams revealed a fairly uniform macrostructure as seen in figure 1. The target porosity and cell size of each foam panel is presented in table II along with the measured density. Metallographic examination revealed most foam ligaments had a hollow core, which is not unusual for metal foams. In addition, a significant amount of microporosity, about 10 percent, was observed in the ligament walls, figure 2. The microporosity level was determined using a minimum of five random sections for each foam sample shown in figure 2. While the sintering phase of the Porvair fabrication process was not expected to produce complete consolidation of powder in the walls of the foam ligaments, the microporosity level observed was a source of concern from a structural standpoint. For this reason some of the test coupons to be used for compressive "crush" testing were HIPed at 1149 °C and 172 MPa for 3 hr in an attempt to increase the level of powder consolidation.

Determination of room temperature compressive "crush" strength as a function of porosity, cell size, and composition are tabulated in table III. A typical load-displacement curve is presented in figure 3. As shown here, the compressive load builds to a maximum and then decreases to some nonzero level followed by successive oscillations in load. In most cases, the maximum load corresponds to the initial peak and in all cases the foam failed by brittle fracture of individual ligaments. The compressive "crush" strength documented in table III was taken to be the initial peak load divided by the circular area of the test coupon, 4.91 cm^2. For each foam panel, three or four tests were run. Examination of the data revealed the standard deviation for any group of tests was generally less than 10 percent of the mean for that group. An estimate of the pooled standard deviation for all groups ran about 0.1 MPa. The average crush strength of all nonHIP foams are plotted in figure 4. Several trends are readily seen. First, Alloy 10 foams were generally stronger and exhibit a range of strength levels which show significant variation with porosity and cell size. Second, Haynes 230 foams tend to be weaker and show very little variation in strength levels. While Alloy 10 is stronger than Haynes 230 at room temperature, the difference between foam strength for the two alloys cannot be fully attributed to alloy strength. Processing issues associated with foam production are likely to be of greater importance with respect to this issue as Porvair was "learning" the production issues for both alloys. This point will be discussed in more detail in the following paragraph. Finally, comparing the shaded region in table III, it is obvious that HIPing did not improve strength levels of either superalloy foam.

Analytical models of foam strength, such as those proposed by Gibson and Ashby (ref. 2), predict strength is proportional to relative density, i.e., foam strength should increase as porosity decreases. This trend is definitely reflected in the Alloy 10 data, but is less apparent in the Haynes 230 data. Further, the measured strength levels of all foams was significantly lower than that predicted by these models, which predict foam strength to be about one third the product of relative density and yield strength for metal foams failing by plastic collapse. Using a conservative estimate for superalloy yield strength of 500 MPa, foam strength should be about 8 to 16 MPa for relative densities between 5 and 10 percent, i.e., target porosity levels between 95 and 90 percent. This is about five times greater than that observed in this study. Undoubtedly, the low level of powder consolidation observed in the foam ligaments was a major factor producing the low strength and ductility of the foams in this study. Clearly, refinement of processing issues associated with foam production for these two alloys is needed.

The thermal conductivity of the superalloy foams was significantly lower than "solid" superalloy, which is about 0.01 W/cm-C at room temperature. The conductivity of Alloy 10 foams is plotted in figure 5 from room temperature to 1000 °C. To conserve funds, the conductivity of the Haynes 230 foams was not measured, but is expected to be similar based on comparison of bulk properties. As expected, the conductivity of the Alloy 10 foam decreases with increasing porosity level. At low temperatures, cell size has little effect on conductivity, but at temperatures where radiation becomes significant, the larger cell size, 2 pores/cm, results in higher conductivity values for a given porosity level. This is logical as foams with larger cell sizes are more "transparent" to radiation.

SUMMARY AND CONCLUSIONS

Lightweight superalloy foams, weighing less than 0.8 g/cc, were fabricated by Porvair Corporation using a patented metal foam fabrication process. Porosity, cell size, and alloy composition were varied in this study to produce superalloy foams of potential interest for aeroshell applications. Structural and thermal characterization of the foams showed strength levels of 3.7 MPa or less at room temperature with thermal conductivity levels well below that of "solid" superalloy. While the density and conductivity of the foams were desirable for aeroshell applications, strength and ductility levels were somewhat disappointing. It is believed that the strength and ductility of the foam was compromised, as significant levels of microporosity were observed in the ligaments of the foam. Improvement in the Porvair process, to achieve higher levels of densification in the ligaments of the superalloy foams, is clearly an area for future research.

