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TRANSVERSE TENSILE AND STRESS RUPTURE PROPERTIES OF γ/γ'-δ DIRECTIONALLY SOLIDIFIED EUTECTIC

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16. Abstract

Both tensile and stress rupture properties have been determined primarily at 760° C for specimens oriented at various angles (0°, 10°, 45°, and 90°) from the solidification direction of bars and/or slabs of the Ni-20Cb-6Cr-2.5Al (γ/γ'-δ) eutectic. Threaded-head specimens yielded longer rupture lives with significantly less scatter than did tapered-head specimens. Miniature specimens are suitable for determining transverse tensile and rupture properties of 1.2 centimeter diameter bar stock. The 300 hour rupture stress at 760° C for specimens oriented at 10° from the solidification direction was reduced from 740 to 460 MPa, and to 230 MPa for material oriented at either 45° or 90°.

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SUMMARY

Both tensile and stress rupture properties have been determined primarily at 760° C for specimens oriented at various angles (0°, 10°, 45°, and 90°) from the solidification direction of bars and/or slabs of the Ni-20Cb-6Cr-2.5Al (γ/γ'-δ) eutectic alloy. For baseline stress rupture data on longitudinally oriented bar and slab material, threaded-head specimens yielded longer lives with significantly less scatter than did tapered-head specimens. These data suggest the necessity for good specimen alignment during stress rupture testing, particularly at intermediate testing temperatures where such a eutectic, and possibly other directional materials, have relatively low transverse ductility.

Miniature specimens are suitable for determining the transverse tensile and rupture properties of 1.2 centimeter diameter bar stock of directionally solidified eutectic alloys.

Specimens oriented at 10° from the slab solidification direction exhibited reductions in stress rupture lives corresponding to 4 Larson-Miller parameters from longitudinally oriented specimens (300 hour rupture stress at 760° C reduced from 740 to 460 MPa). The 300 hour rupture stress at 760° C for slab material oriented at either 45° or 90° was approximately 230 MPa.

Tensile tests at 760° C on transversely oriented specimens from either bars or slabs indicated strengths approximately 30 percent lower than for longitudinally oriented specimens. Transverse tensile fracture strain at 760° C was only about 0.2 percent, and could not be improved by a selected heat treatment. Transverse tensile strength at 1040° C was about 60 percent lower than longitudinal tensile strength. Transverse

fracture strain at 1040° C was 5 percent, compared with 11 percent elongation for longitudinally oriented specimens.

INTRODUCTION

A directionally solidified gamma/gamma prime-delta (γ/γ'-δ) eutectic alloy (Ni-20Cb-6Cr-2.5Al-0.06C) has been shown to have considerable potential as a turbine blade material in advanced aircraft gas turbine engines. This alloy offers an increase of about 40° C in use temperature capability or a 40 percent increase in strength at current airfoil operating temperatures compared with currently available directionally solidified alloys (ref. 1). The higher use-temperature capability would permit an increase in turbine inlet gas temperature over current levels without compromising engine performance with additional cooling air The higher strength of the alloy at existing blade metal temperatures would permit an increase in rotor speed, which would also contribute to increased engine performance.

In addition to these properties, turbine blade alloys must have other characteristics, such as cyclic oxidation resistance, thermal fatigue resistance, and thermal stability. A previous investigation (ref. 2) has shown that the γ/γ'-δ alloy has only marginal oxidation resistance at the projected use temperatures under isothermal and cyclic conditions. However, protective coatings are being developed to satisfactorily protect the alloy (ref. 3). Substantial data have demonstrated that the alloy has excellent thermal stability under both isothermal and cyclic conditions (refs. 1 and 4-7).

Directionally solidified alloys, such as the γ/γ'-δ eutectic, possess highly anisotropic mechanical properties due to the very nature of the directional solidification process. In particular, off-axis properties such as shear strength, transverse strength and transverse ductility are of particular importance because they may be design limiting for advanced hollow blade applications. Specifically, shear properties may influence root designs, while transverse tensile and rupture strength and ductility may determine airfoil thermal fatigue lives and root tooth bending capabilities. Improvements in these properties have been obtained recently by optimizing the microstructure and composition. A fully lamellar microstructure was found to be preferable to the original, partially cellular microstructure, and the addition of 0.06 weight percent carbon further improved properties (ref. 1). The adequacy of these improved off-axis properties for advanced hollow turbine blades is currently being evaluated (ref. 8).

The purposes of this investigation were: first, to evaluate a previous hypothesis (refs. 4 and 9) that the tapered-head specimen design was responsible for the observed scatter in longitudinal stress rupture lives; second, to provide a baseline specimen design and testing procedure for determining the transverse mechanical properties of 1.2 centimeter diameter bar stock of directionally solidified eutectics; and third, to determine baseline off-axis properties of the γ/γ'-δ eutectic for comparison with subsequent investigations of the off-axis mechanical properties of advanced eutectics. To accomplish the first purpose, rupture tests of both tapered-head and threaded-head specimens were conducted and evaluated. To accomplish the second purpose, rupture and tensile tests on both standard size and miniature size threaded specimens were performed. To accomplish the third purpose, the rupture and/or tensile properties of the γ/γ'-δ eutectic alloy were determined at angles of 10°, 45°, and 90° to the direction of solidification. The alloy used throughout this investigation was the γ/γ'-δ eutectic with the nominal composition Ni-20Cb-6Cr-2.5Al.

MATERIAL, SPECIMENS, AND PROCEDURE

Material

The gamma/gamma prime-delta (γ/γ'-δ) eutectic alloy used throughout this investigation was produced by United Technologies Corporation (UTC). The alloy had a nominal composition by weight of nickel-20 columbium-6 chromium-2.5 aluminum (did not contain carbon, as per ref. 1).

Bar stock. - Bar stock was directionally solidified at a rate of either 3 or 4 centimeters per hour in a modified water-quench Bridgman furnace having a thermal gradient of at least 300° C per centimeter (ref. 1). Each heat resulted in a casting approximately 20 centimeters in length and 1.2 centimeters in diameter. The castings were then cut into two bars approximately 7.5 centimeters long. Specimens are identified in tables I to III by heat number (A74-xxx and A75-xxx) and bar location, with the bottom bar from each casting identified as "01" and the top bar as "02".

Metallographic screening of a transverse section of all bars by UTC assured a minimum of 75-volume-percent aligned lamellar structure. The microstructure which is typical of material produced under these conditions is shown in figure 1. A longitudinal flat was ground on each bar and macroetched by UTC to also assure aligned structures. All bars were inspected at NASA by both dye penetrant and x-ray techniques to determine soundness.

Slab stock. - Slab stock was directionally solidified at a rate of either 0.63 or 1.2 centimeters per hour in a modified Bridgman furnace with a thermal gradient on the order of 100° C per centimeter (ref. 1). Each heat resulted in a casting approximately 0.8 centimeter in thickness, 8 centimeters in width, and 20 centimeters in length.

A longitudinal flat was ground on the edge of these slabs and macroetched by UTC to assure aligned structures. Typical transverse microstructures of specimens machined from one of the slabs grown at 1.2 centimeters per hour are shown in figure 2. This microstructure is typical of that expected to be produced under these growth conditions (ref. 1). Both the lamellar spacing and grain size are substantially larger than in the bar stock, as expected from the lower gradient furnace and reduced growth speed (ref. 1).

