NASA/TM—2004-213109

Superalloy Lattice Block Structures

M.V. Nathal and J.D. Whittenberger
Glenn Research Center, Cleveland, Ohio

M.G. Hebsur and P.T. Kantzos
Ohio Aerospace Institute, Brook Park, Ohio

D.L. Krause
Glenn Research Center, Cleveland, Ohio

June 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-213109

Superalloy Lattice Block Structures

M.V. Nathal and J.D. Whittenberger
Glenn Research Center, Cleveland, Ohio

M.G. Hebsur and P.T. Kantzos
Ohio Aerospace Institute, Brook Park, Ohio

D.L. Krause
Glenn Research Center, Cleveland, Ohio

Prepared for the
10th International Symposium on Superalloys
cosponsored by the Seven Springs International Symposium Committee,
the Minerals, Metals, and Materials Society (TMS), the TMS High Temperature
Alloys Committee, and ASM International
Champion, Pennsylvania, September 19–23, 2004

National Aeronautics and
Space Administration

Glenn Research Center

June 2004

This report is a preprint of a paper intended for presentation at a conference. Because of changes that may be made before formal publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Superalloy Lattice Block Structures

M.V. Nathal and J.D. Whittenberger
National Aeronautics and Space Administration
Glenn Research Center
Cleveland Ohio 44135

M.G. Hebsur* and P.T. Kantzos*
Ohio Aerospace Institute
Brook Park, Ohio 44142

D.L. Krause
National Aeronautics and Space Administration
Glenn Research Center
Cleveland Ohio 44135

Abstract

Initial investigations of investment cast superalloy lattice block suggest that this technology will yield a low cost approach to utilize the high temperature strength and environmental resistance of superalloys in lightweight, damage tolerant structural configurations. Work to date has demonstrated that relatively large superalloy lattice block panels can be successfully investment cast from both IN-718 and Mar-M247. These castings exhibited mechanical properties consistent with the strength of the same superalloys measured from more conventional castings. The lattice block structure also accommodates significant deformation without failure, and is defect tolerant in fatigue. The potential of lattice block structures opens new opportunities for the use of superalloys in future generations of aircraft applications that demand strength and environmental resistance at elevated temperatures along with low weight.

Introduction

The development of advanced aerospace vehicles is reliant on strong, lightweight structures capable of withstanding high temperature, oxidative environments. Because of this interest, considerable effort has been expended on the study of lightweight "alternative materials" to superalloys, such as ceramics, intermetallics and metal matrix composites. For example, the intermetallic TiAl is a promising candidate for intermediate temperature applications (~750 °C), and the strength levels of the newest generation of TiAl alloys (ref. 1) are approaching 1000 MPa at a density of about half of that of common superalloys. Clearly on the basis of strength/density, the newer TiAl materials are very attractive. However, superalloy lattice block structures can provide lightweight high temperature structures with the damage tolerance and moderate cost inherent in superalloys which have a long history of use in aerospace applications.

In their simplest form, lattice block panels are produced by casting and result in lightweight, fully triangulated truss-like configurations that provide strength and stiffness (refs. 2 to 4). Figure 1(a) illustrates the ligaments in an idealized open lattice block cell which can be repeated in the "x" and "y" directions to form thin panels, and when stacked in the "z" direction, will produce three dimensional structures. Figure 1(b) is a photograph of an investment cast, relatively large open cell IN-718 superalloy lattice block panel comprised of repetitions of the cell in figure 1(a). This panel contains about 2250 ligaments approximately 1.6 mm in diameter and about 11 mm in length and has a density of ~1.2 g/cm^3 that corresponds to about 15 percent of the density of IN-718. Other simple lattice block architectures are possible, and these include thin face sheet(s) on the exterior

* NASA Resident Research Associate at Glenn Research Center.

surface(s) such as that in figures 1(c) and (d) cast from Mar-M247 with a density of about 1.9 g/cm^3 (~22 percent of Mar-M247). While the exterior surface of face sheeted lattice block is smooth, figure 1(c), the interior surface possesses half diameter ligament outlines and nodes, figure 1(d), which were used to complete the network structure defined by figure 1(a).

The earliest realizations of lattice block were made from aluminum and steels (ref. 5), primarily under funding from the U.S. Navy (refs. 6 and 7). Theoretical studies have shown that the mechanical efficiency (specific stiffness) of lattice block structures approach that of honeycomb structures (refs. 3 and 4). Further modeling (ref. 8) has indicated that the fully triangulated lattice block panels, as shown in figure 1(b), can be extremely defect tolerant, where it was predicted that a random removal of 10 percent of the ligaments would result in only ~20 percent reductions in stiffness, and yield and peak strengths. A similar removal of 10 percent of the load bearing elements from a honeycomb panel would reduce the strength and modulus by ~65 percent (refs. 8 and 9).

The lattice block produced by the investment casting route can provide a large advantage in cost and temperature capability over honeycomb panels which are limited to alloys that can be processed into foils. Furthermore, investment casting allows complex shaped (curves, twists, etc.) lattice block to be directly fabricated as long as the design is within the limitations of the wax pattern, shell mold and casting technology. Additionally, the openness of the superalloy lattice block structure would permit secondary use applications such as channels for fluid flow/cooling air or locations for additional thermal/sound insulation.

Based on the above efforts, a program was initiated to determine the feasibility of producing simple superalloy lattice block panels (ref. 10). The objective of this work was to provide an alternative to intermetallics and composites in achieving lightweight, high temperature structures without sacrificing the damage tolerance and moderate cost inherent in superalloys.

Experimental Procedures

To establish the feasibility of the superalloy lattice block concept, work was performed in conjunction with JAMCORP,[†] Inc. Billerica, MA, to produce a number of lattice block panels by investment casting in both the open configuration (figure 1(b)) and with an integral face sheet cast on one side (figures 1(c) and (d)). JAMCORP developed the tooling to produce the wax patterns (ref. 11) which were utilized by outside vendors to fabricate shell molds that were used for casting the lattice block panels. These were forwarded to NASA Glenn Research Center for Hot Isostatic Pressing (HIP), heat treatment and testing. To represent common cast superalloys with different degrees of castability and temperature capability, both IN-718 and Mar-M247 lattice block panels were produced. Mechanical testing primarily consisted of compression and bend testing of subelements machined in different orientations from the panels (ref. 12). In addition, conventional uniaxial tension tests of individual ligaments and samples machined from the face sheets were performed.

Results and Discussion

Casting Quality

As JAMCORP's business model only permitted purchase requests for finished superalloy lattice block panels by NASA, a number of different casting houses were utilized by JAMCORP to produce panels. This approach meant that different shell mold practices, gating configurations and pouring conditions were employed every time the casting vendor was changed. While these disruptions required a new learning curve at each vendor, eventually all were able to produce lattice block panels which were visually acceptable. In general, early casting trials at each vendor resulted in numerous casting defects such as incomplete mold fill, partially filled ligaments and nodes, porosity, and hot tears; although eventually castings of the quality shown in figures 1(b) through (d) were produced. Overall the IN-718 lattice block castings were of higher quality than the Mar-M247 panels, which was a function of both the castability differences of the two alloys plus the greater number of casting trials performed with IN-718.

