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Background

The amplifier top plates are monolithic, cast aluminum structures from which the amplifier frame assembly units (FAUs), and the line-replaceable flash lamp units (LRUs) inside them, are hung on the support rails in the laser bays. When fully assembled, each plate must support a static weight of 10,600 or 16,000 pounds, depending upon whether two or three loaded FAUs are attached. The top plates are fabricated from "ALCA Plus™," a zinc-containing aluminum casting alloy[1] similar in composition to some standard alloys in the 7000-series. For electrical reasons, all of the plate with the exception of the support "ears," is encased in epoxy as shown in Figure 1. The nominal chemistry of the aluminum alloy is summarized in Table 1 and the nominal mechanical characteristics are summarized in Table 2. For comparison, wrought alloys of similar composition in the 7000-series have ultimate strengths of approximately 33-76 ksi and elongations of 11-17%, depending upon the temper[2].

Table 1: ALCA Plus™ Nominal Composition*

Element	Typical Composition (wt%)
Si	0.70
Fe	0.70
Cu	1.20
Mn	0.20
Mg	1.70
Cr	0.10
Zn	3.80
Al	Balance

*Material specification provided by the manufacturer

Table 2: ALCA Plus™ Nominal Mechanical Properties*

[1] Pechiney Cast Plate, 3200 Fruitland Avenue, Vernon, CA, 90058, www.castplate.com.
[2] The mechanical properties of 7000 series wrought aluminum alloys are controlled by precipitation and growth of $MgZn_2$ particles in the aluminum matrix using heat-treatments. Various heat-treatment "tempers" achieve different mechanical properties. Generally speaking, the 7000 series alloys are among the strongest of all aluminum alloys. See, for example, William F. Smith, *Structure and Properties of Engineering Alloys*, McGraw-Hill, New York, 1981, pp195-201.

Property	Minimum	Typical
Yield strength (ksi)	11	15
Ultimate strength (ksi)	19	26
Elongation in a 2" gauge: 0.25" to 1" thickness (%)	3	7
Elongation in a 2" gauge: >1" to 2"	1.5	5
Modulus (psi)	---	10.3×10^6
Specific gravity	---	2.80

*Material specification provided by the manufacturer

Measured Mechanical Properties

Tensile Properties:

A series of tensile and fracture specimens of ALCA Plus™ were cut from two sample plates taken from top plate castings[3]. The sample plates were designated Plates 1 and 3. A third sample plate, designated Plate 2, is discussed in Appendix 1. Thirteen samples with a 1" gauge length and 0.25" diameter (sample type "A") were prepared from Plate 1 in the "short transverse" direction, normal to the broad surface of the plate (through the thickness)[4]. Three samples with a 1" gauge length and 0.25" diameter were prepared from the same plate in the longitudinal direction (in the plane of the broad surface, parallel to the long dimension of the plate) for comparison to the short transverse direction. Three samples of 2" gauge length and 0.5" diameter (sample type "B"), also from Plate 1, were prepared in the longitudinal direction for comparison to the small gauge length samples oriented in the same direction. Six samples were prepared from Plate 3 in the "long transverse" direction, in the plane of the broad surface normal to the long dimension as illustrated in Figure 2. All samples were tested in tension at a fixed crosshead speed of 0.075 in/minute[5]. The results of the tests of each of these sets of samples are summarized in Tables 3[6], 4 and 5, and a typical flow curve is shown in Figure 3. From these results, the yield and modulus appear to be independent of sample orientation, but the material is weakest and the ductility (elongation) smallest in the "short-transverse" direction normal to the plane of the plate. In particular, comparison with Table 2, indicates that the smallest measured values of the ultimate strength and elongation in the short-transverse direction are less than the minimums specified by the manufacturer for specimens of this size. The flow curve in Figure 3 shows a clear yield and a small amount of work-hardening prior to failure which is typical for this material.

[3] Provided by Everson Electric.
[4] Details of the test samples and procedure are provided in memorandum ETR/WO #M0106812, "NIF-FAU Aluminum Base Properties" from A. Shields to W. H. Gourdin and P. Biltoft, September 4, 2001.
[5] This corresponds to strain rates of 8×10^{-4}/s for type A specimens and 6×10^{-4}/s for type B specimens. Like other fcc metals, aluminum is not very strain-rate sensitive, so the small difference between these values does not affect the interpretation of the results.
[6] Sample 10 in Table 3 broke during installation in the test machine.

Table 3: Measured Mechanical Properties of ALCA Plus™ sample Plate 1 in the short transverse direction

Specimen	Type	Orientation	Ultimate (ksi)	Yield (ksi)**	Elongation (%)*	Modulus (Msi)
1Y	A	Short-trans	18.9	13.2	---	9.5
2Y	A	Short-trans	20.1	13.2	2.7	9.7
3Y	A	Short-trans	17.5	13.3	2.5	9.7
4	A	Short-trans	21.3	13.1	3.4	9.4
5	A	Short-trans	21.2	13.2	2.8	9.5
6	A	Short-trans	20.5	13.2	2.9	9.6
7	A	Short-trans	20.7	13.1	2.7	9.6
8	A	Short-trans	19.4	13.1	2.3	9.5
9	A	Short-trans	19.0	13.0	2.6	9.9
11	A	Short-trans	18.8	13.2	---	9.6
12	A	Short-trans	19.7	13.1	2.2	9.8
13	A	Short-trans	22.7	13.4	2.9	10.3

*A dash indicates that the sample failed outside the gauge length.
**0.2% offset

Table 4: Measured mechanical properties of ALCA Plus™ sample Plate 1 in the longitudinal direction

Specimen	Type	Orientation	Ultimate (ksi)	Yield (ksi)**	Elongation (%)*	Modulus (Msi)
4Z	A	Longitudinal	22.9	13.3	4.6	9.8
5Z	A	Longitudinal	22.0	13.2	---	9.5
6Z	A	Longitudinal	21.8	13.3	4.5	9.7
7Z	B	Longitudinal	24.0	13.7	3.2	10.1
8Z	B	Longitudinal	22.1	13.2	3.5	9.6
9Z	B	Longitudinal	24.0	13.6	3.7	9.9

*A dash indicates that the sample failed outside the gauge length.
**0.2% offset

Table 5: Measured mechanical properties of ALCA Plus™ sample Plate 3 in the long transverse direction

Specimen	Type	Orientation	Ultimate (ksi)	Yield (ksi)**	Elongation (%)*	Modulus (Msi)
3-T1	A	Long-trans	23.9	12.9	4.6	9.9
3-T2	A	Long-trans	22.7	12.9	3.4	10.0

3-M1	A	Long-trans	19.7	12.6	---	9.6
3-M2	A	Long-trans	19.4	12.9	---	9.8
3-B1	A	Long-trans	23.9	13.0	3.7	10.0
3-B2	A	Long-trans	22.9	12.9	---	10.0

*A dash indicates that the sample failed outside the gauge length.
**0.2% offset

Fracture toughness.