REFERENCES

1. Sushil Jain: High OPR Core Materials-Regional Engine Disk Development, Final Report NASA Contract NAS3–27720, November 1999.
2. Lorna Gibson and Michael Ashby: Cellular Solids-Structure and Property, Cambridge University Press, 1997, Chapter 5.

TABLE I.—COMPOSITION OF SUPERALLOY POWDERS IN W/O.

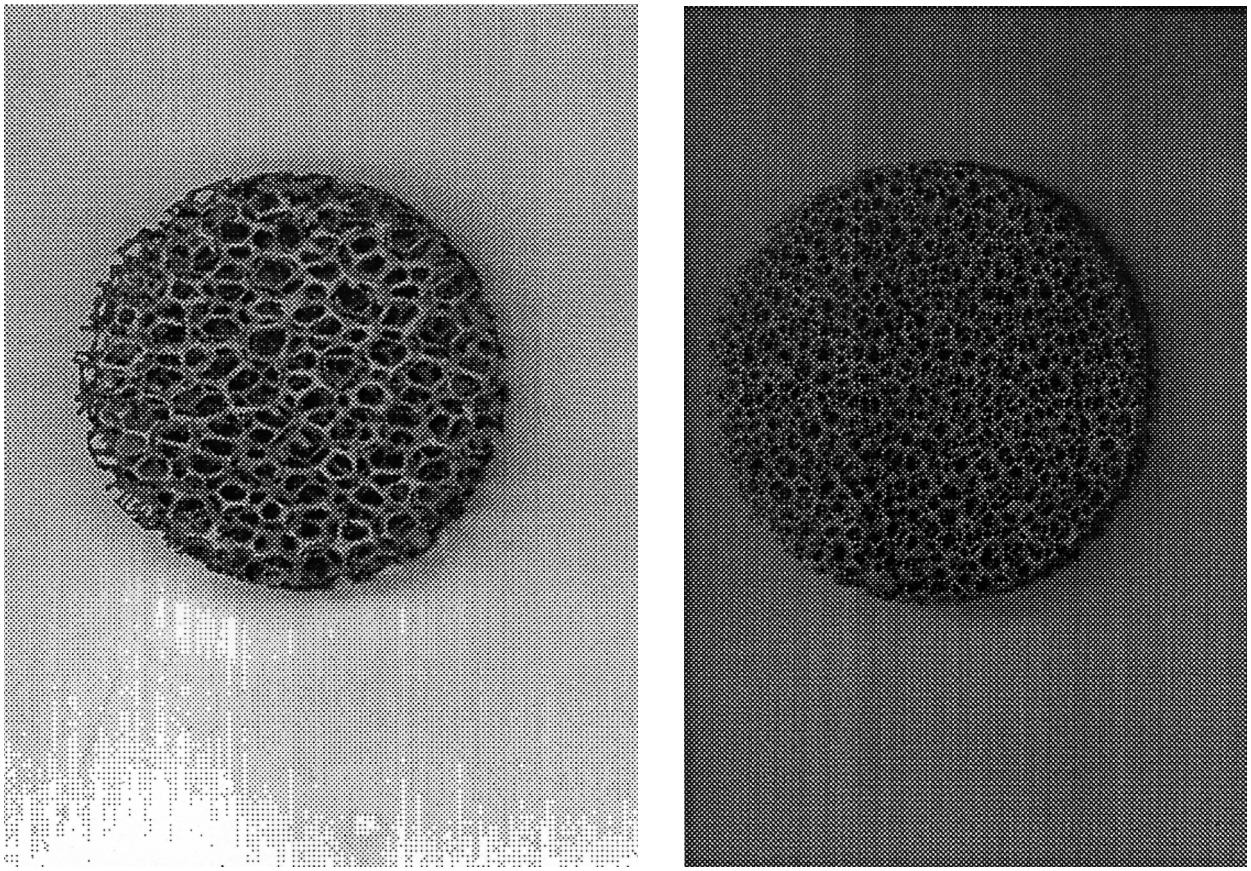
Element	Co	Cr	Mo	W	Fe	Nb	Ta	Al	Ti	Mn	Si	C	B	Zr	Ni
Alloy10	15	11	2.5	5.7		1.8	0.9	3.8	3.8	– –	– –	0.04	0.03	0.10	Bal
Haynes 230	– –	22	1.3	14	1.2	– –	– –	0.4	– –	0.48	0.44	0.11	– –	– –	Bal

TABLE II.—FOAM PANELS FABRICATED IN MITAS STUDY.