Metallographic investigations of samples taken from the lattice block panels indicated that shrinkage

[†] JAMCORP's lattice block technology has been recently acquired by Federal Technology Group, Inc., 235 S. Enterprise Boulevard, Bozeman, MT 59718-6062; http://www.fedtechgroup.com

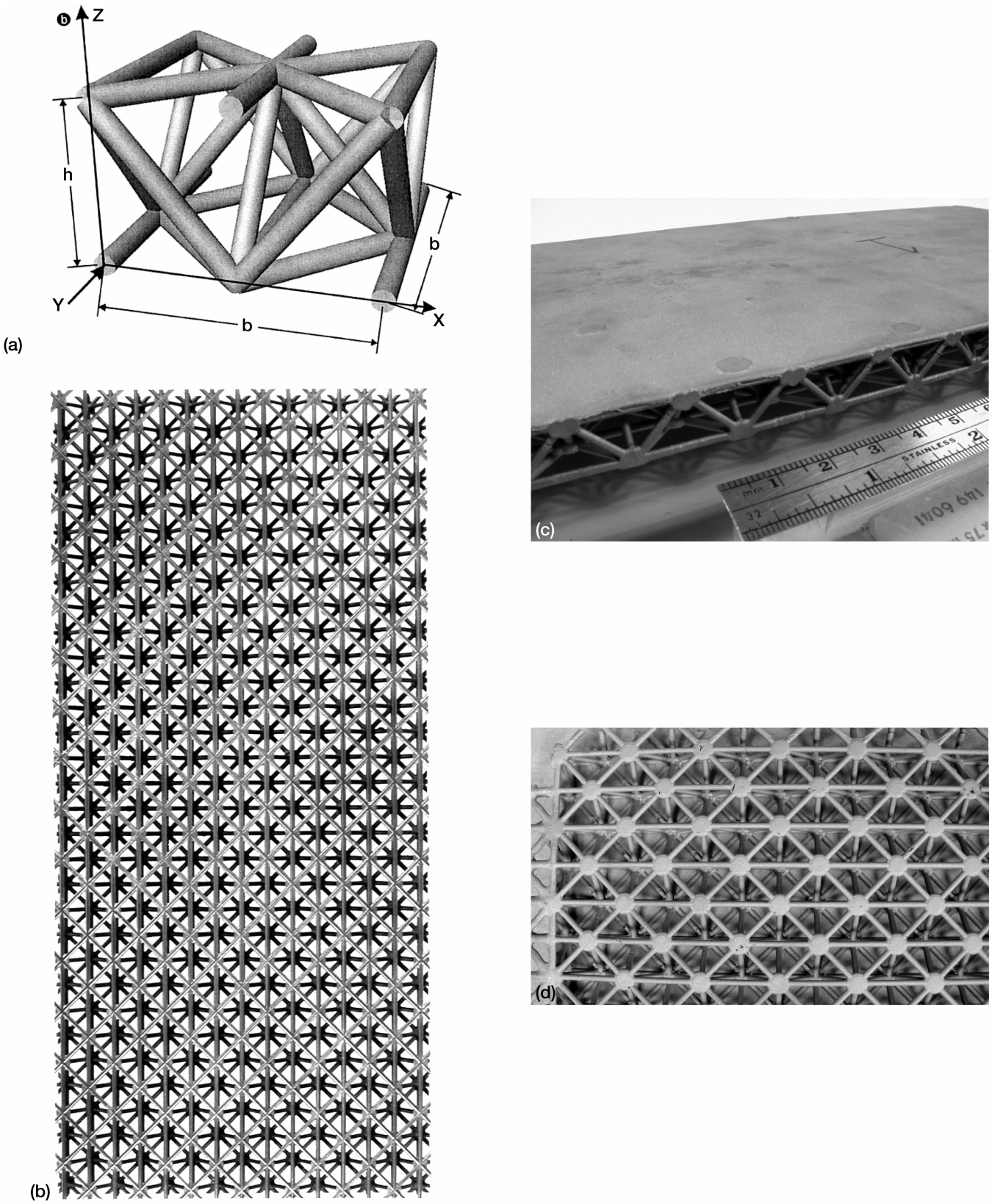

Figure 1.—An idealized cell (a) for constructing open cell triangulated lattice block [2], (b) an open cell IN-718 lattice block panel 130 mm by 290 mm by 11 mm thick and (c) face sheet side and (d) open mesh side views of a corner section of a 130 mm by 290 mm by 11 mm Mar-M247 lattice block panel with a ~1.2 mm thick face sheet on one side.

porosity and other casting defects were still prevalent, even in the best castings, indicating that further process development is required. Figure 2 illustrates some of the typical defects remaining after the HIP/heat treatment cycles that were observed in different geometric parts of the superalloy lattice block panels.

The amount of porosity in representative sections from selected lattice block panels was estimated by quantifying the percentage of cross sections exhibiting at least one pore. In order to quantify the "Percent Defective Elements" in the lattice block, the following criteria were used during metallographic examination: 1. for ligament cross sections and nodes, the percentage of sections/nodes with at least one pore was used; and 2. for longitudinal ligament or face sheet sections, the linear fraction of regions containing defects was used. These measurements tend to be very conservative measures of the casting quality. For example, the small amount of porosity in figure 2(c) would nevertheless yield a measurement of 11 percent defective because the linear fraction measurement counts the entire face sheet thickness as defective.

The results of this investigation are given in table 1 for three different lots (casting vendors) of open cell and single face sheet superalloy lattice block.

Table I.—Occurrence of one or more casting defects in as-polished sections of superalloy lattice block

Lot	Alloy	Condition	Type	Percent Defective Elements			
				Face Sheet	Long. Lig.	Trans. Lig.	Node
1	718	HIP[1]	Open	--[4]	--	22	--
3	718	HIP[1]	Open	--	13	7	47
3	718	HIP[1]	Face	6	4	9	47
3	247	HIP[2]	Open	--	17	7	67
3	247	HIP[2]	Face	4	11	6	14
5	718	S. HIP[3]	Open	--	--	83	83
5	718	S. HIP[3]	Face	17	15	93	83

[1] HIP'ed at 1120 °C at 103.4 MPa for 4h followed by a heat treatment per AMS 5383: 1010 °C/Ar quench; age at 718 °C for 8 h; furnace cool to 620 °C, hold for 10 h, AC.
[2] HIP'ed at 1090 °C, 172.4 MPa for 4 h followed by heat treatment at 1190 °C/ AC and 871 °C for 20 h/AC.
[3] Simulated HIP; Same temperatures, time periods as [1] but without any pressure.
[4] Not measured.