The fracture toughness of the sample plate was determined using standard one inch-thick specimens[7] in various orientations[8]. The results of these measurements are summarized in Table B1 of Appendix 2. The lowest measured value, about 12 ksi$\sqrt{\text{in}}$, is lower by about a factor of two than typical values for 7000-series wrought aluminum[9]. At the lowest measured ultimate stress of 17.5 ksi (Table 3), this corresponds roughly to a critical flaw size of 3-7 mm[10]. However, because the number and size of existing flaws are statistical quantities, it is impossible to know with complete certainty what they will actually be in any given plate.

Fatigue behavior:

The numbers of constant amplitude cycles at a fixed stress amplitude required to fail samples of the ALCA Plus™ material are summarized in Tables 6 and 7 and Figure 4. Samples taken from the surface of the plate ("T") and middle ("M") of the plated were cycled between compression and tension states at a selected stress until the sample failed.

Table 6: Cycles to failure of samples of ALCA Plus™ taken from near the surface of plate 3

Sample	Stress (ksi)	Number of cycles to failure
T2	24	1
T7	22	55
T11	22	33
T1	20	3558
T5	20	17821
T8	18	12140
T4	18	56748
T3	16	144510

[7] ASTM Standard E399.
[8] ASTM Designation: E 1823-96, page 18.
[9] The fracture toughness of 7075 varies from 16 to 33 ksi$\sqrt{\text{in}}$ depending upon heat-treatment and orientation; typical values are 25-30 ksi$\sqrt{\text{in}}$.
[10] For a penny shaped flaw of extent 2a, $K_{IC} = \beta\sigma\sqrt{\pi a}$. For $\beta=1$ and $\sigma = 17.5$ksi, 2a = 0.3" = 7 mm. If $\beta=1.5$ and $\sigma = 17.5$ksi, 2a = 0.1" = 3.3mm.

T6	14	479679

Table 7: Cycles to failure of samples of ALCA Plus™ taken from near the middle of plate 3

Sample	Stress (ksi)	Number of cycles to failure
M4	19.4	1
M2	19	1
M3	22	22
M6	20	25
M10	20	168
M11	18	128
M8	18	30
M9	16	339
M7	14	2154

To simulate conditions comparable to those expected during an earthquake, a variable amplitude cyclical loading sequence was devised as follows. Finite element calculations[11] were used to estimate the cyclical loads produced by a design-basis earthquake at critical locations in the plate. From the measured load and strain data[12] for a full-sized plate shown in Figure 5, these loads were converted to equivalent strains. Using the stress-strain curve in Figure 3, these strains were then converted to material stresses and, using the fatigue sample cross section dimensions[13], to sample loads. For example, finite element calculations suggested that the maximum load experienced by the plate during the design basis earthquake was approximately 44,000 pounds, which corresponds to a strain of 0.0021 (Figure 5), equivalent to a sample stress of approximately 12,000 psi (Figure 3) and a sample load of 1920 pounds. The "dead" weight (gravitational) load of the plate is about 16,000 pounds, which corresponds to a sample load of about 800 pounds[14]. This was taken as the mean tensile load about which the actual stress oscillated during the tests. Two samples, T2a and B2a, both from near the surface where calculated stresses were greatest, were subjected to a loading schedule, shown in Figure 6, which is generally consistent with the pattern expected during a design basis earthquake. The test was conducted at a frequency of 1 Hz (200 cycles for a

[11] M. A. Gerhard, documented in a separate report.
[12] The strain was measured in many locations using film gauges. The strains used here are identified as "BLI Bottom Surface Microstrain: Microstrain between back left fourth and fifth holes from left" in a spreadsheet provided by Robert Sanchez.
[13] 0.625" x 0.25" (1.59cm x 0.64cm) = 0.16in^2 (1cm^2). The sample gauge length was 1.5" (3.81cm).
[14] The strain from Figure 5 is approximately 0.0005, so the sample stress (Figure 3) is about 5000 psi. The load is thus 5000psi x 0.16in^2 = 800 pounds.

total of 200 seconds) and the actual loads are summarized in Table 8[15]. Neither sample failed in the course of these 200-cycle variable amplitude tests. Afterward, however, the same samples were subjected to 5 loading cycles at each of several successively higher load levels[16], beginning with a load of about 1900 pounds, also summarized in Table 8. Buckling of the samples commenced on cycle 221 and the test was stopped at cycle 240 when the test machine reached its programmed limit. Near the end of the test, the maximum sample tensile load was 2634 pounds, which corresponds to a sample stress of 17ksi and an estimated plate load of approximately 76,000 pounds. Full-sized plates failed at loads of 76,000-77,000 pounds when tested under conditions consistent with the design basis earthquake[17], in excellent agreement with the value estimated from the fatigue testing.

Table 8: Load schedule for simulated seismic fatigue tests

Cycles	Mean Load (lb)	Amplitude (lb)	Maximum load (lb)	Minimum load (lb)
1-30	829	466	1295	363
31-50	833	728	1560	105
51-60	821	877	1697	-56
61-65	673	1115	1788	-442
66-70	628	1230	1857	-602
71-80	670	1120	1789	-450
81-100	772	928	1699	-156
101-140	833	728	1560	105
141-200	829	468	1295	359
201-205	630	1232	1861	-602
206-210	585	1420	2004	-835
211-215	536	1613	2149	-1077
216-220	293	1916	2209	-1623
221-225	336	2056	2392	-1720
226-230	124	2346	2470	-2222
231-235	6	2634	2640	-2628

Microstructure

An optical micrograph of a polished section through the fragment broken from the top plate, shown in Figure 7, clearly shows the presence of significant porosity (black areas) as well as intermetallic particles common in alloys of this composition. Measurement of