Panel	Alloy	Target porosity, percent	Target cell size, pores/cm	Actual density, g/cc
1	Alloy 10	90	2	0.78
2	Alloy 10	90	8	0.81
3	Alloy 10	95	2	0.41
4	Alloy 10	95	8	0.44
5	Haynes 230	90	2	0.80
6	Haynes 230	90	8	0.79
7	Haynes 230	95	2	0.44
8	Haynes 230	95	8	0.46

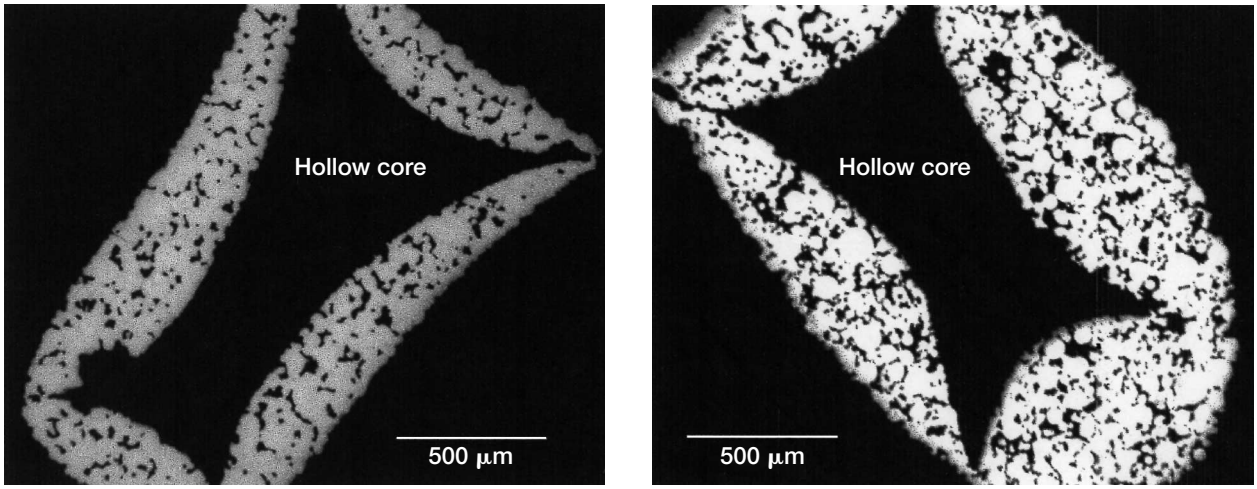
TABLE III.—CRUSH STRENGTH OF SUPERALLOY FOAM.

Alloy	Target porosity, percent	Target cell size, pores/cm	Hip	Strength
Haynes 230	95	8	NO	0.79
Haynes 230	95	8	NO	0.81
Haynes 230	95	8	NO	0.65
Haynes 230	95	8	YES	0.33
Haynes 230	95	8	YES	0.59
Haynes 230	95	8	YES	0.70
Alloy 10	95	8	NO	0.57
Alloy 10	95	8	NO	0.52
Alloy 10	95	8	NO	0.63
Alloy 10	95	2	NO	2.12
Alloy 10	95	2	NO	2.48
Alloy 10	95	2	NO	2.25
Alloy 10	95	2	YES	1.90
Alloy 10	95	2	YES	2.35
Alloy 10	95	2	YES	2.35
Haynes 230	95	2	NO	0.67
Haynes 230	95	2	NO	0.66
Haynes 230	95	2	NO	0.70
Haynes 230	95	2	NO	0.77
Haynes 230	90	2	NO	0.68
Haynes 230	90	2	NO	0.49
Haynes 230	90	2	NO	0.88
Haynes 230	90	8	NO	0.88
Haynes 230	90	8	NO	1.01
Haynes 230	90	8	NO	1.01
Alloy 10	90	2	NO	2.81
Alloy 10	90	2	NO	3.68
Alloy 10	90	2	NO	3.61
Alloy 10	90	8	NO	1.40
Alloy 10	90	8	NO	1.48
Alloy 10	90	8	NO	1.41



2 pores/cm 8 pores/cm

Figure 1.—Macrostructure of superalloy foam.



Macroporosity level: 95%
Microporosity: 7%

Macroporosity level: 90%
Microporosity: 11%

Figure 2.—Microstructural characterization of superalloy foams showing cross-section of a single ligament.