Only ligament cross sections were studied for Lot 1 panels and about 22 percent were found to have one or more defects. Considering both alloy compositions and types of lattice block material, in general, the integrity

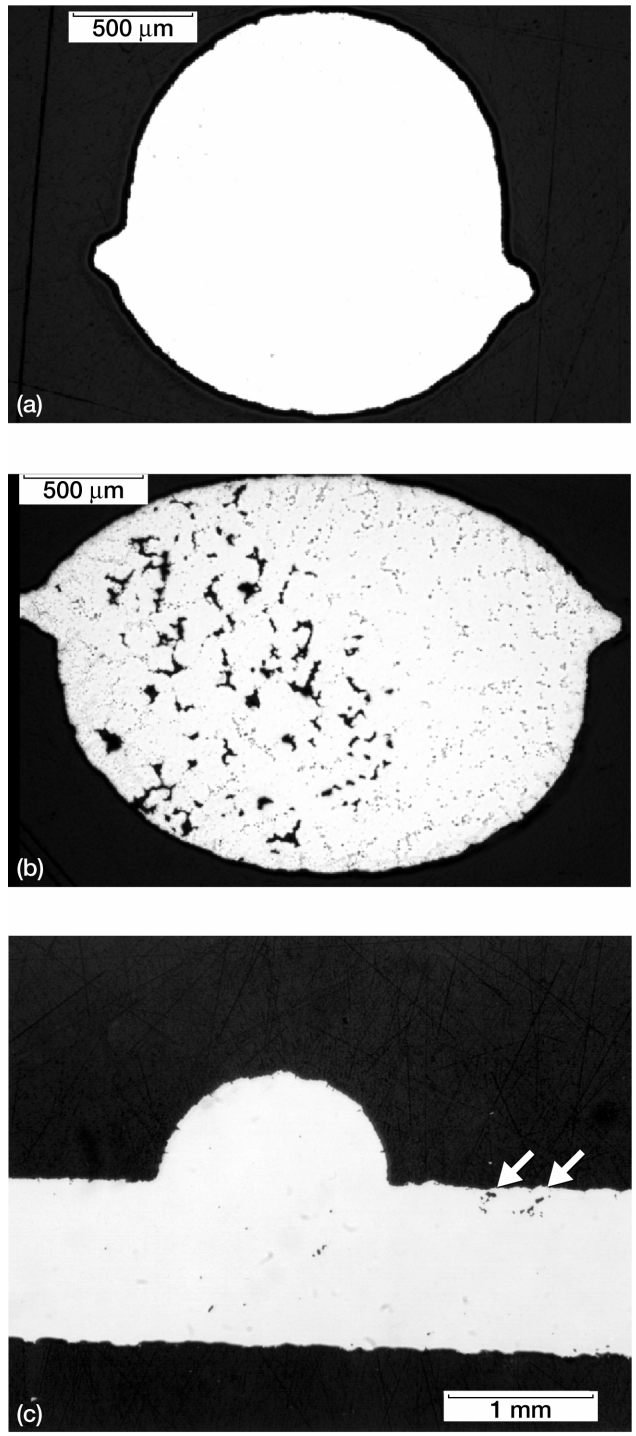

Figure 2.—Typical unetched metallographic sections illustrating portions of the superalloy lattice block geometry. (a) Defect-free IN-718 ligament cross section. (b) Porosity in IN-718 ligament cross section. (c) Minor porosity (at arrows) in Mar-M247 section containing the intersection of a ligament with face sheet.

of the face sheet was much better than that for the longitudinal ligament sections in either face sheeted or open cell lattice block panels from Lot 3. While less than 10 percent of transverse ligament cross sections for Lot 3 were defective, nearly half of the Lot 3 ligament nodes were faulted. In comparison almost all of the ligament nodes and ligament cross sections in Lot 5 were found to have one of more pores, and the face sheets for Lot 5 contain a much larger amount of defective region than those for Lot 3. It is possible that these very high percentages in Lot 5 are due to a difference in thermomechanical processing, as the simulated HIP cycle given to Lot 5 could not heal internal porosity; however this must be considered conjecture until a panel of Lot 5 is examined in the HIP'ed condition.

Nondestructive evaluation techniques would be of great utility in determining the quality of these complex structures. Preliminary examinations with X-ray, pulse echo ultrasound, and thermal imaging techniques were all used to detect inhomogeneities in the lattice structure. The techniques were effective in detecting flaws, especially when multiple techniques were used in combination. Figure 3 shows an example of an X-ray image showing an area with broken ligaments.

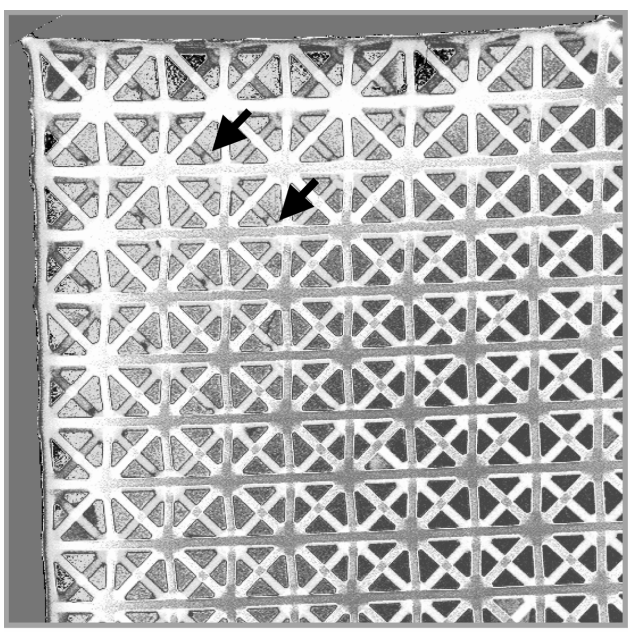

Figure 3.—X-ray evaluation on the superalloy lattice blocks revealing cracked ligaments (arrows).

Mechanical Behavior of Lattice Block Elements

The presence of casting defects was evident in the tensile behavior of individual ligaments machined from the first lot of HIP/heat treated open IN-718 cell panels (ref. 12). The ligaments exhibited strength values expected from conventional casting, but the ductility values could be quite low, even zero. Tests as a function of ligament gage length showed that shorter lengths produced higher ductilities which suggests a volume effect where the longer lengths increased the probability of a casting defect causing premature failure. Another example of individual element testing is shown in figure 4, where pin and clevis tensile specimens were water-knife machined from face sheets of Lot 3 superalloy lattice block and tested in tension as a function of temperature. Photographs of a typical specimen layout and the back side of a specimen are shown in figures 4(a) and (b), respectively. Two tensile sample geometries {6.3 by 25.4 and 9.5 by 31.8 mm gage sections} were taken parallel to and perpendicular to the panel length (figure 4(a)) to maximize the number of coupons. Both sample geometries (figure 4(b)) contained partial ligament outlines and face nodes from the interior side of lattice block face sheet. All samples were tested in the condition shown by figure 4(b) with as-water-knife edges and the face ligaments/nodes intact. While the latter results in an irregular cross sectional area along the tensile gage section, it would be representative of the material under stress when a lattice block is loaded.