[15] The mean loads vary somewhat for part of the test because of a small amount of plastic flow in the specimen. The cross-sections at the conclusion of testing were 0.156in^2.
[16] Because of the manner in which the full-sized dynamic plate test was conducted at the Pacific Earthquake Engineering Research Center (University of California Richmond Field Station), the negative amplitude portion of the load cycle was gradually increased in these final tests.
[17] G. L. Fenves and D. Clyde, "Cyclic Testing of Amplifier System Top Plate," Pacific Earthquake Engineering Research (PEER) Center, University of California, Berkeley, April 22, 2002, NIF0082219.

the micrograph suggests that porosity in the material is approximately 1-2 vol%, and that the individual pores are roughly 100μm in size. Pore agglomerate features, however, appear to be as much as 0.5-1mm in extent. Scanning electron micrographs generally confirm this assessment (Figure 8). Figure 9 shows that the amount and size of porosity is less at the outside surfaces of the plate than the interior. A detailed analysis shows that the porosity near the plate surface is 1.6±0.4 vol% and in the interior (mid-thickness position) 2.2±0.5 vol%. The size distribution of the porosity in both locations is shown in Figure 10. Comparison of the two distributions shows that there are more fine and coarse pores in the interior than near the surface.

Discussion and assessment

The fine porosity throughout the ALCA Plus™ is a common feature of castings, and is the primary cause of its inherent weakness. The pore agglomerates serve to concentrate stress in the webs between them, and failure proceeds as ductile cracks form and propagate from agglomerate to agglomerate. The volume fraction and size of the porosity is greatest away from the edges of the plate, a characteristic typical of continuously- cast aluminum plate.

The mechanical measurements reflect the distribution of porosity in the plate. The ultimate stress and maximum elongation are least in the short transverse direction because the gauge length is entirely within the center of the plate where the volume fraction of porosity and the pore size are greatest. Similarly, the ultimate stresses, elongations and fatigue resistance in the long-transverse direction, are greatest near the surface, where the porosity is least, and are least in the center of the plate where the amount of porosity is greatest. It is important to note that the yield stress, a material characteristic not strongly dependent on porosity, is very nearly constant at about 13 ksi independent of the sample location.

Because of its low ductility, ALCA Plus™ should be considered to be a brittle material for design purposes. Furthermore, with ultimate stresses of 17.5-19 ksi and maximum elongations of 2.3-2.6%, ALCA Plus™ is less capable in its weakest direction than the design material, which had an ultimate of 20 ksi and a maximum elongation of at least 4%[18]. However, in the most competent regions away from the center of the plate, the ultimate strengths exceed that of the design material and the elongations are slightly less, but comparable. Because of this variability, structural analyses that seek to characterize the behavior of the top-plates under extreme conditions should take into account the changes in materials properties as a function of position in the plate. The fatigue data also suggest that top plates made of ALCA Plus™ can withstand the dynamic loads that have been calculated to occur during a design basis earthquake, despite the inherent weakness of the material

Summary

[18] The original material selected in the design process was "MIC-6." ALCA Plus was substituted at some later date as a less costly, but equivalent, alternative. The design was not reanalyzed in view of the considerably lower *minimum* mechanical properties of ALCA Plus.

1. ALCA Plus™ continuously cast aluminum contains fine porosity which is concentrated in the center of the top-plates, away from outside surfaces.
2. The yield strength of ALCA Plus™ is approximately 13 ksi, independent of sample position.
3. ALCA Plus™ is least capable away from outside surfaces, where it has an ultimate strength of 17.5-20 ksi and a maximum elongation of 2.3-2.6%, and where the size and volume fraction of porosity are greatest.
4. ALCA Plus™ is most capable adjacent to outside surfaces, where it has an ultimate strength of 23-24 ksi and a maximum elongation of 3.8-4.6% and where the size and volume fraction of porosity are least.
5. For design purposes, ALCA Plus™ plate should be considered to be a brittle material. However, test data show that this material has substantial low-cycle fatigue resistance and suggest that it is capable of supporting the cyclical loadings sustained during a design basis earthquake.
6. Because of the variability in ultimate strength and elongation, structural analyses that seek to characterize the behavior of the top-plates under extreme conditions should take into account the differences in materials properties which occur as a function of position in the plate.

Appendix 1: Sample Plate 2.

A full-sized amplifier top plate, designated Plate 2, was subjected to a compressive failure test. Failure occurred in the vicinity of single support ear at a load of approximately 84,000 pounds. Six tensile samples of this plate were prepared after the failure test was complete. All of these samples were oriented in the long-transverse direction and were taken from locations away from the vicinity of the failures. As is indicated by the higher yield strength of these samples given in Table A1 (15.5 ksi) relative to the undeformed plate material (13 ksi), some amount of plastic flow occurred during the compression testing. As a result, these data are not considered representative of undeformed ALCA Plus™.

Table A1: Measured mechanical properties of sample Plate 2.

Specimen	Type	Orientation	Ultimate (ksi)	Yield (ksi)**	Elongation (%)*	Modulus (Msi)
1	A	Long-trans	25.2	15.5	2.9	9.9
2	A	Long-trans	25.0	15.6	2.5	10.0
3	A	Long-trans	25.1	15.5	2.9	9.6
4	A	Long-trans	24.5	15.6	2.5	10.1
5	A	Long-trans	25.0	15.5	2.8	9.9
6	A	Long-trans	25.2	15.4	2.8	9.8

Appendix 2:

The fracture toughness measurements summarized in Table B1 fail to meet criteria 9.1.2 and 9.1.3 specified in ASTM Standard E399 for a valid determination of K_{IC}, hence the interpretation of the results is uncertain. Nevertheless, we have assumed that the conditional results, K_Q, offer at least an approximate indication regarding flaw sizes.

Table B1: Fracture toughness data.