Specimens

All of the specimen types used in this investigation are shown in figure 3. Machined specimens were always inspected by both dye penetrant and x-ray techniques to ensure soundness.

Bar stock. - Both the threaded-head (fig. 3(a)) and tapered-head (fig. 3(b)) specimen designs were machined from bar stock in the longitudinal orientation, parallel to the solidification direction. Miniature, threaded-head specimens (fig. 3(e)) were machined from bars in the transverse orientation, as shown in figure 4(a).

Slab stock. - Both the threaded-head (fig. 3(d)) and tapered-head (fig. 3(c)) specimens were machined from the slab stock in the longitudinal orientation, as shown in figure 4(b). Threaded specimens (fig. 3(d)) were also cut from the slabs at angles of 10°, 45°, and 90° to the solidification direction, as shown in figure 4(b). In addition miniature threaded specimens (fig. 3(e)) were also machined from slabs transversely to the solidification direction.

Test Procedure

Stress rupture tests were performed over the temperature range 760° to 1040° C at stresses of 760 to 150 MPa. All tests were performed in air. Results are listed in tables I and II. Stress rupture elongations were determined by measuring the total length of the fractured specimen. Then elongation was calculated by assuming that deformation occurred only over the specimen gage length.

Tensile tests were conducted primarily at 760° C, plus a few tests at 1040° C. Tensile tests were done in air at a crosshead speed of 0.05 centimeter per minute. Transverse tensile fracture strain was determined from strip chart load-displacement curves, as shown in figure 5. All tensile test results are listed in table III.

RESULTS AND DISCUSSION

Stress Rupture Scatter

As discussed in reference 4, a significant amount of scatter was observed in longitudinal rupture lives of γ/γ'-δ with tapered-head specimens, particularly in the temperature range 670° to 870° C. Specifically, at 760° C and a stress of 690 MPa, rupture lives for six specimens ranged from 14 to 2012 hours (Larson-Miller parameters 39.3 to 43.4). It was postulated (ref. 9) that such scatter could be due to improper seating of the tapered-head specimen in the mating grip assemblies. The observations reported in reference 4 of specimens occasionally exhibiting partial shearing of heads support this hypothesis. Improper seating of the specimen head could result in a bending moment on one side of the specimen gage section with bending stresses in excess of the 10 percent maximum typically specified (ASTM E21-70) in stress rupture testing of superalloys. For example, a bending stress of 15 percent greater than the applied stress could result in a reduction in rupture life equivalent to 2-3 Larson-Miller parameters at temperatures near 760° C, particularly for a material which has relatively low transverse ductility, such as this γ/γ'-δ eutectic.

In order to evaluate this postulate, both tapered-head and threaded-head specimens from bars and slabs (longitudinal orientation) were tested in stress rupture under identical conditions. These results are shown in figure 6, with the scatter band representing the previously reported data obtained with tapered-head specimens (ref. 4).

From the rupture data shown in figure 6(a) and table I, it is immediately apparent that:

1. Threaded specimens taken from bar stock exhibited good reproducibility (rupture times) over the entire temperature range 760° to 1040° C.

2. Lives for threaded specimens taken from bar stock are equivalent to the longest lives obtained with the tapered-head specimens.

3. Lives for threaded specimens were substantially greater than for tapered-head specimens machined from the same slab and then tested under identical stress rupture conditions.

4. Bar stock with finer lamellar spacing and grain size exhibited longer rupture life than did slab stock with coarser lamellar spacing and grain size (see also ref. 1).

Although most of the bar stock tested in this investigation had been grown at 4 centimeters per hour, rather than the 3 centimeters per hour of reference 4, the eight tests performed at 760° C and 760 MPa demonstrated that the rupture lives and ductility of material grown at either speed are essentially equivalent (see data in table I).

From the rupture elongation data presented in figure 6(b) and table I, it also appears that threaded specimens exhibited greater average elongation to rupture than did tapered-head specimens machined from bar stock.

This effect (6 percent compared with 3 percent elongation) was particularly evident at the lowest test temperature, 760° C, where improved axial alignment might be expected to increase the rupture elongation of a relatively brittle material.

Off-Axis Mechanical Properties

Stress rupture properties. - The influence of specimen orientation on stress rupture properties was examined by testing specimens that had been machined from bars and/or slabs at specific angles of 10°, 45°, and 90° to the solidification direction of the castings. Rupture lives determined at 760° C are plotted both in the conventional Larson-Miller manner, figure 7(a), and as stress required for rupture in 300 hours, figure 7(b). The following observations can be made from these test data determined at 760° C:

1. Specimens oriented at 10° from the slab solidification direction had rupture lives about 4 parameters lower than did longitudinally oriented specimens (300 hour rupture stress reduced from 740 to 460 MPa).

2. The 300 hour rupture stress for slab specimens oriented at either 45° or 90° was approximately 230 MPa.

3. Equivalent results were obtained for both standard size and miniature size specimens oriented at 90° to the slab solidification direction.

4. The 300 hour rupture stress for miniature bar specimens oriented at 90° was approximately 255 MPa, once again substantiating previous observations (fig. 6 and ref. 1) that material with finer lamellar spacing and finer grain size has superior rupture properties.

5. The rupture lives of these transversely oriented, miniature specimens machined from partially cellular bars and tested in air are approximately equal to lives obtained on transversely oriented, standard size specimens machined from fully lamellar slabs and then tested in a coated condition (ref. 1).

Tensile properties. - Both the tensile strength and elongation (fracture strain) were determined at 760° C for bar and slab specimens and at 1040° C for a few bar specimens, in both longitudinal and transverse orientations, see figure 8 and table III. The following results were obtained:

1. Average tensile strengths of transversely oriented specimens from bars and slabs at 760° C were approximately 30 percent lower than strengths of longitudinally oriented specimens.

2. Equivalent strengths at 760° C were obtained for both standard size and miniature size specimens oriented at 90° to the slab solidification direction.

3. Tensile fracture strain at 760° C for transversely oriented specimens from bars and slabs was approximately 0.2 percent, as compared with 12 to 14 percent elongation for longitudinally oriented specimens.

4. Tensile strengths of transversely oriented specimens at 1040° C were approximately 60 percent lower than strengths of longitudinally oriented specimens.

5. Tensile fracture strain at 1040° C for transverse specimens was about 5 percent, compared to 11 percent elongation determined for longitudinal specimens.

Metallography. - Typical fracture profiles of stress rupture specimens oriented at 10°, 45°, and 90° to the solidification direction are shown in figure 9. Failures appeared to be primarily intergranular, as noted previously (ref. 1). It should also be noted from figure 9(a) and (b) that preferential oxidation of the delta lamellae occurred during rupture testing at 760° C. This effect has been reported previously (refs. 1 to 3), but it is interesting to note that there does not appear to be any significant effect on rupture lives. As discussed in connection with figure 7, the rupture lives obtained in this investigation with miniature (large surface to volume ratio) specimens tested in air are essentially equivalent to the results obtained with larger specimens tested with a protective coating (ref. 1).