Tensile curves from single Mar-M247 tests at room temperature, 650 and 982 °C are given in figure 4(c), and multiple room temperature and 650 °C plots from IN-718 are presented in figure 4(d). In both figures 4(c) and (d) room temperature elongation was measured by a 12.7 mm extensometer attached to the gage section; and, due to the architecture of the interior side of the face sheet (figure 4(b)), the span of the extensometer included one or more partial ligaments crossing the gage width. Elevated temperature strain was estimated from load-crosshead motion plots with the assumption that all plastic deformation occurred over the entire length of the gage section which per figure 4(b) could include several face nodes as well as partial ligaments. All strength calculations utilized the cross sectional area of ligaments which were parallel to the specimen length (Fig 4. (b)); however contributions due to area of the nodes or partial ligaments which crossed the gage width were not included.

In general multiple samples were tested at each temperature utilizing both gage sizes and both orientations, but not all experiments failed within the gage section. A number of samples failed at pin holes or shoulder regions. In terms of tensile strength levels for Mar-M247 in figure 4(c), values which were reasonably consistent with the expectations for the cast and heat treated material (ref. 13) could be attained. The room temperature strength of IN-718 also met expectation (figure 4(d)), but the 650 °C values were low. All the 650 °C IN-718 tensile tests were accompanied by audible cracking and discontinuous load drops in the load-time curves which started during elastic deformation or immediately after yielding (the serrations from 650 °C testing have not been reproduced in figure 4(d)). The cause for the paradox in behavior between room temperature testing, where 3 out of 4 tests exhibited ductility values greater than 2 percent, and 650 °C testing of IN-718 is not known.

Irrespective of alloy or test temperature, the tensile ductilities of superalloy samples cut from lattice block face sheets were significantly less than the typical values for cast and heat treated alloys, ~8 percent (ref. 13). Certainly some of the low elongation values are due to existing casting defects in the microstructure (figure 2) and inhomogeneities in the local cross sectional area which would concentrate plastic flow into the thinner regions. In any case from the room temperature testing figures 4(c) and (d) it is clear that some tensile ductility can be expected in properly cast superalloy lattice block materials. Lastly with regard to tensile testing of the face sheet, no strong dependency of properties on sample orientation or gage size was found.

Other testing of ligaments machined from cast lattice block has also been undertaken; for example Zhou, et al. (ref. 14) recently conducted room temperature tensile testing of samples cut from the ligaments of a cast Al-6Mg-1Si (weight percent) alloy. Because the alloy chemistry did not correspond to any commercial composition, they were not able to make a direct comparison to baseline properties. However they demonstrated that the 0.2 percent yield stress was consistent and predictable and that low ultimate tensile strength values could be traced to casting flaws (i.e., large scale porosity).

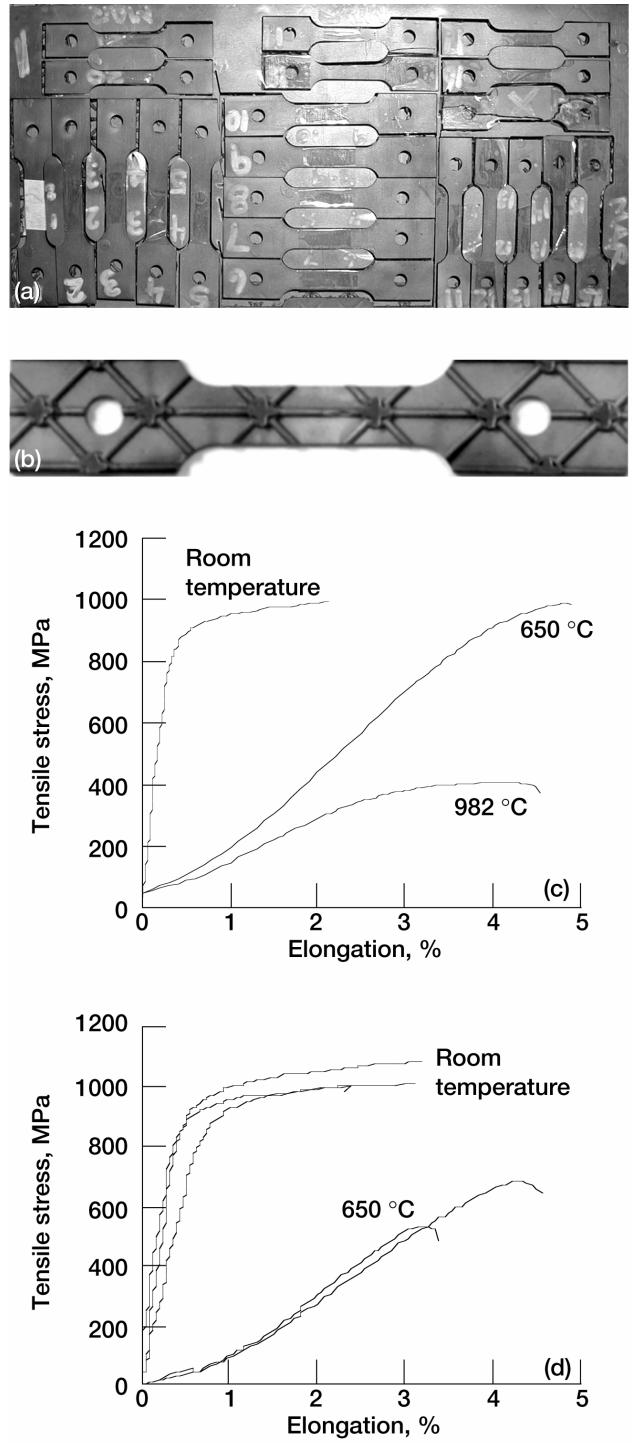

Figure 4.—(a) Layout of tensile samples taken from the ~1.2 thick mm face sheet of a MAR-M 247 lattice block panel 150 mm by 310 mm by 11 mm. (b) The back side of a Mar-M247 tensile specimen (9.5 mm gage width by 31.8 mm gage length) after the connecting lattice structure had been cut away. (c) Tensile results from room temperature, 650 °C and 982 °C testing of Mar-M247 specimens. (d) From room temperature and 650 °C of IN-718 specimens.