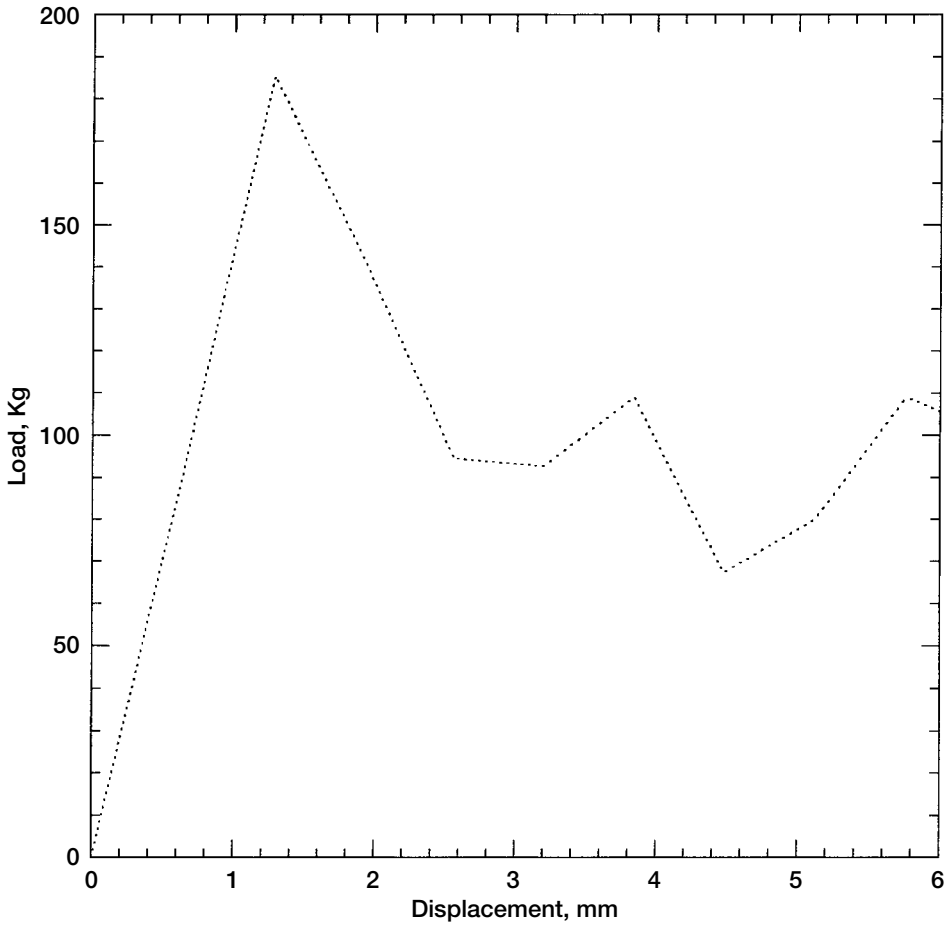


Figure 3.—Typical load-displacement curve.