A large number of transversely oriented specimens taken from slab E455 (see tables II and III) were tested in this investigation and failed during set-up, at low tensile loads, or during stress-rupture loading. For those specimens that survived testing, significant scatter was observed in strength, ductility or life. An extensive metallographic evaluation of specimens machined from this fully lamellar slab revealed that large, primary delta lamellae existed in many of the specimens, see figure 10. Some of these delta lamellae traversed the entire specimen gage diameter and presumably were responsible for many of the premature failures (see also ref. 1).

Limited stress rupture data at 760° C indicates that fully lamellar material, free of primary delta lamellae, does not have a rupture life superior to that of partially cellular material, in contrast to previously reported results (ref. 1). However, two transverse tensile tests on fully lamellar material, free of primary delta lamellae, did indicate average fracture strains at 760° C of 0.40 percent, while the delta containing eutectic had 0.12 percent and the partially cellular bar material had 0.19 percent (see table III).

Effect of heat treatment. - A previous investigation (ref. 9) has shown that partial solutioning at 1210° C and aging at 900° C resulted in improved longitudinal lives and reduced scatter in the temperature range 760° to 870° C, even when using tapered-head specimens (as in ref. 4). It was suggested that such improvements may be indicative of improved transverse ductility and, hence, the ability of the material to withstand slight axial misalignments. Such an improvement in transverse tensile strain was indeed confirmed in another investigation with fully lamellar $\gamma/\gamma'-\delta$ eutectic material (ref. 1). Specifically, at 760° C the transverse strain to fracture was increased from 0.33 percent to 0.58 percent by heat treating at 1155° C for 4 hours followed by 900° C for 24 hours.

However, no significant effect of heat treating was determined in this current investigation when partially cellular bar material was heat treated and tensile tested at 760° C. For example, the average transverse tensile fracture strain was 0.25 percent, as compared with 0.19 percent for as-cast bar material (see table III). Perhaps such heat treating effects are more pronounced with fully lamellar eutectic, as demonstrated in the research of reference 1.

Metallographic examination of selected transverse tensile specimens revealed significant differences in fracture mode. As shown in figure 11, as-cast eutectic alloy exhibits a brittle, interlamellar and intergranular shear failure when tested in the transverse orientation. In contrast, the heat-treated specimen which exhibited the largest amount of fracture strain at 760° C (0.50 percent) had a significantly different fracture mode, see figure 12. Specifically, several indications of secondary cracking were evident on the fracture surface, as well as large areas with dimple-like features, similar to features normally observed on fracture surfaces of ductile alloys. Additional optical metallography failed to reveal any microstructural differences between the as-cast and heat treated specimens except for coarsened gamma prime and precipitated Widmanstatten delta, both observed in the heat treated material of this investigation and that of several other investigations (ref. 1, 2, 4 to 7, and 9).

CONCLUDING REMARKS

All three objectives of this investigation were fulfilled: first, threaded-head specimens were shown to give substantially more reproducible stress rupture results than tapered-head specimens, and are recommended for future testing of directional materials, particularly those with relatively low transverse ductility; second, miniature test specimens machined from 1.2 centimeter diameter bar stock are suitable for determining the transverse tensile and stress rupture properties of directionally solidifed alloys; and third, the off-axis tensile and stress rupture properties of γ/γ'-δ were determined and are now available as a baseline for comparison with the off-axis properties of advanced directionally solidified eutectics of subsequent investigations.

In the course of this investigation several microstructural features were qualitiatively confirmed as significantly influencing the mechanical properties of the γ/γ'-δ eutectic. For example, volume percent lamellar structure, volume percent primary delta lamellae, lamellar spacing, and eutectic "grain size" are important microstructural features.

SUMMARY OF RESULTS

The purposes of this investigation were: first, to evaluate a previous hypothesis that the tapered-head specimen design was responsible for the observed scatter in longitudinal stress rupture lives; second, to provide a baseline specimen design and testing procedure for determining the transverse mechanical properties of 1.2 centimeter diameter bar stock of directionally solidified eutectics; and third, to determine the off-axis mechanical properties of the γ/γ'-δ eutectic to serve as the baseline for subsequent investigations of advanced directionally solidified eutectics.

Both tapered-head and threaded-head specimens were stress rupture tested in the longitudinal orientation over the temperature range 760° to 1040° C. Standard size and miniature size threaded specimens were machined from bars and/or slabs at angles of 0°, 10°, 45°, and 90° to the solidification direction. These specimens were than tested in stress rupture and tension, primarily at 760° C, but also with a few tests at 1040° C. The following results were obtained:

1. Threaded specimens exhibited longer stress rupture lives with significantly less scatter than did tapered-head specimens over the temperature range 760° to 1040° C for longitudinally oriented bar and slab material.

2. Miniature specimens yielded both stress rupture and tensile results equivalent to those obtained with standard size specimens.

3. Specimens oriented at 10° from the slab solidification direction had rupture lives at 760° C corresponding to 4 Larson-Miller parameters lower than longitudinally oriented specimens (300 hour rupture stress reduced from 740 to 460 MPa).

4. The 300 hour rupture stress for slab material oriented at either 45° or 90° was approximately 230 MPa, while the 300 hour rupture stress for miniature specimens from bar material oriented at 90° was approximately 255 MPa.

5. Transverse tensile strengths at 760° C were approximately 30 percent lower than longitudinal tensile strengths. Transverse fracture strains were about 0.2 percent and were not improved by a selected heat treatment.

6. Transverse tensile strengths at 1040° C were approximately 60 percent lower than longitudinal tensile strengths. Transverse fracture strains were approximately 5 percent, compared with 11 percent elongation for longitudinally oriented specimens.

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TABLE I. - STRESS RUPTURE RESULTS OF γ/γ'-δ BAR STOCK

Specimen	Growth speed, cm/hr	Temperature, ^{o}C	Stress		Life, hr	Reduction of area, percent	Elongation, percent
			MPa	KSI			
Large threaded specimens, fig. 3(a), 0^{o} orientation							
A74-868-02	3	760	760	110	662	2	2
866-01					748	2	2
943-01					1074	13	7
941-01					1292	13	9
A75-137-01	4				924	12	4
137-02					1133	10	9
A74-1068-01					1081	7	7
1068-02					1106	6	6
969-01			690	100	2376	9	6
969-02					1346	7	5
970-01					1714	12	4
970-02					2002	12	8
959-01					2564	14	11
959-02					2232	13	6
1015-01		870	515	75	129	9	4
1015-02					150	19	8
1073-01					439	16	12
1073-02					464	17	12
A75-161-01					99	19	9
161-02					122	16	11
A74-1023-01		1040	150	22	183	27	10
[a]1023-02					236	23	--
A75-132-01					161	27	11
[a]A75-156-02					171	24	--
Miniature threaded specimens, fig. 3(e), 90^{o} orientation							
A75-180-02-11[a]	4	760	275	40	109	---	---
5[a]			260	38	174	---	---
10			260	38	232	1.6	2.5
4			240	35	840	8.3	3

[a]Specimen seized in grips - no elongation measurement.