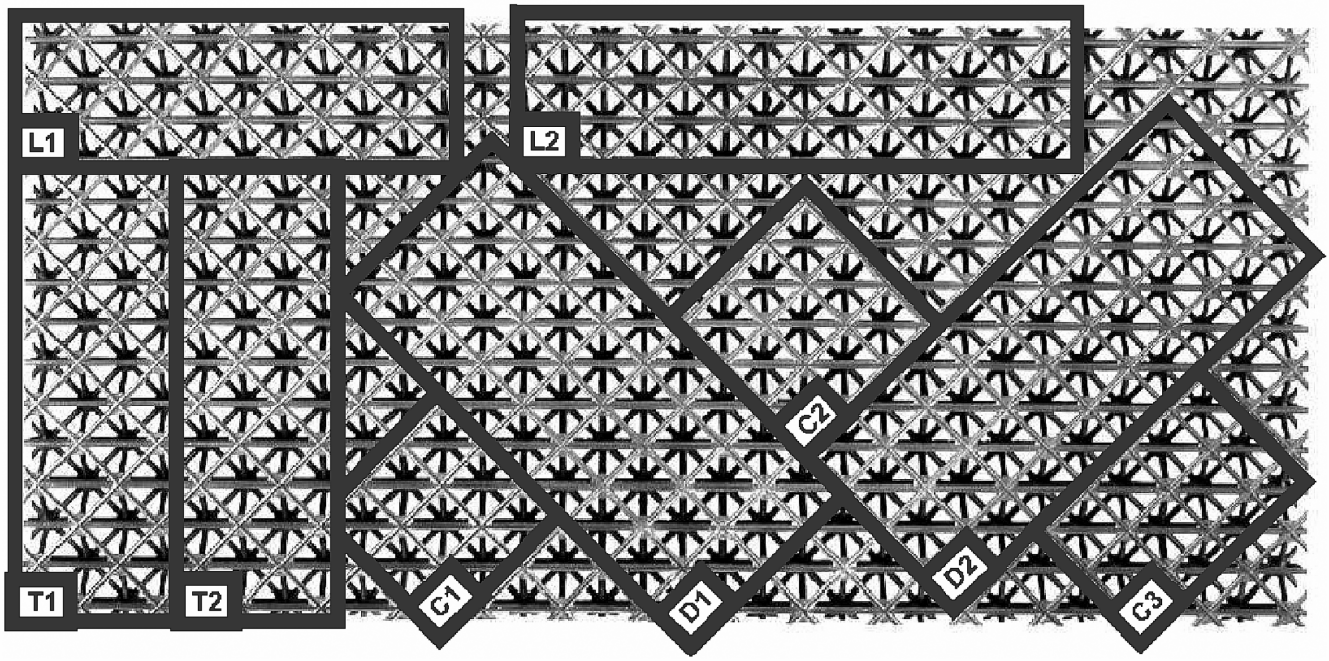

Figure 5.—Typical specimen layout for superalloy lattice block illustrating longitudinal (L), transverse (T), and diagonal (D) bend samples and compression (C) coupons.

Mechanical Behavior of Lattice Block

Bend testing at room temperature.—Longitudinal, transverse, and diagonal subelement samples were cut from lattice block panels and tested in both monotonic and fatigue bend modes (ref. 12). Figure 5 illustrates a typical specimen layout for open cell lattice block; a similar design was also used for face sheeted panels. Because the basic building unit of this lattice block architecture is not symmetric (figure 1(a)), strength was expected to be directional, as the three samples possess differing numbers and orientations of load bearing ligaments in the outer surfaces. Strength anisotropy was confirmed by room temperature experiments (figure 6(a)) on the first lot of open cell IN-718 lattice block panels {longitudinal and transverse samples were tested in 4 point bend while the diagonal specimens had to be tested in 3 point bending, (ref. 12)}, where these load-displacement curves have been normalized to indicate the capacity per unit of sample width. Even in its weakest direction this figure demonstrates that the current open cell IN-718 superalloy lattice block panels can support large loads. Linear-elastic beam-element finite element analysis of each specimen configuration was quantitatively consistent with the experimentally measured anisotropy. In addition, the finite element analysis produced stress levels in the individual ligaments that indicate that the IN-718 ligaments were exhibiting properties equivalent to a more conventional casting given a similar heat treatment.

Normalized load-deflection curves for three longitudinal specimens taken from a Lot 5 IN-718 open cell lattice block panel (density ≈ 1.1 g/cm^3 with ~1.5 mm diameter ligaments) given the simulated HIP cycle per table 1 are presented in figure 6(b). These particular tests did exhibit sharp load drops, indicating that individual ligaments had failed. While each event did lessen the ability of the lattice block sample to support additional load, such localized fractures are clearly not catastrophic for the structure as a whole. Comparison of the results for Lot 1 (figure 6(a)) and Lot 5 (figure 6(b)) longitudinal samples reveal that strengths of the lattice block from two different casting vendors are reproducible. This conclusion is remarkable, given the significantly higher level of defects in the Lot 5 castings.

The tests in figures 6(a) and (b) were stopped when the limits of the bend fixture were reached, not when the specimens completely fractured. The high degree of deformation experienced by the subelement samples is portrayed in figures 6(c) and (d), where the side view