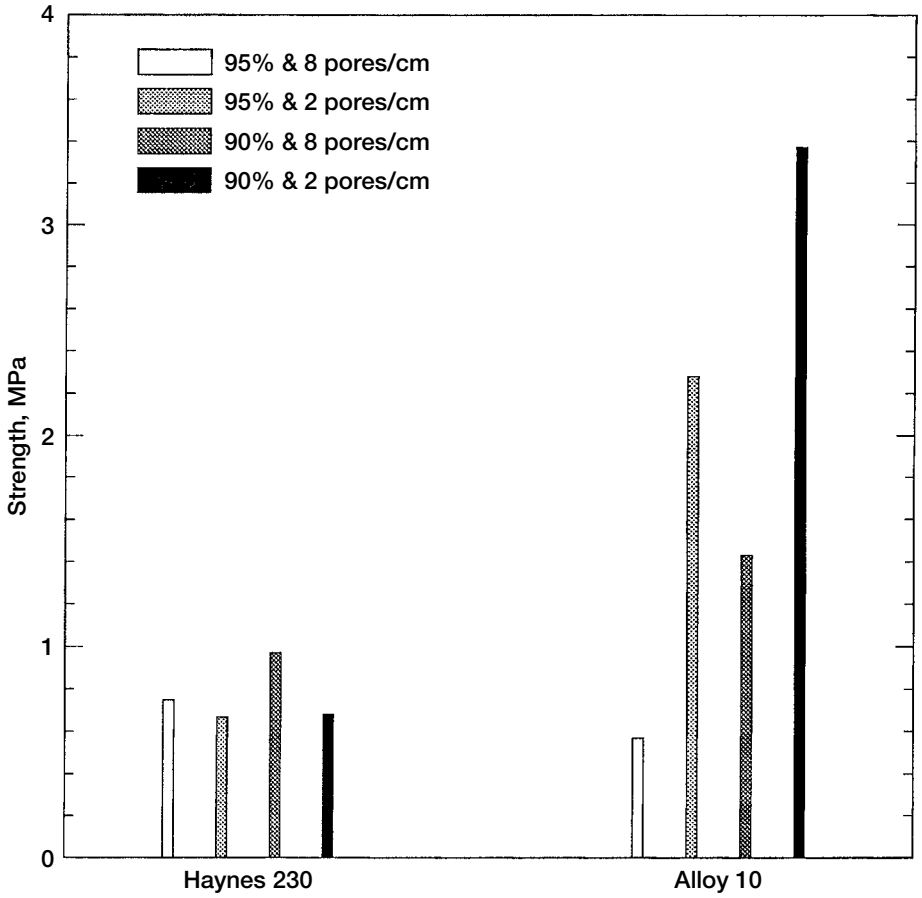


Figure 4.—Average room temperature crush strength of non-HIP foam panels.

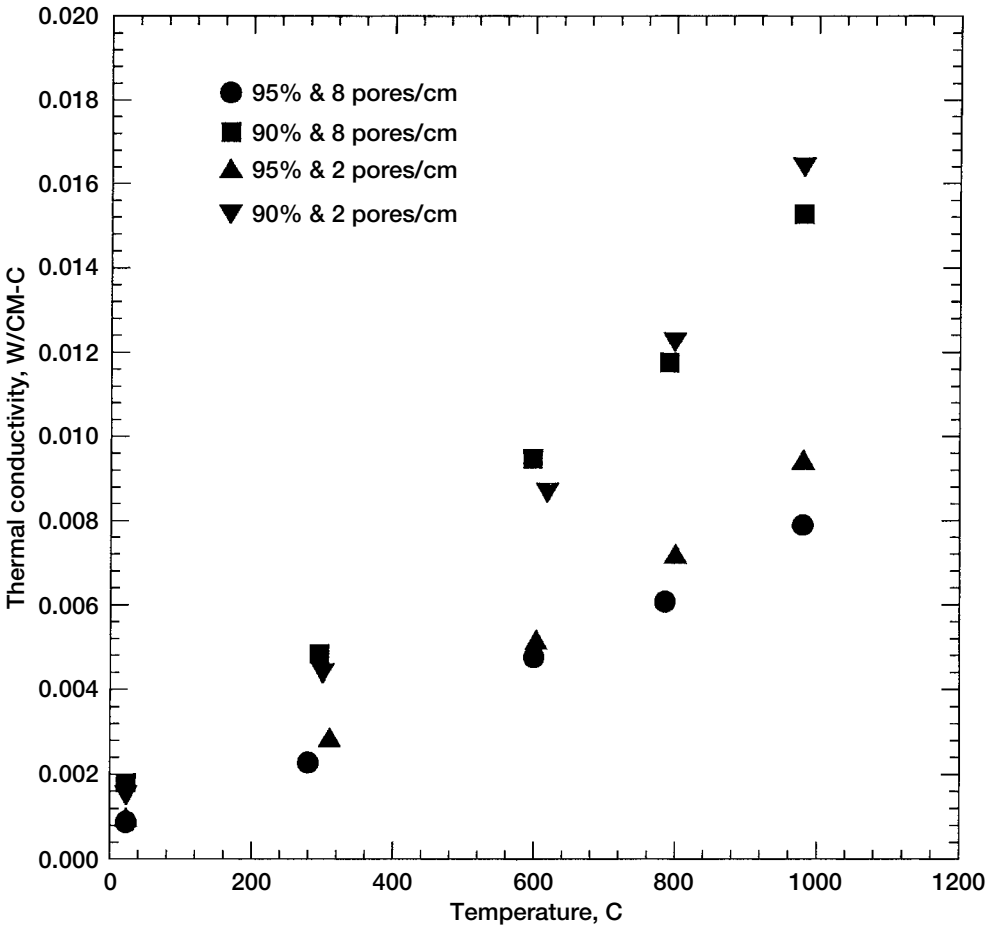


Figure 5.—Thermal conductivity of alloy 10 foams.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 2001	Technical Memorandum

4. TITLE AND SUBTITLE

Superalloy Foams for Aeroshell Applications

5. FUNDING NUMBERS

WU–706–85–33–00

6. AUTHOR(S)

John Gayda and Santo Padula II

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13103

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2001-211305

11. SUPPLEMENTARY NOTES

Responsible person, John Gayda, organization code 5120, 216–433–3273.

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Unclassified - Unlimited
Subject Category: 26 Distribution: Nonstandard

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12b. DISTRIBUTION CODE

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14. SUBJECT TERMS	15. NUMBER OF PAGES
Superalloy foam	13
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	