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TABLE II. - STRESS RUPTURE RESULTS OF γ/γ'-δ SLAB STOCK

Specimen	Growth speed, cm/hr	Temperature, °C	Stress MPa	Stress KSI	Life, hr	Reduction of area, percent	Elongation, percent
Tapered-head specimen, fig. 3(c), 0° orientation							
E306-1	1.2	760	690	100	27	<1	1
2	↓	↓	↓	↓	15	↓	3
3	↓	↓	↓	↓	14	↓	2
4	↓	↓	↓	↓	20	↓	1
5	↓	↓	↓	↓	29	↓	3
6	↓	↓	↓	↓	18	↓	2
Threaded specimen, fig. 3(d), 0° orientation							
E-306-7	1.2	760	690	100	473	2	2
a8	↓	↓	↓	↓	521	3	---
9	↓	↓	↓	↓	197	2	2
10	↓	↓	↓	↓	281	1	1
11	↓	↓	↓	↓	519	2	1
12	↓	↓	↓	↓	444	2	2
a13	↓	1040	150	22	123	34	---
a14	↓	1040	150	22	109	36	---
Threaded specimen, fig. 3(d), various orientations							
E306-18-45°	1.2	760	365	56	1.5	<1	<1
19-45°	↓	↓	240	35	128	↓	↓
20-45°	↓	↓	205	30	818	↓	↓
21-10°	↓	↓	550	80	21	↓	↓
22-10°	↓	↓	485	70	124	↓	↓
Threaded specimen, fig. 3(d), 90° orientation							
E306-16	1.2	760	260	38	47	<1	<1
E302-16	↓	↓	260	38	53	↓	↓
E306-17	↓	↓	240	35	180	↓	↓
E302-14	↓	↓	240	35	284	↓	↓
Miniature threaded specimen, fig. 3(e), 90° orientation							
E455-3[b]	0.63	760	260	38	76	<1	<1
-7	.63	↓	260	38	14	5	2.5
-8[b,a]	.63	↓	240	35	269	1.6	---
E302-8	1.2	↓	[illegible]	30	517	---	---

[a]Specimen seized in grips - no elongation measurement.
[b]Large primary δ lamellae.

TABLE III. - TENSILE RESULTS OF γ/γ'-δ BAR AND SLAB STOCK

Specimen	Growth speed, cm/hr	Temperature, °C	Ultimate tensile strength MPa	Ultimate tensile strength KSI	Reduction of area, percent	Total elongation, percent	Fracture[a] strain, percent
Tapered-head specimen, fig. 3(b), 0° orientation							
Ref. 4	3	760	1040-1055	151-153	10-22	7-13	----
Ref. 4	3	1040	635-660	92-96	9-24	6-16	----
Threaded specimen, fig. 3(a), 0° orientation							
A75-130-01	4	760	1020	148	16	12	----
Threaded specimen, fig. 3(d), 0° orientation							
E306-15	1.2	760	840	122	23	14	----
Threaded specimen, fig. 3(d), 90° orientation							
E302-19	1.2	760	615	89	0	0	----
E455-17[b]	0.63	↓	270	39	0	0	0.04
18[b]	.63	↓	360	52	0.5	1.7	0
19[b]	.63	↓	510	74	0	0	.04
Miniature threaded specimen, fig. 3(e), 90° orientation							
E302-6	1.2	760	565	82	5	2	----
-10	1.2	↓	565	82	.3	.5	.03
E455-1	0.63	↓	620	90	1.8	1.5	.35 }
2[b]	↓	↓	635	92	2.4	1.2	.10 }
4[b]	↓	↓	560	81	1.1	2.0	.15 }
5[b]	↓	↓	545	79	---	---	.07 } 0.20
26[b]	↓	↓	670	97	.4	2.0	.25 }
27	↓	↓	690	100	0	2.5	.45 }
28[b]	↓	↓	600	87	1.1	2.0	.05 }
A75-180-02-2	4	↓	695	101	1.6	1.7	----
3	↓	↓	725	105	1.6	1.0	.12 }
8	↓	↓	675	98	1.3	1.5	---- }
9	↓	↓	685	99	.7	1.5	.22 } .19
12	↓	↓	690	100	.9	1.6	.13 }
13	↓	↓	765	111	.7	0	.27 }
7	↓	1040	305	44	---	---	4.8
[c]A74-1098-1	↓	760	695	101	0	.25	.10 }
2	↓	↓	730	106	0	0	.23 }
3	↓	↓	725	105	2.2	1.25	.50 } .25
4	↓	↓	695	101	.5	.75	.18 }

[a]Fracture strain determined from tensile load-displacement chart (see fig. 5)
[b]Large primary δ lamellae.
[c]Heat treated 1210° C/4 hr, 900° C/24 hr.

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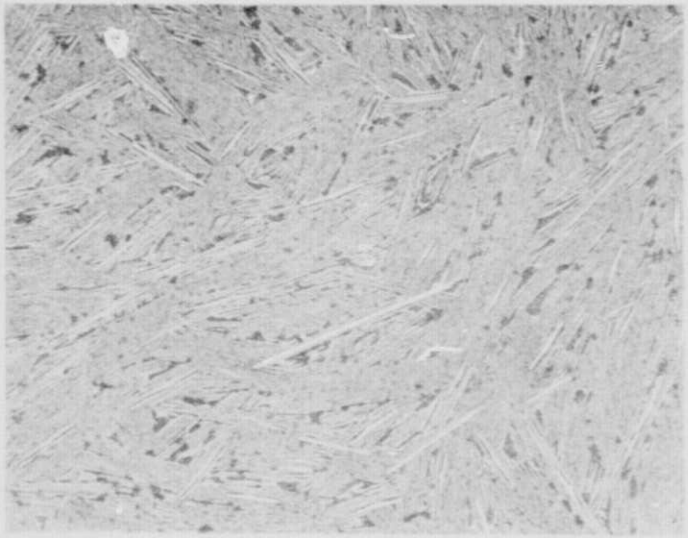
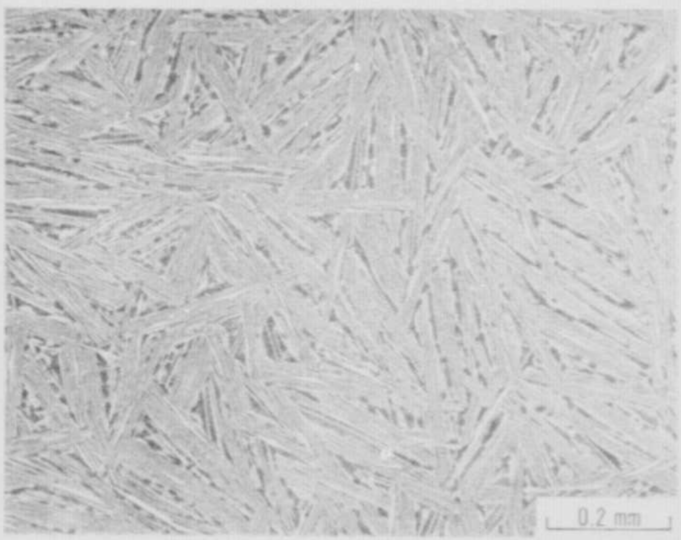
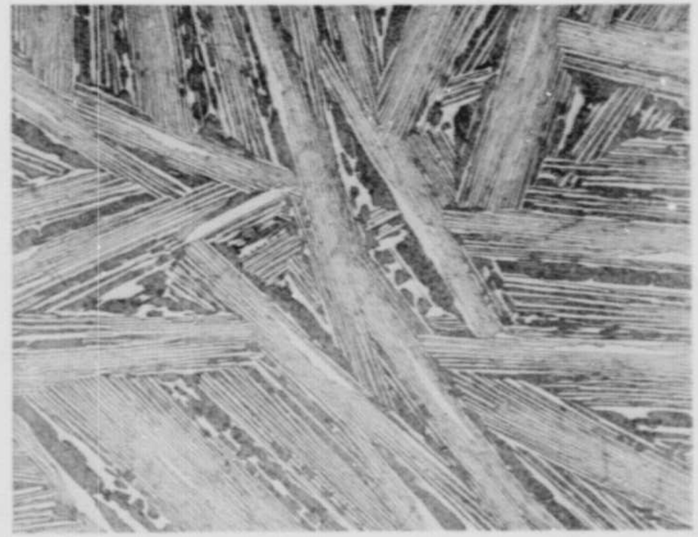