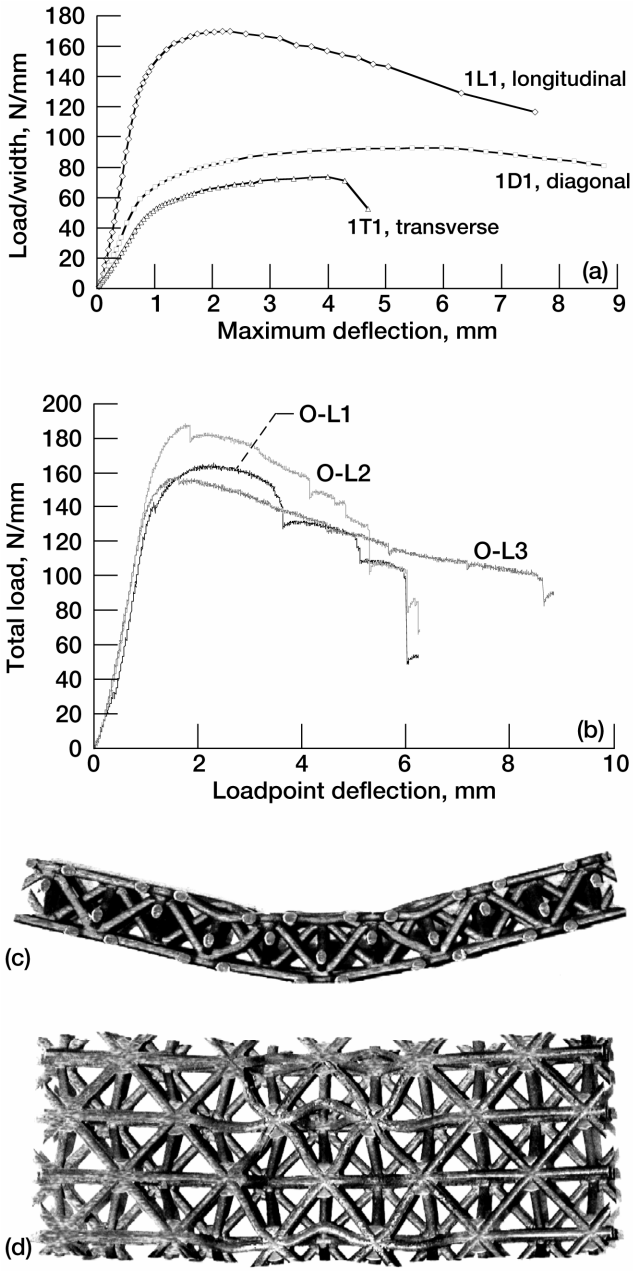

Figure 6.—(a) Load-deflection behavior in room temperature bending of Lot 1 open cell IN-718 lattice block subelement longitudinal, transverse and diagonal samples. (b) Load-deflection curves from room temperature four point bend testing of three longitudinal Lot 5 open cell IN-718 lattice block subelement samples (outer and inner roller separations of 73.5 and 18.5 mm, respectively). Side (c) and (d) top views of longitudinal sample L1 from part (a) after four point bend testing (outer and inner roller separations of 75.1 and 18.7 mm, respectively).

shows the ~7 mm of permanent set and the top view illustrates the distortion without failure of individual ligaments. Based on the deflections reported in figures 6(a) and (b), deformation ranging from 40 to 80 percent of the panel thickness over short spans (~75 mm for longitudinal and transverse specimens; ~93 mm for diagonal samples) are easily possible which indicates that the truss configuration of the lattice block provides considerable damage tolerance. If an individual ligament or node starts to fail, the neighboring ligaments pick up the load and allow for continued deformation.

Room temperature bend testing of Lot 5 IN-718 lattice block panels cast with a face sheet has also been undertaken. In these panels the thickness of the face sheets was about 1 mm and the ligament diameter was ~1.5 mm which increased the density of the IN-718 panels to about 1.6 g/cm^3 or ~20 percent of solid IN-718.

Normalized load-deflection curves obtained from longitudinal subelement specimens are presented in figure 7(a), and they demonstrate that the maximum load carrying capability is significantly higher when the face sheet is in compression instead of tension. In fact comparison of the load-deflection curves for longitudinal specimens in figures 6(a) and (b) and 7(a) suggest superalloy lattice block with a face sheet in tension would not be any stronger than an open cell panel. This result was initially puzzling but is explained by detailed consideration of the potential failure modes. For this specimen/loading combination, the buckling strength of ligaments on the compressive side of the sample is less than the tensile strength of ligaments on the tensile side. By reinforcing the weaker side, the face sheet provides an advantage only when it is located on the compressive side. When the face sheet is placed on the tensile side, the weaker compressive side sees no benefit and fails in buckling at approximately the open cell level.

The load discontinuities in the load-deflection curves in figure 7(a) for the samples with the face sheet in compression are the result of local ligament failures. Based on the smooth load-deflection curve for sample L3, bending with the face sheet in tension did not produce any localized failure that resulted in any noticeable load drops. Instead as shown by the post-test photograph of the open cell side of sample L3 (figure 7(b)), the IN-718 ligaments underwent extensive deformation without fracturing.

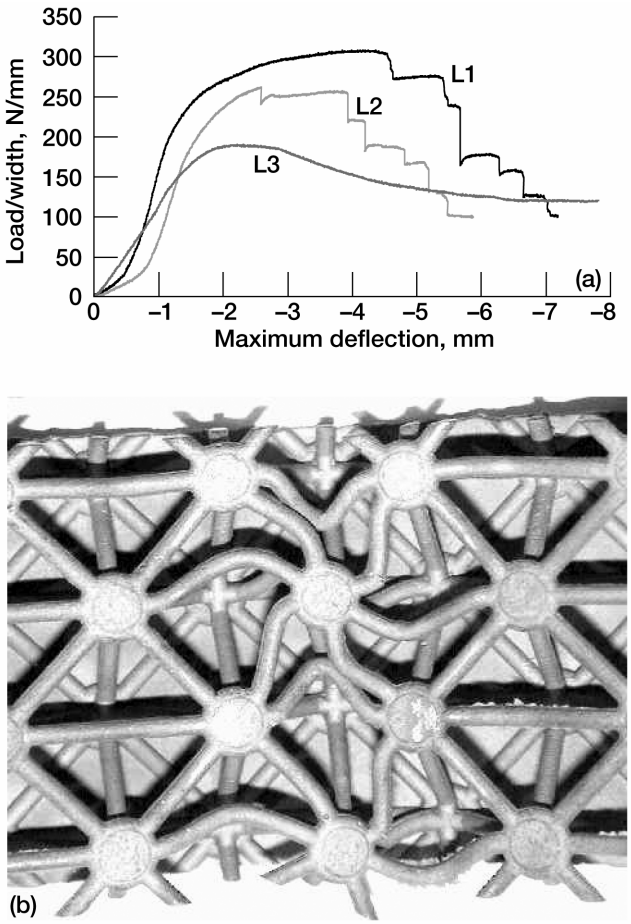

Figure 7.—Load-deflection curves (a) from four point room temperature bend testing (outer and inner roller separations of 73.5 and 18.5 mm, respectively) of Lot 5 longitudinal face sheeted IN-718 lattice block specimens where the face is in compression for samples L1 and L2 and in tension for L3 and a photograph (b) of the open cell (compression) side of sample L3 after bending.