Sample	Orientation per ASTM E 1823	K_Q (ksi$\sqrt{in}$)	$(K_Q/\sigma_{YS})^2$ * σ_{YS} = 13 ksi	Fail E399 criterion
1	S-L	14.3	1.2	9.1.3
2	S-L	14.0	1.2	9.1.3
1T	S-T	14.0	1.2	9.1.3
2t	S-T	11.8	0.8	9.1.2**
1	L-S	14.5	1.2	9.1.3

*The 9.1.3 criterion for a valid test is $(K_Q/\sigma_{YS})^2 < 1.10$
**See ASTM E399 for explanation. Here P_{MAX}/P_Q =1.23. The test is valid when this ratio does not exceed 1.10

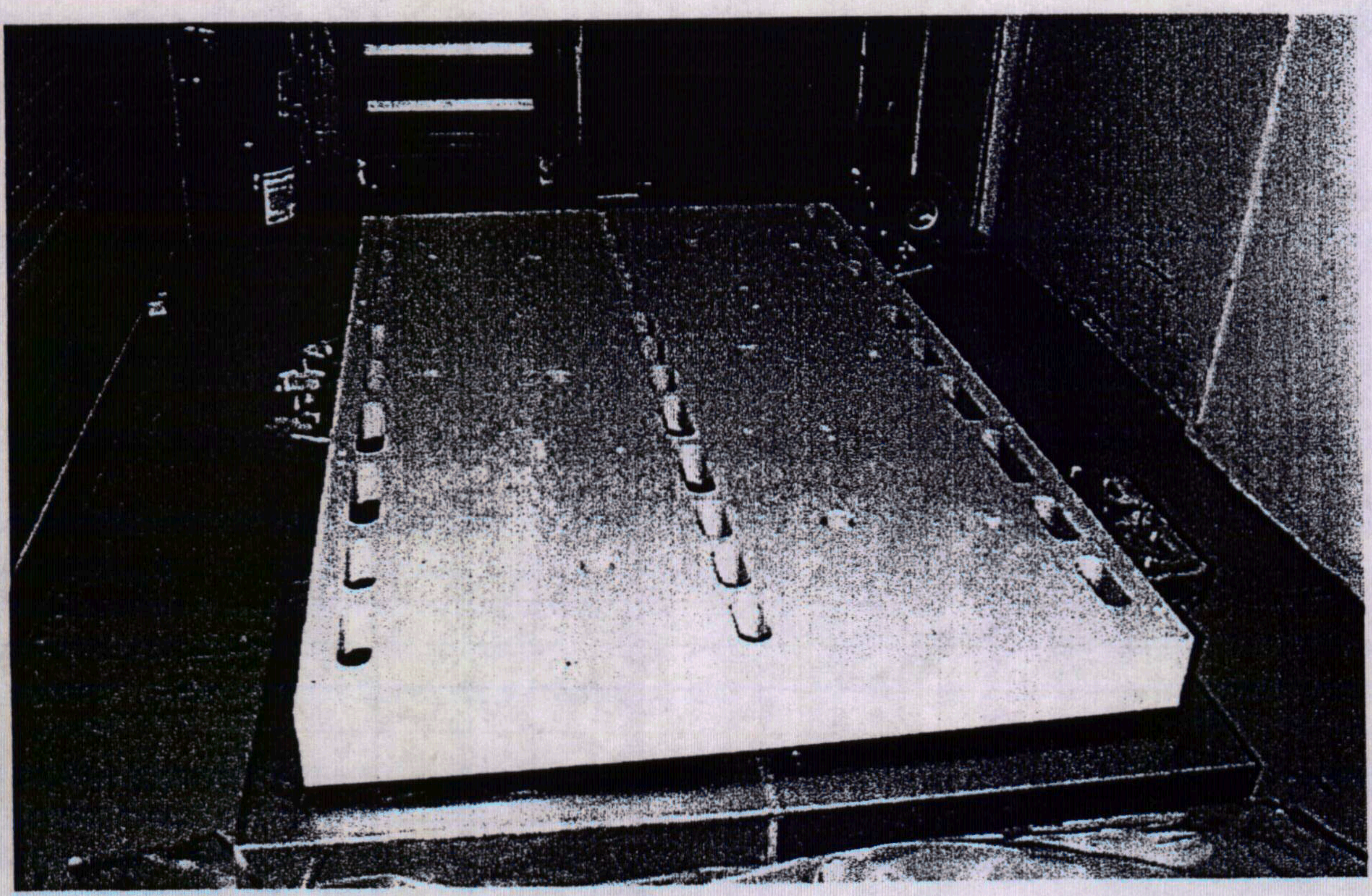

Figure 1. View of an amplifier top-plate. The ALCA Plus™ cast aluminum plate is entirely encapsulated in a dielectric epoxy potting material except for the support "ears" which can be seen on the right and left edges.

Mechanical Properties of the Top Plate (Plate No. 3)