(a) A74-868-02, 3 cm/hr, 760° C/760 MPa/662 hrs.

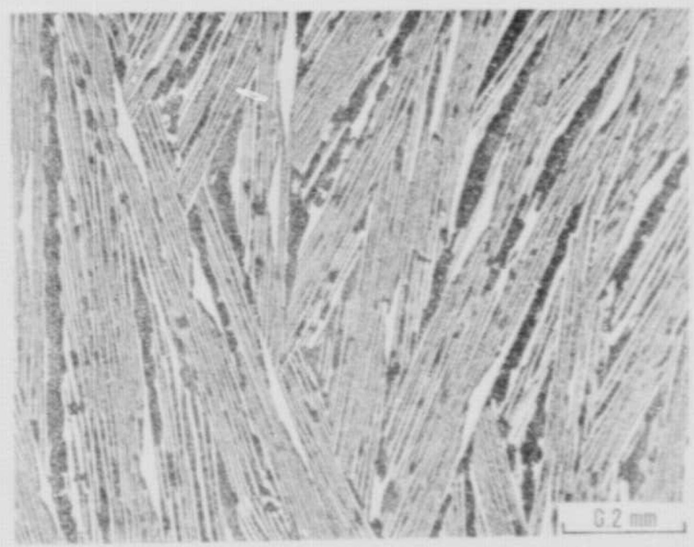


(b) A74-969-02, 4 cm/hr, 760° C/690 MPa/1346 hrs.

Figure 1. - Typical transverse microstructures of bar stock.



(a) E306-7L, 1.2 cm/hr, 760° C/690 MPa/472 hrs.



(b) E306-1L, 1.2 cm/hr, 760° C/690 MPa/26.8 hrs.

Figure 2. - Typical transverse microstructures of slab stock.

E-8810

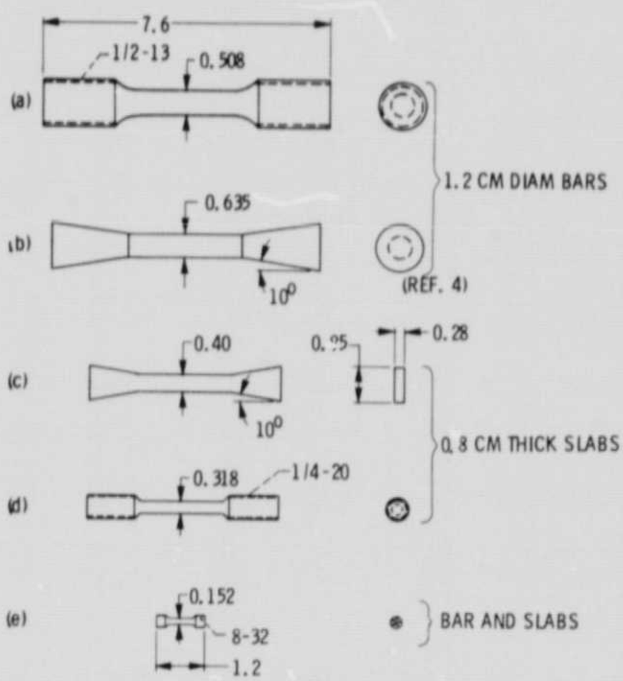
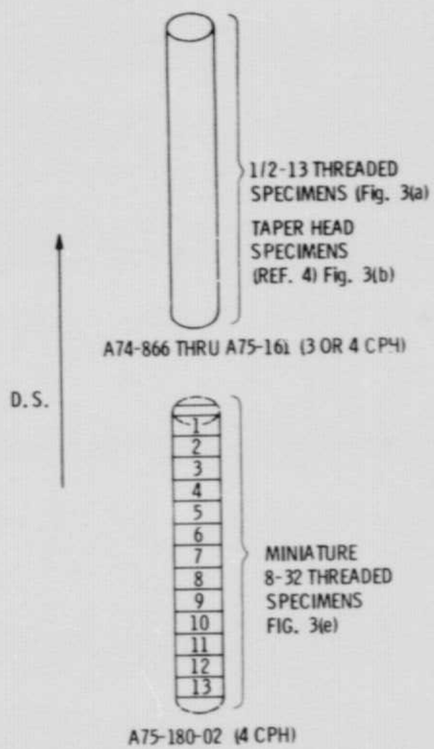
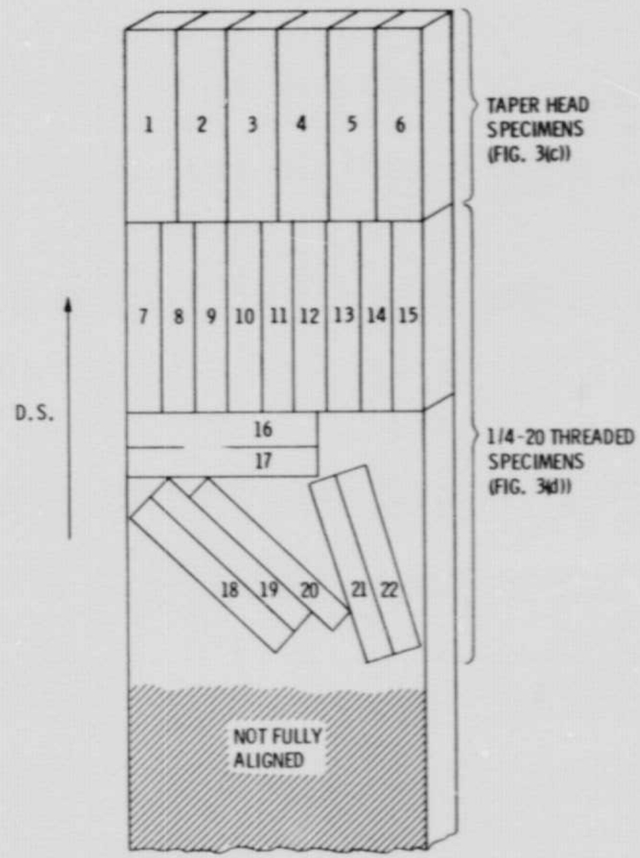


Figure 3. - Specimens used in this investigation and ref. 4. (Dimensions are in cm.)