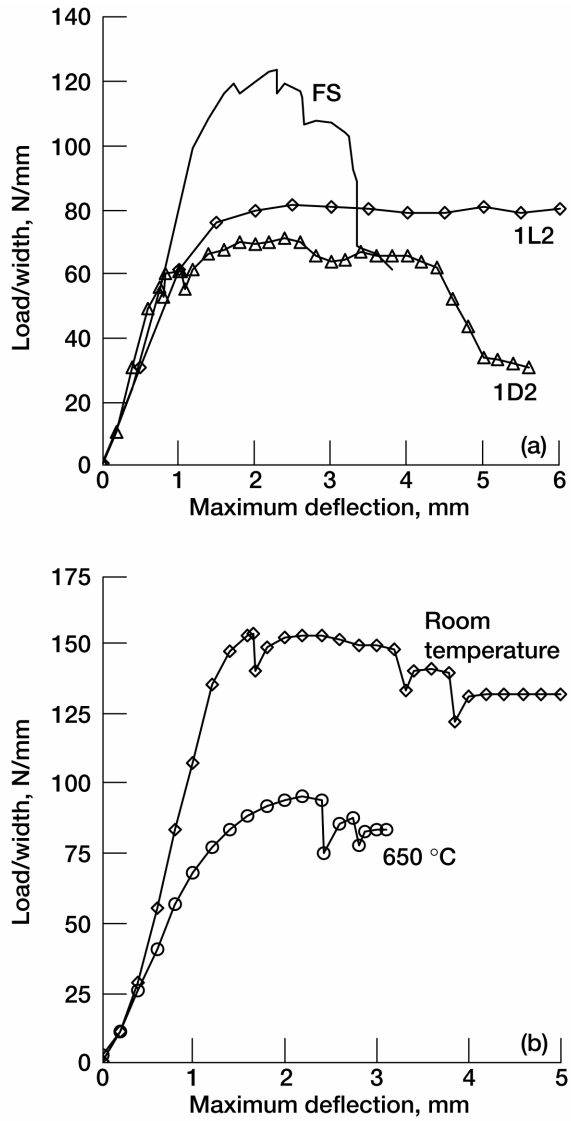

Figure 8.—Load-deflection curves (a) from 650 °C bend testing of a Lot 3 longitudinal face sheeted (FS) sample and Lot 1 open cell (1L2) and diagonal (1D2) specimens machined from IN-718 lattice block panels, where the face is in compression; Load-displacement plots (b) for Lot 3 longitudinal open cell Mar-M247 subelement samples tested at room temperature and 650 °C.

Bend testing at 650 °C.—A few bend tests were performed at 650 °C, which represents the limit of the available fixtures and furnace. The load-deflection plots in figure 8(a) illustrate the behavior of both face sheeted and open cell IN-718 specimens during 650 °C bending, and they demonstrate that strength can be maintained in superalloy lattice block panels at elevated temperature. The ordering of the data agrees with the expectations from room temperature testing (figures 6(a), 7(a)) where the longitudinal specimen with the face sheet in compression is stronger than the longitudinal open cell sample which, in turn, is stronger than the open cell diagonal specimen.

Only a few bend tests have been undertaken on Mar-M247 lattice block to date, and a load-deflection curve for a 650 °C test of a longitudinal specimen machined from a Lot 3 open cell lattice block (density = 1.2 g/cm^3, ligament diameter = 1.5 mm) is shown in figure 8(b). For comparison this figure also has the results from a room temperature bend test of a longitudinal sample. Additional samples were tested under both conditions, but premature failures were encountered due to casting faults. In spite of this difficulty, it is clear from figure 8(b) that Mar-M247

lattice block panels can be produced with acceptable strength properties. The strength levels of the IN-718 and Mar-M247 lattice blocks are comparable at 650 °C, which again is the expected result from handbook data on these alloys. However, Mar-M247 maintains useable strength levels to much higher temperatures, which should allow use of the lattice block concept at temperatures exceeding 1000 °C.

Bend fatigue testing at room temperature.—Bend fatigue studies of IN-718 were conducted on Lot 1 subelement samples (ref. 12) using step tests, where blocks of 0.25 x 10^6 cycles were applied, and if failure did not occur, the load was increased and another block of cycles was initiated. Figure 9(a) illustrates a diagonal specimen that failed at 160 k cycles at 50 percent of the peak monotonic tensile load, after surviving two prior testing blocks at 20 percent and 40 percent load levels. Detailed examination of the fracture surface of this sample lead to a recreation of the sequence of individual ligament failures. Measurement of the fatigue striation spacing on the fracture surfaces of individual failed ligaments figures 9(b) and (c) allowed the local crack growth rates to be estimated. Combined with the increased strain range measured throughout this load-controlled test, the sequence of ligament failures was recreated, figure 9(d). The first ligaments to fail will be determined by the localized stress, which is highest on the tensile surface of the bend specimen, and the presence of casting defects, and will have the finest striation spacing. Individual ligament failure is followed by load shedding to neighboring ligaments and continued fatigue life. This progression again shows that the lattice block geometry is damage tolerant, in contrast to a scenario where the first crack would lead to catastrophic immediate failure of the entire structure.

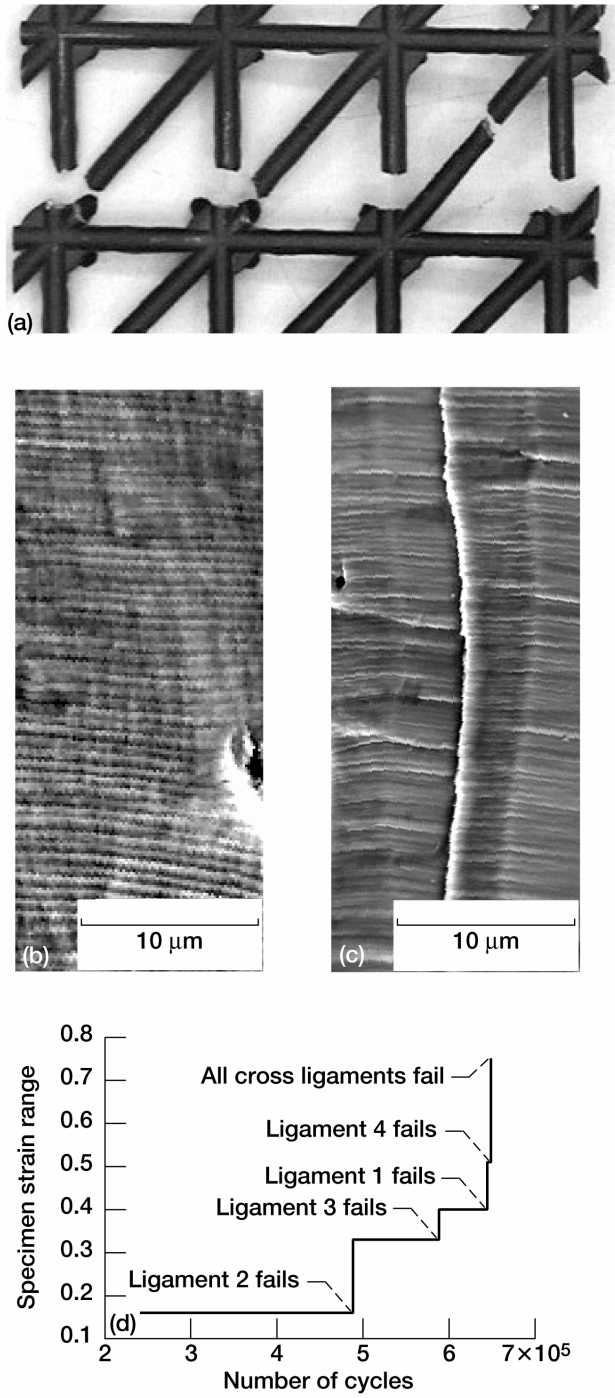

Figure 9.—Room temperature bend fatigue test results from the first lot of IN-718 superalloy lattice block. (a) Macrophotograph showing failed diagonal specimen. (b) Fatigue striations on the fracture surface of Ligament 2, which produced an estimated crack growth rate of 2.3×10^{-7} m/cycle. (c) Fatigue striations on the fracture surface of Ligament 1, which produced an estimated crack growth rate of 6.7×10^{-7} m/cycle. (d) Strain history and recreated failure sequence of ligament failures.