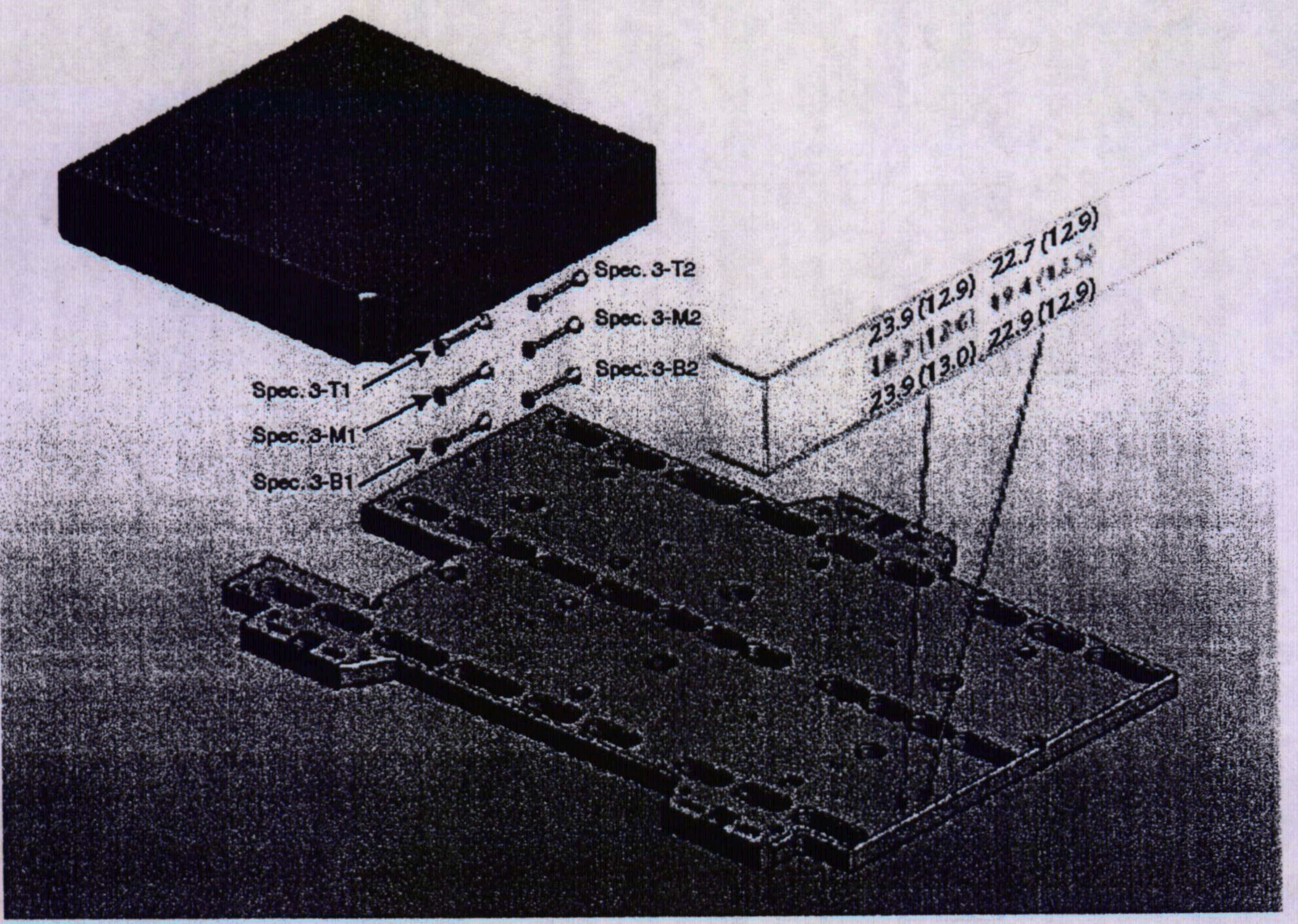

Figure 2. A view of the position of sample Plate 3 relative to the entire amplifier top plate, and the locations of the long transverse tensile samples.

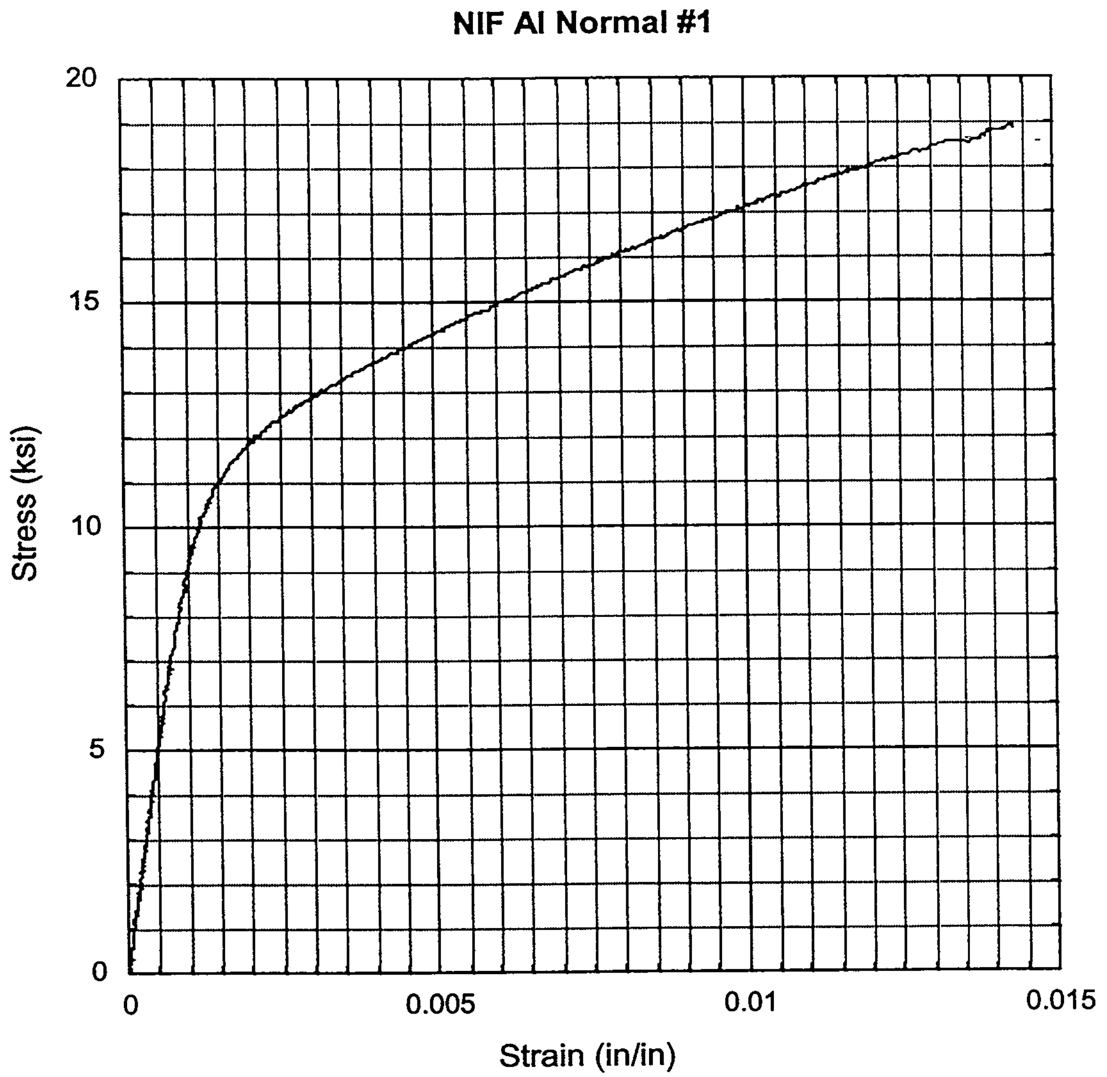

Figure 3. Stress-strain curve for ALCA Plus™ plate obtained in the short-transverse direction (Sample 1Y), specimen type A.