(a) BAR STOCK (3 OR 4 CPH).

Figure 4. - Specimen stock and orientation.



(b) E306 SLAB (1, 2 CPH).

Figure 4. - Concluded.

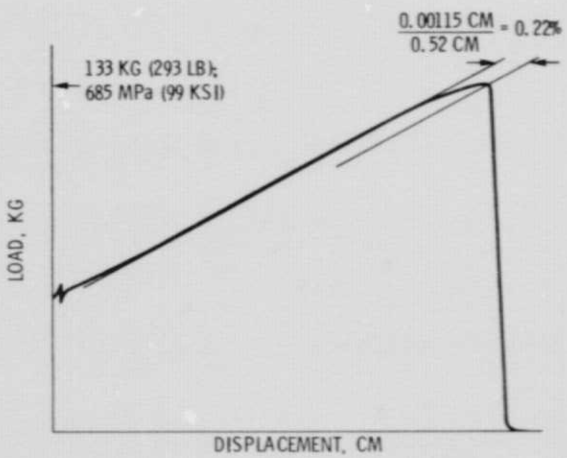
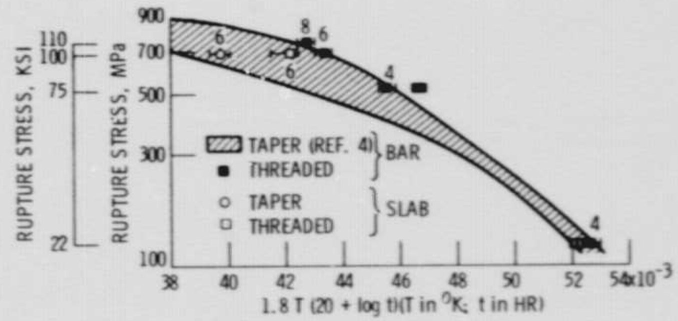
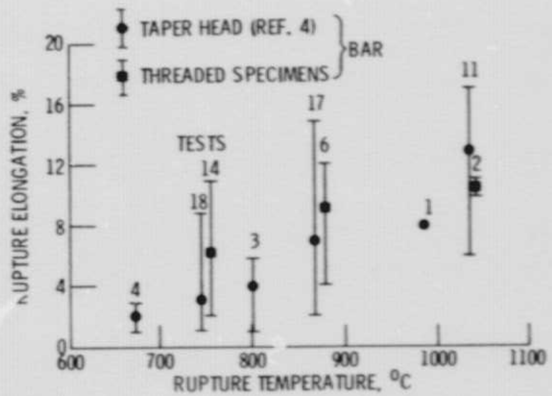


Figure 5. - Load-displacement curve for transverse tensile test at 760° C (A-75-180-02-9, 50 cm/min chart speed, 0.05 cm/min crosshead speed).

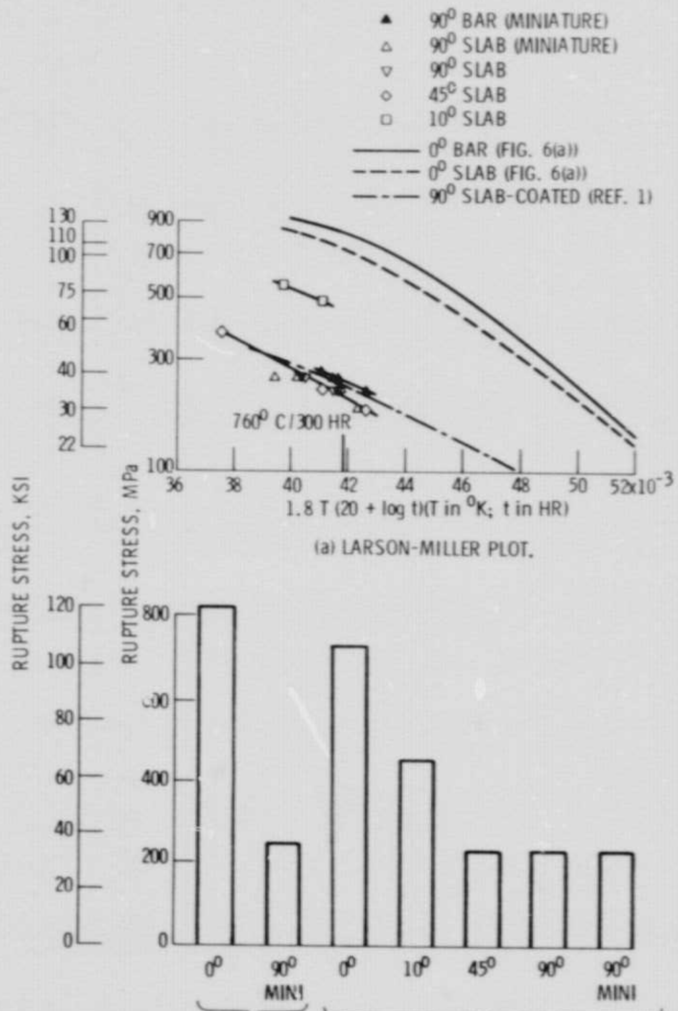


(a) LARSON-MILLER PLOT.



(b) RUPTURE ELONGATION.

Figure 6. - Effect of specimen head design on longitudinal stress rupture properties of γ/γ'-δ. (Numbers shown above scatter bands represent the number of tests within each scatterband.)



(a) LARSON-MILLER PLOT.

(b) RUPTURE STRESS FOR 300 HR LIFE AT 760° C.

Figure 7. - Stress rupture properties of γ/γ'-δ threaded specimens oriented at various angles to direction of solidification.