Aerospace Use of Lattice Block Materials

At the initiation of this work, superalloy lattice block was considered an attractive candidate for the large exhaust nozzle structures needed to reduce noise in advanced supersonic transports. Other static parts such as compressor and turbine cases also appeared to be suitable. A recent study by Ott (ref. 15) examined potential application of superalloy lattice block structures in advanced and current gas turbine engines. His assessment indicated that there existed several

components which could significantly benefit by the incorporation of superalloy lattice block materials. However, in addition to development of an acceptable investment casting practice, the current modeling of how such complex panels would behave under multistress loading conditions is lacking. In particular factors leading to and control of truss buckling need to be characterized. Also modeling of the basic geometry of lattice block and its effects on density and mechanical properties is needed. Another difficulty which needs to be overcome is inspection of the cast lattice block panels for defects. Ott's (ref. 15), as well as, Lipetzky and Warren's (ref. 16) studies of nondestructive examination of lattice block noted significant limitations in our present ability to find casting porosity, unfilled regions, cracks, etc. in panels. While Wallach and Gibson's work (ref. 5) suggests that lattice block can be very defect tolerant, some limits on the types and density of flaws will eventually be defined; thus a means of detection must be established.

Summary

There are several aspects of lattice block technology that are still immature; in particular, further casting development is still required to improve the quality of the panels, and modeling efforts are required to define appropriate geometries that maximize the strength/weight characteristics and are compatible with investment casting. However, we feel that the feasibility of superalloy lattice block structures has been demonstrated. Relatively large superalloy lattice block panels have been successfully investment cast, to the level that reasonable mechanical performance has been measured. Second, the lattice block structure accommodates significant deformation without failure, and is defect tolerant in fatigue. The ability to cast high temperature superalloys, such as Mar-M247, demonstrates that light weight structures with temperature capability beyond any wrought alloy-based concept (i.e., honeycomb) can be fabricated. The potential of lattice block structures opens new opportunities for the use of superalloys in future generations of aircraft in applications that demand strength and environmental resistance at elevated temperatures along with low weight.

References

1. S.L. Draper, G. Das, I. Locci, J.D. Whittenberger, B.A. Lerch, and H. Kestler, Titanium Aluminides 2003 (eds. Y.W. Kim, H. Clemens, and A.H. Rosenberger) TMS, Warrendale, PA, 2003, pp. 295–304.
2. J.C. Wallach, L.J. Gibson, *Inter. J. Solids Structures*, 38, 2001, 7181–96.
3. A.G. Evans, J.W. Hutchison, N.A. Fleck, M.F. Ashby, and H.N.G. Wadley, *Prog. Mater. Sci* 46 (2001) 309–27.
4. A.G. Evans: MRS Bull. 26 #10 (2001) 790–97.
5. M.L. Renauld, A.F. Giamei, M.S. Thompson, and J. Priluck, Porous and Cellular Materials for Structural Applications (eds. D. S. Schwartz, D. S. Shih, A. G. Evans, and H. N. G. Wadley), Mater. Res. Soc. Proc., vol. 521, MRS, Pittsburgh, PA 1998, pp. 109–21.
6. Website: http://www.navsbir.brtrc.com/SucessStories/jamcorp_98141_onr.p3.html.
7. Website: http://www.dt.navy.mil/pao/excerts%20pages/2001/shipDoors4_01.html.
8. J.C. Wallach, L.J. Gibson, *Scripta Materialia*, 45, 2001, 639–644.
9. J.M. Albuquerque, M. Fatima Vaz, and M.A. Fortes, *Scripta Materialia*, 41, 1999, 167–174.
10. M.G. Hebsur, NASA Glenn Research Center, personal communication, 2000.
11. M.G. Hebsur, Processing and Properties of Lightweight Cellular Metals and Structures, (eds. Amit K. Ghosh, T.H. Sanders, and T.D. Claar) TMS, Warrendale, PA, 2002, pp. 85–96.
12. D.L. Krause, J.D. Whittenberger, P.T. Kantzos, and M.G. Hebsur, Processing and Properties of Lightweight Cellular Metals and Structures, (eds. Amit K. Ghosh, T.H. Sanders, and T.D. Claar) TMS, Warrendale, PA, 2002, pp. 233–242.
13. C.T. Sims, N.S. Stoloff, and W.C. Hagel, Superalloys II, John Wiley and Sons, New York, 1987, pp. 582–4.
14. J. Zhou, P. Shrotriya, and W.O. Soboyejo, *Mechanics of Materials*, 2004, in press.
15. Eric A. Ott, Superalloy Lattice Block, NASA/CR—2003-212719, November 2003.
16. K.G. Lipetzky and J.M. Warren, CP615, Review of Nondestructive Evaluation, vol. 21, (eds. D.O. Thompson and D.E. Chimenti) 2002 American Institute of Physics, pp. 1447–1454.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
June 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Superalloy Lattice Block Structures

5. FUNDING NUMBERS
WBS–22–714–04–06

6. AUTHOR(S)
M.V. Nathal, J.D. Whittenberger, M.G. Hebsur, P.T. Kantzos, and D.L. Krause

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–14448

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—2004-213109

11. SUPPLEMENTARY NOTES
Prepared for the 10th International Symposium on Superalloys cosponsored by the Seven Springs International Symposium Committee, the Minerals, Metals, and Materials Society (TMS), the TMS High Temperature Alloys Committee, and ASM International, Champion, Pennsylvania, September 19–23, 2004. M.V. Nathal, J.D. Whittenberger, and D.L. Krause, NASA Glenn Research Center; and M.G. Hebsur and P.T. Kantzos, Ohio Aerospace Institute, Brook Park, Ohio 44142 and NASA Resident Research Associate at Glenn Research Center. Responsible person, M.V. Nathal, organization code 5120, 216–433–9516.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 26 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

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

Initial investigations of investment cast superalloy lattice block suggest that this technology will yield a low cost approach to utilize the high temperature strength and environmental resistance of superalloys in lightweight, damage tolerant structural configurations. Work to date has demonstrated that relatively large superalloy lattice block panels can be successfully investment cast from both IN-718 and Mar-M247. These castings exhibited mechanical properties consistent with the strength of the same superalloys measured from more conventional castings. The lattice block structure also accommodates significant deformation without failure, and is defect tolerant in fatigue. The potential of lattice block structures opens new opportunities for the use of superalloys in future generations of aircraft applications that demand strength and environmental resistance at elevated temperatures along with low weight.

14. SUBJECT TERMS
Lattice block; Truss structures; Honeycomb; Casting; Superalloy

15. NUMBER OF PAGES
17

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	