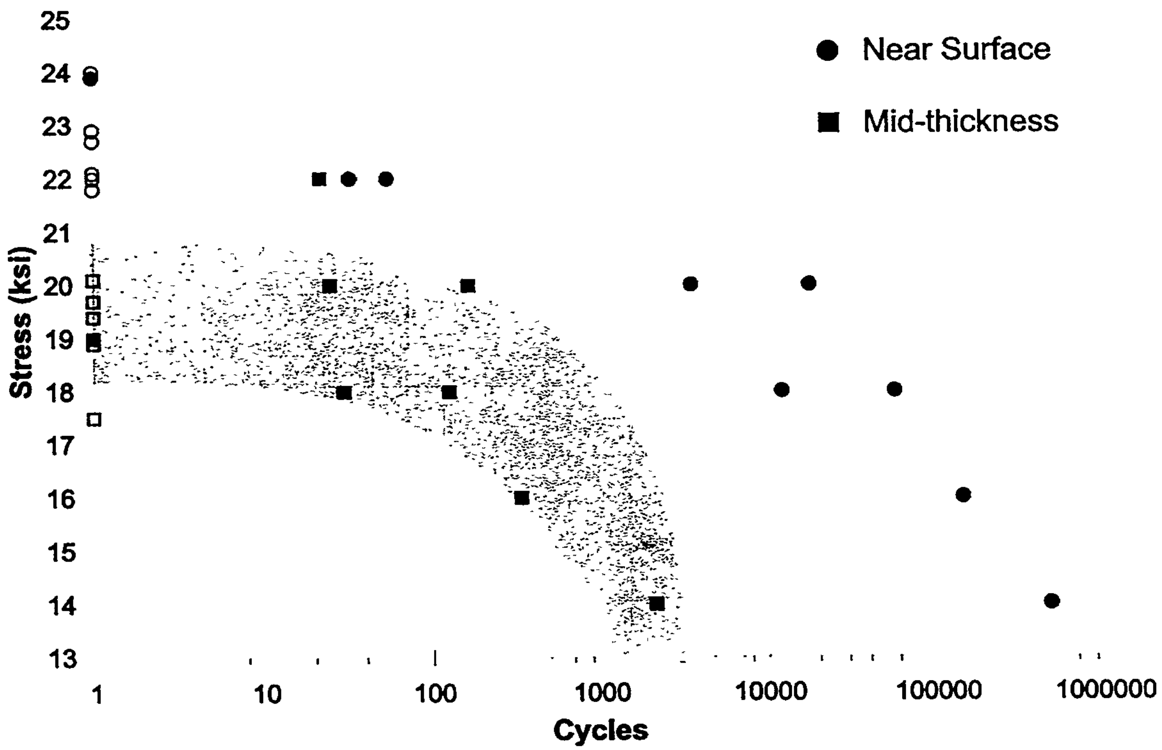

Figure 4: Cycles-to-failure at fixed stress amplitude ("S-N curve") for samples of ALCA Plus™ taken from near the surface (lower porosity) and the middle of plate? Samples were oriented in the long transverse direction. The plot includes the ultimate stresses from Table 5 for which the cycles-to-failure is 1.

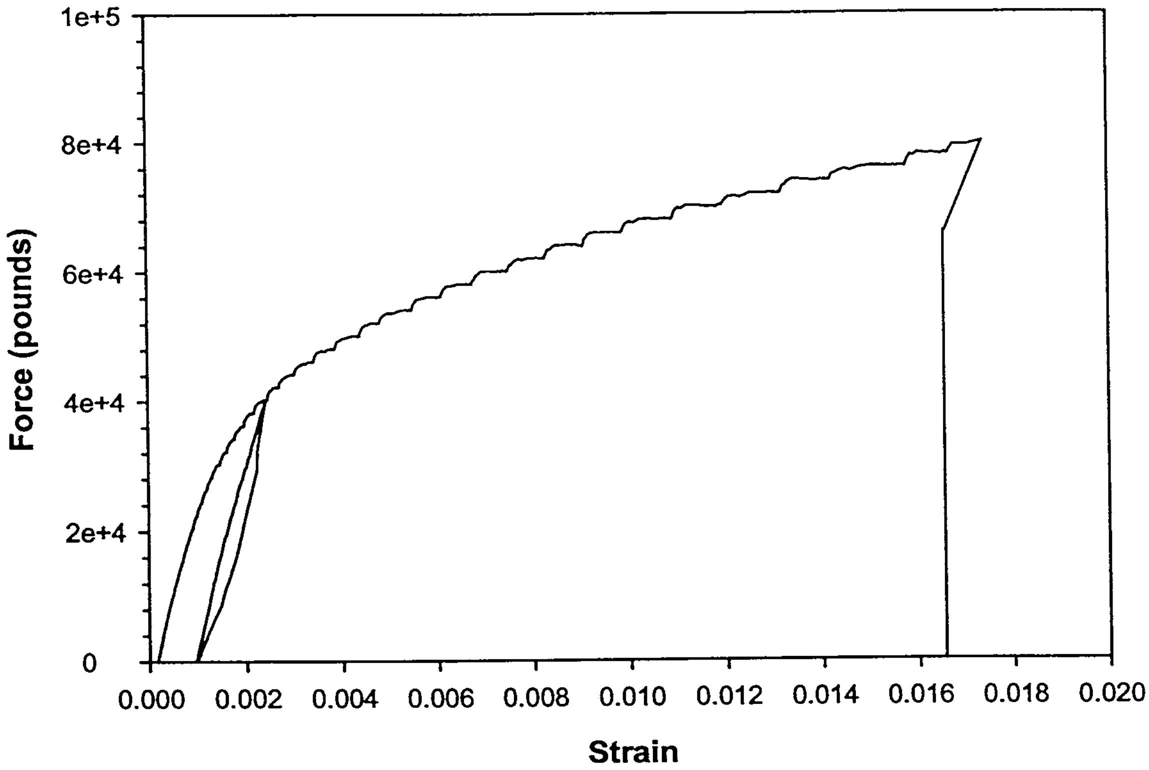

Figure 5: Applied force as a function of measured strain during a static test of a complete ALCA Plus™ top plate, Plate 2.