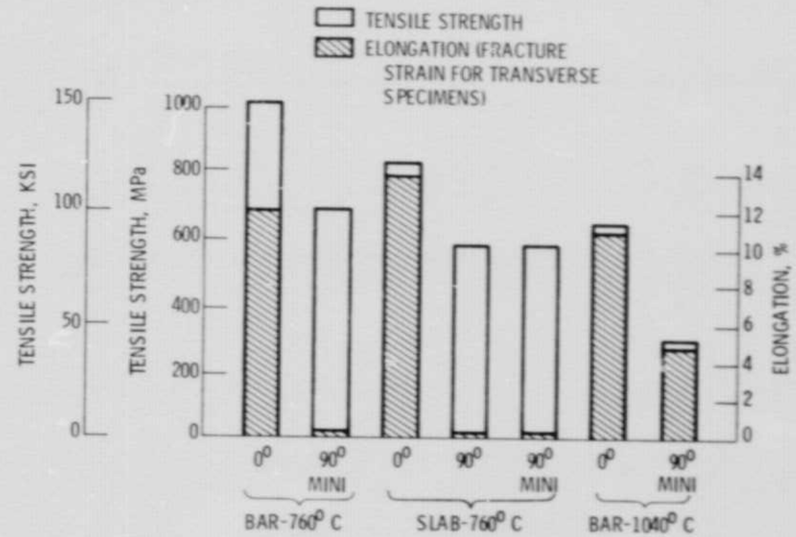
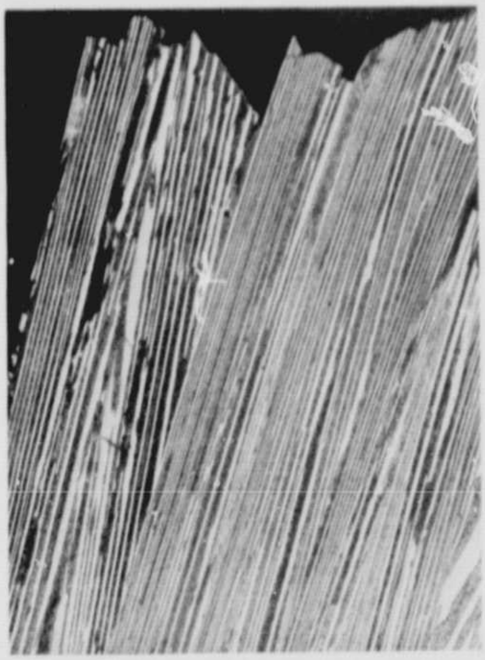
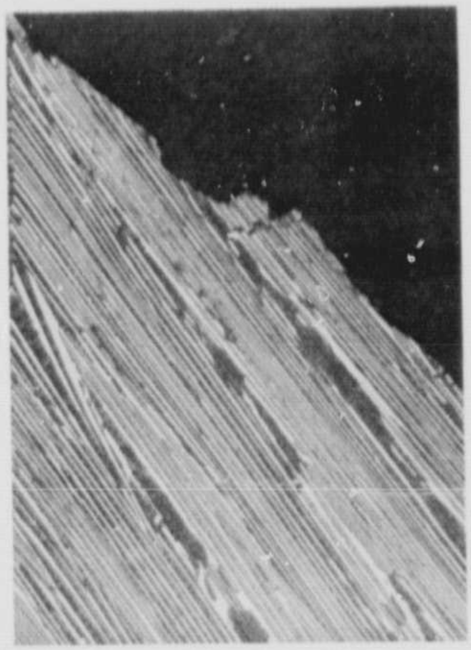


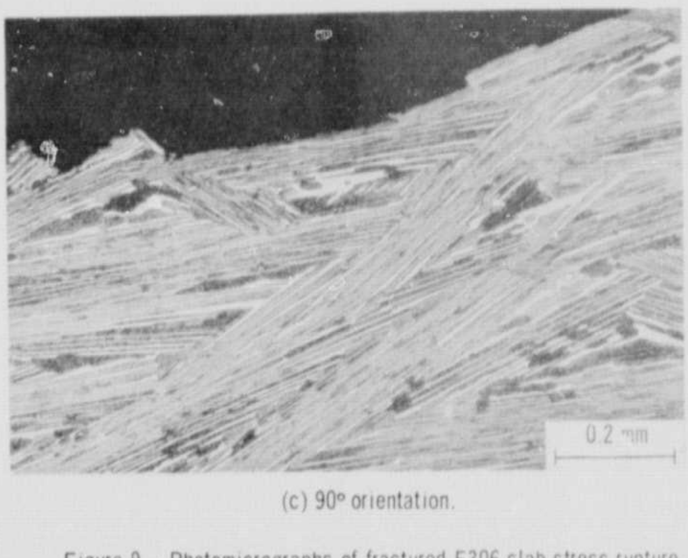
Figure 8. - Average tensile properties at 760° C and 1040° C.



(a) 10° orientation.

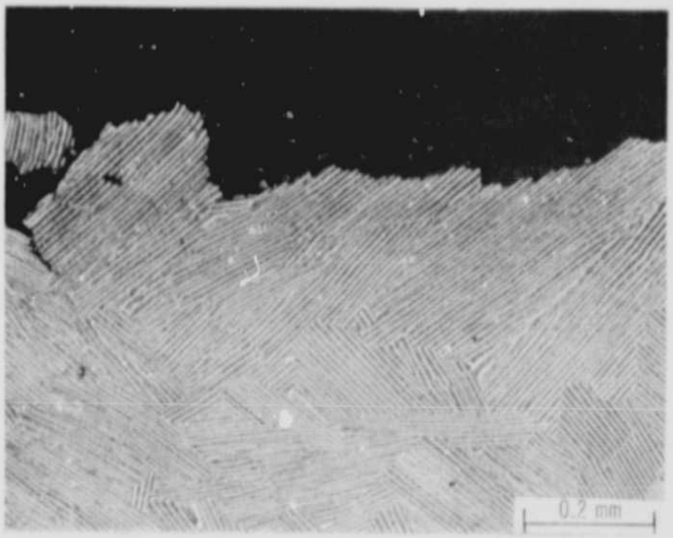


(b) 45° orientation.

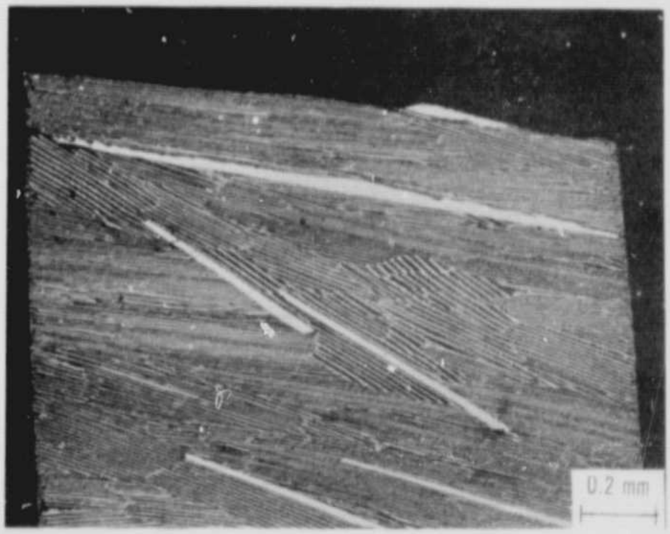


(c) 90° orientation.

Figure 9. - Photomicrographs of fractured E306 slab stress rupture specimens.



(a) E455-1, 0.63 cm/hr, 760° C, UTS = 620 MPa.



(b) E455-3, 0.63 cm/hr, 760° C/260 MPa/36 hrs.

Figure 10. - Photomicrographs of E455 transverse specimens.

E-8810

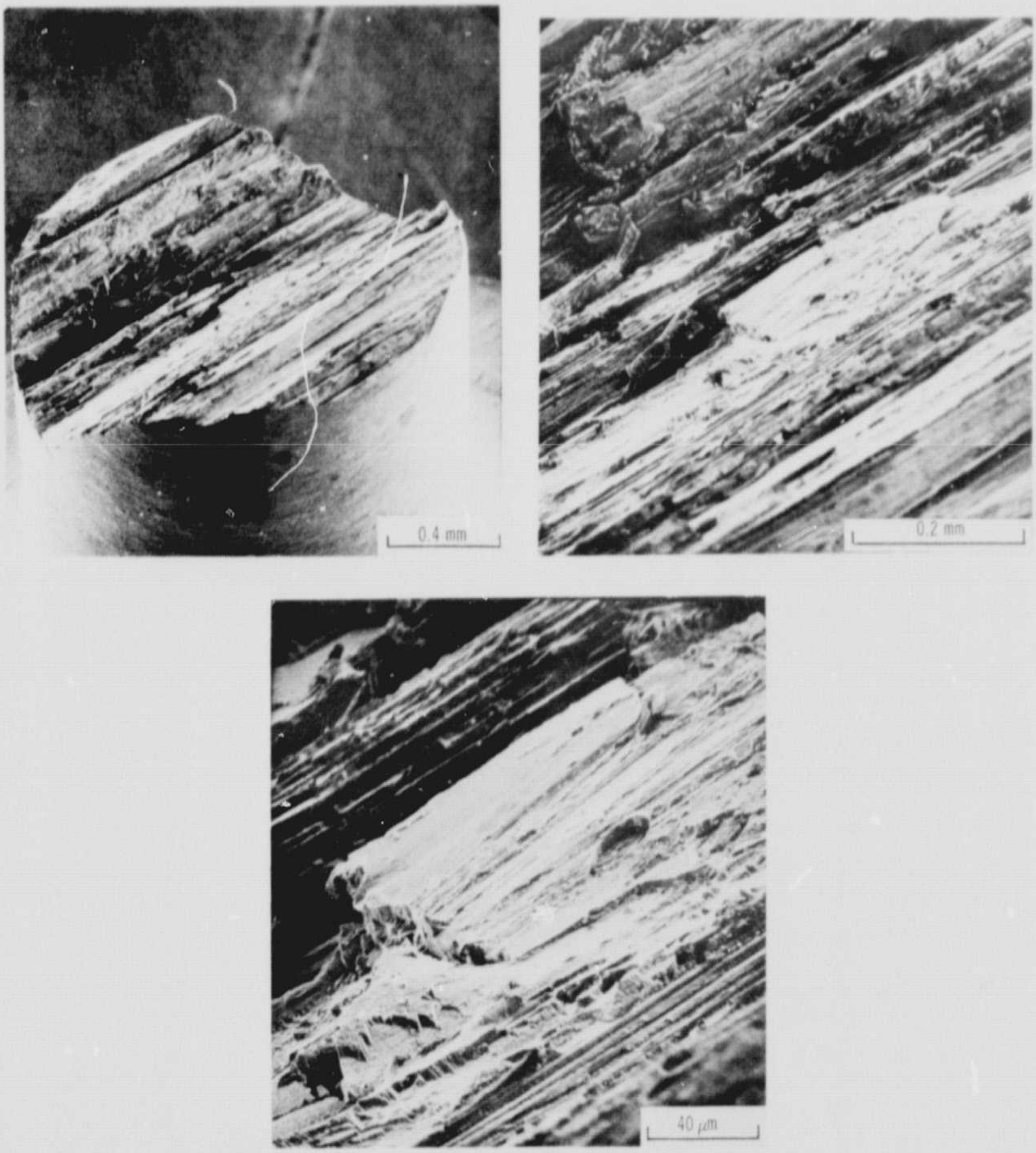


Figure 11. - Scanning electron fractographs of 760° C transverse tensile specimen A75-180-02-3, strain to failure 0.12%.

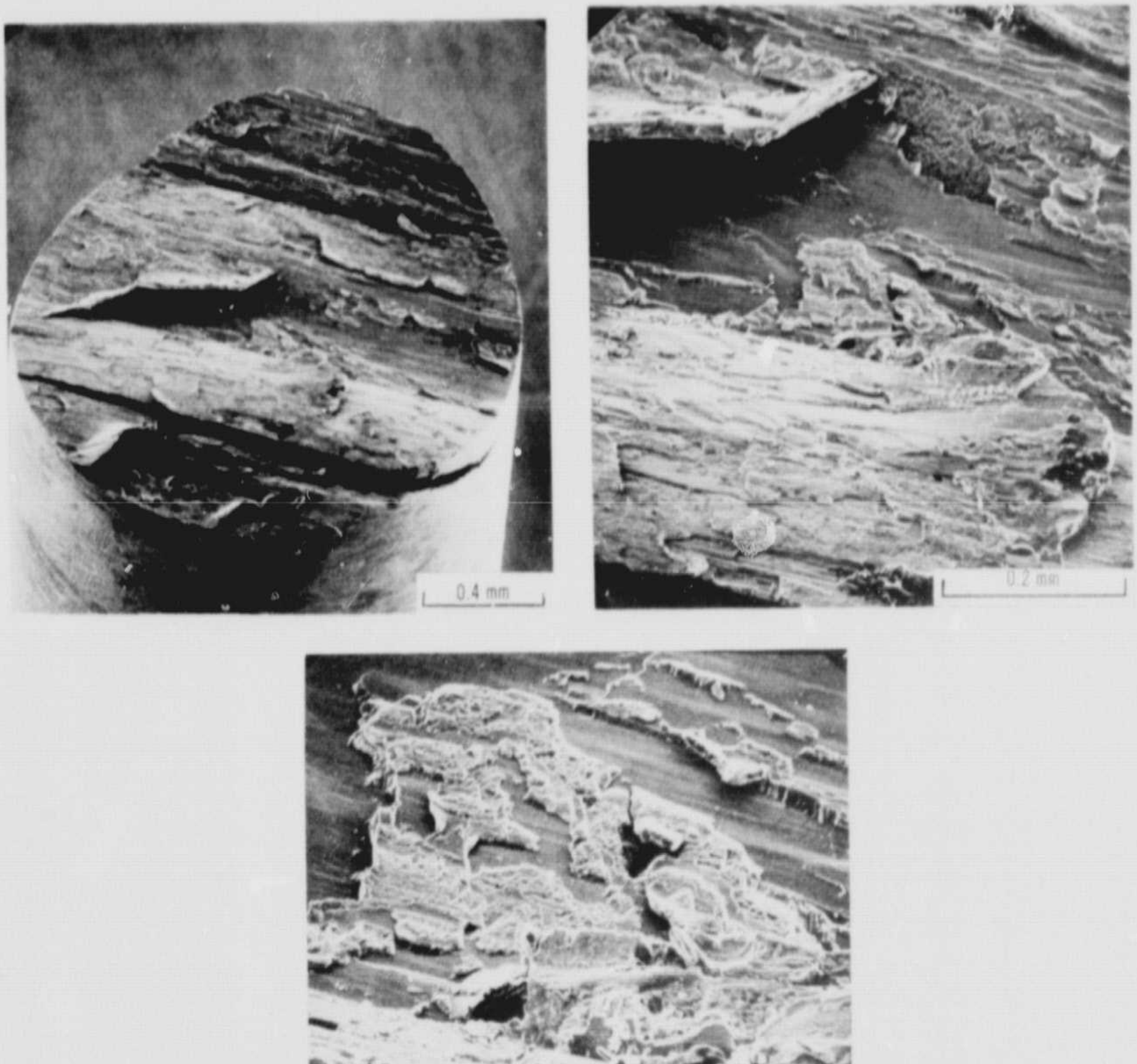


Figure 12. - Scanning electron fractographs of 760° C transverse tensile specimen A74-1098-3, strain to fracture 0.50%. (Heat treated 1210° C/4 hrs, 900° C/24 hrs).