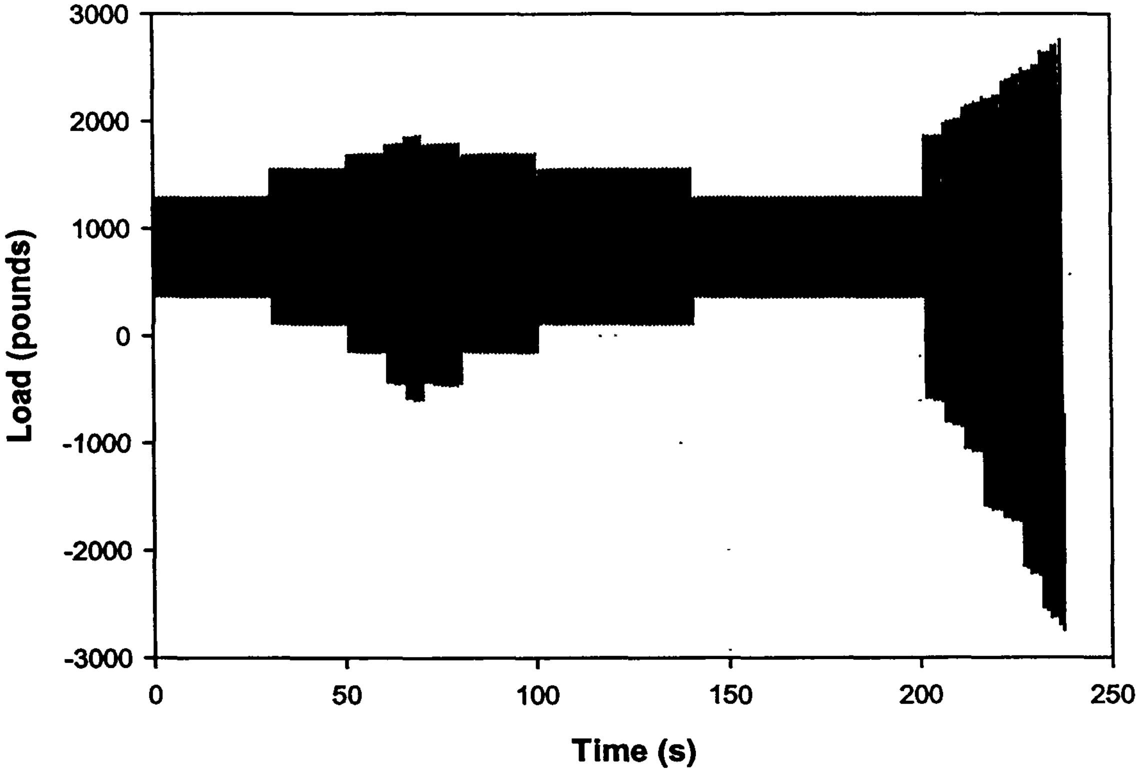

Figure 6: Variable amplitude simulated seismic fatigue test schedule. The test was conducted at 1 Hz.

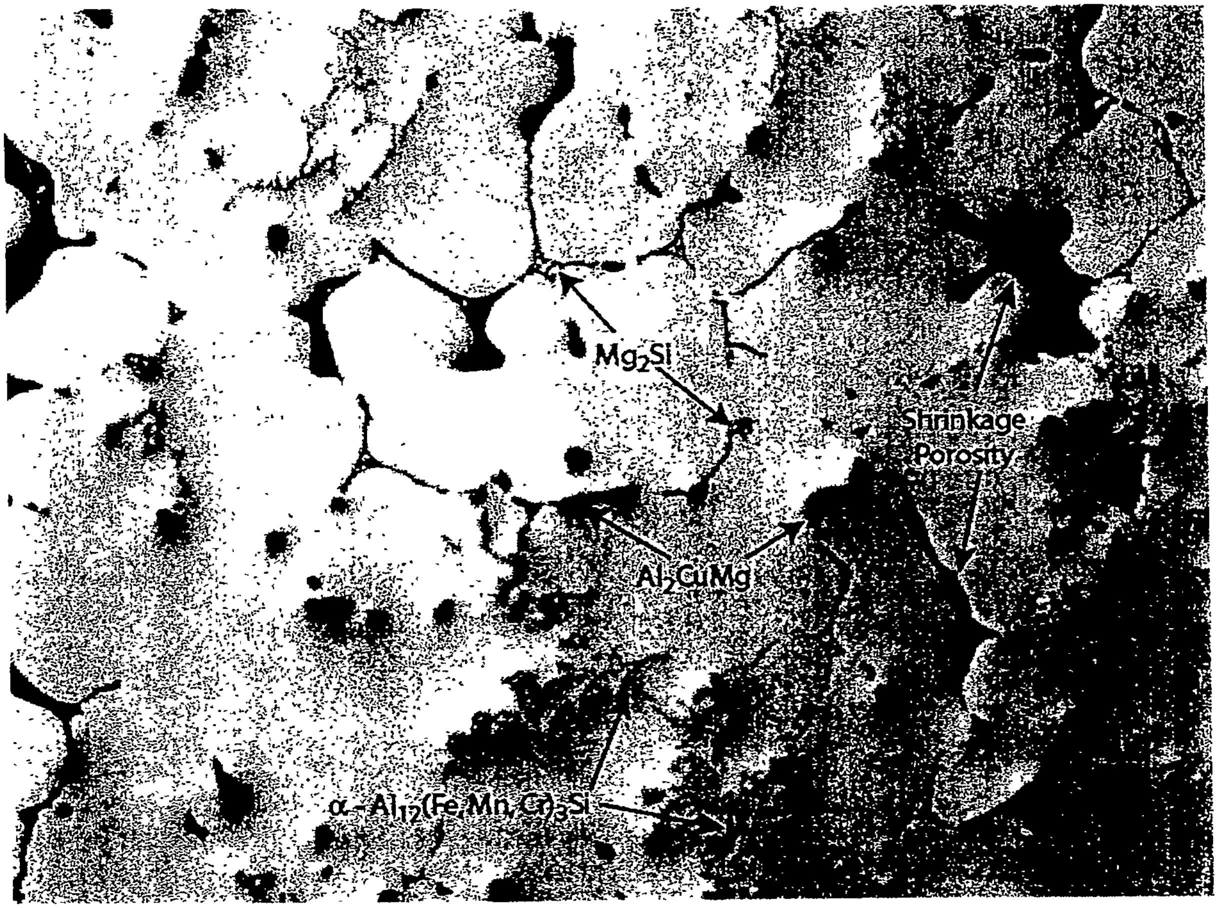

Figure 7. Typical microstructure of ALCA Plus™, as polished.

Figure 8. Scanning electron micrograph of the fracture surface of the ALCA Plus™ top-plate fragment.

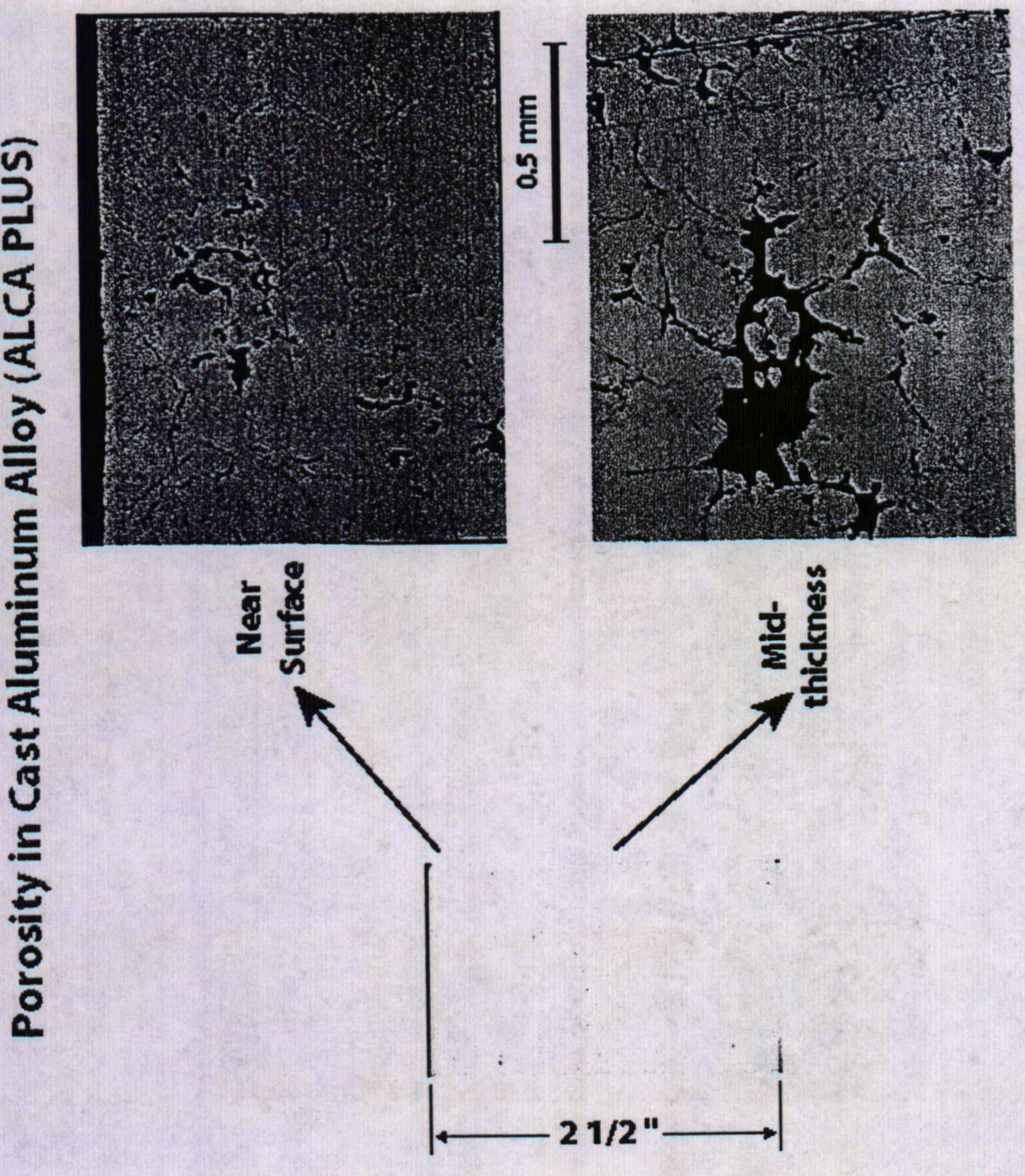

Figure 9. Porosity in a ALCA Plus™ cast aluminum top plate.

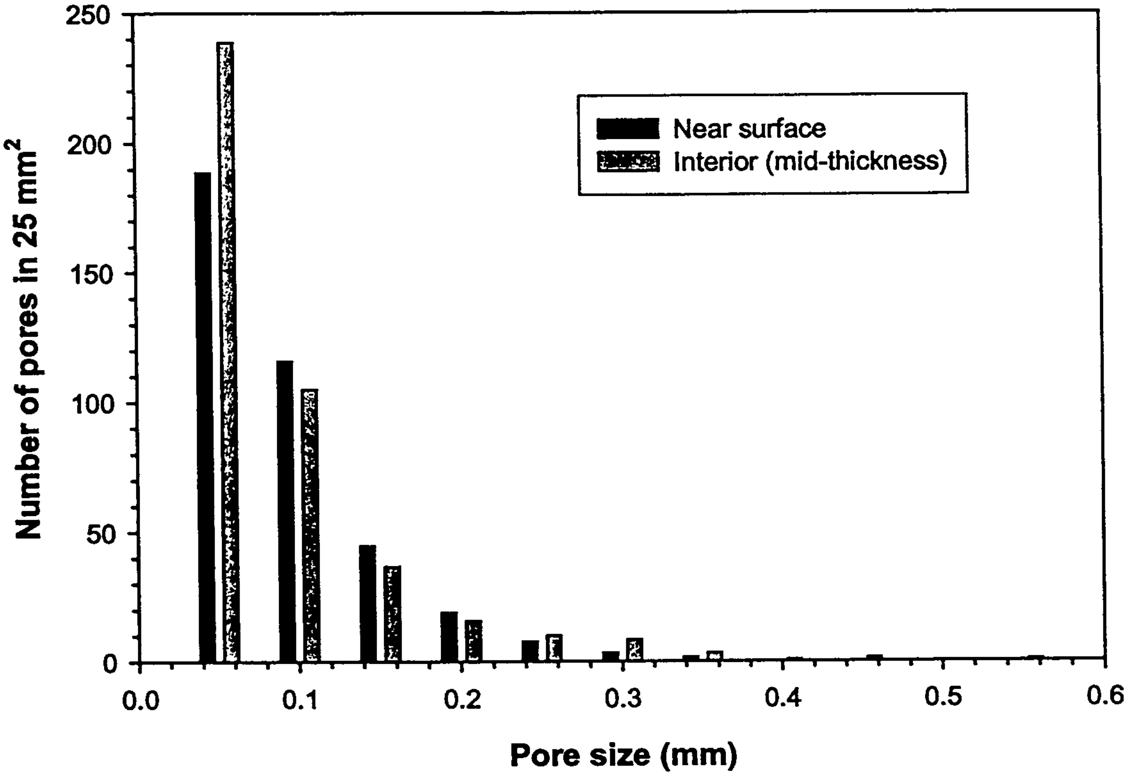

Figure 10: Pore size distribution in ALCA Plus™ near the surface and in the interior (mid-thickness) as a function of pore size. The number and size of pores are larger in the interior than at the surface.