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CREEP-RUPTURE TESTS OF INTERNALLY PRESSURIZED HAYNES ALLOY NO. 25 TUBES

by Klaus H. Gumto

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

Two heats of Haynes Alloy No. 25 tubes 0.953 cm (0.375 in.) o.d. by 0.064 cm (0.025 in.) wall tubes were tested to failure at temperatures from 1099 to 1200 K (1518° to 1700° F) and internal helium pressures from 4.1 to 12.4 MN/m^2 (600 to 1800 psi). Lifetimes ranged from 385 to 4609 hr for one heat, whose creep rupture strength correlated with that of sheet tensile specimens. The other heat, with lifetimes from 144 to 1308 hr, had strengths 20 to 40 percent lower. Larson-Miller parameter correlations and photomicrographs of some specimens are presented.

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SUMMARY

In order to obtain creep rupture data for designing a helium-to-air heat exchanger, 66 seamless Haynes Alloy No. 25 tubes were tested to failure at constant temperature and pressure. The tubes were pressurized internally with helium, but were tested in an air atmosphere.

Two heats of 0.953 centimeter (0.375 in.) outside diameter by 0.064 centimeter (0.025 in.) wall tubes were purchased. This alloy is a cobalt base superalloy, and was selected for its high strength at high temperatures, fabricability, and resistance to oxidation and corrosion.

The test temperatures and pressures were chosen to simulate the proposed service conditions. The test temperatures ranged from 1099 to 1200 K (1518° to 1700° F), with helium pressures from 4.1 to 12.4 MN/m^2 (600 to 1800 psi) corresponding to equivalent stresses from 26.00 to 79.09 MN/m^2 (3.77 to 11.47 ksi). The lifetimes for the two heats ranged from 385 to 4609 hours, and from 144 to 1308 hours.

The test pressures were converted to equivalent stresses, which were correlated to the lifetimes and test temperatures by the Larson-Miller parameter. Comparison with sheet tensile data showed that the creep-rupture strength of one heat was as high as that of the uniaxial test specimens, while the other was from 20 to 40 percent lower. This difference was attributed to inclusions and smaller grain size in the heat having the lower strength.

To show how the test results may be used, the lifetime of a 0.635 centimeter (0.250 in.) outside diameter by 0.076 centimeter (0.030 in.) wall tube was calculated. This tube had an internal pressure of 10.3 MN/m^2 (1500 psi) and a temperature of 1089 K (1500° F), and was made from the heat having the higher strength. For these conditions, and using a safety factor of 1.5, the predicted lifetime is 30 500 hours.

INTRODUCTION

Mobile nuclear powerplants have been proposed for both aircraft and air-cushion vehicles (refs. 1 and 2). One such powerplant consists of a helium cooled nuclear reactor and a helium-to-air heat exchanger located in the combustor section of an aircraft turbofan engine. Both the reactor and the heat exchanger will be designed for a lifetime of 10 000 hours. The heat exchanger will be operating at temperatures of 1089 to 1144 K (1500° to 1600° F) and at helium pressures up to 12.41 MN/m^2 (1800 psi).

In order to make the heat exchanger as light as possible, the creep-rupture properties of the heat-exchanger material must be known accurately. Yield criteria such as those of von Mises or Tresca are useful to predict behavior of materials under multiaxial stress conditions, based on uniaxial test results. Such methods are based on the assumption that the material under investigation is isotropic. Tubes, however, become anisotropic during the manufacturing process. The yield criteria, therefore, cannot accurately predict the creep-rupture behavior when the tube is pressurized internally at high temperature over a long period of time.

Tests were performed on internally pressurized tubes heated in an electric resistance furnace. The temperatures and pressures were selected to simulate the proposed service conditions and to give specimen lifetimes of 200 to 2000 hours. The results will be used in the design of the helium-to-air heat exchanger.

The material chosen for these tests was Haynes Alloy No. 25, which is commercially available in seamless tube form. This alloy is a cobalt base superalloy. It was selected because it has high strength at high temperature, good oxidation resistance, and can be welded and fabricated.

The test results were correlated by Morris' method (ref. 3). Morris assumed that the von Mises criterion holds for creep strain, that the secondary creep rate is a power function of stress, and that for long lifetimes primary and tertiary creep may be neglected. The test results are presented by means of a stress-parameter plot.

All measurements were made in U.S. customary units.

SYMBOLS

B material constant

n stress exponent

P Larson-Miller parameter

p pressure, MN/m^2 (psi)

T temperature, K ($^\circ$F)

t time, hr

$\dot{\epsilon}$ strain rate, hr^{-1}

$\dot{\epsilon}_{\theta a}$ diametral strain rate at the bore of the tube, hr^{-1}

$\dot{\epsilon}_{\theta b}$ diametral strain rate at outside diameter of tube, hr^{-1}

$\dot{\bar{\epsilon}}_a$ equivalent strain rate at the bore of the tube, hr^{-1}

ρ ratio of the outside diameter to the inside diameter of the tube

$\bar{\sigma}$ equivalent stress, MN/m^2 (ksi)

PROCEDURES

Material

Sixty-six seamless tubes of Haynes Alloy No. 25 (refs. 4 and 5) were tested. This alloy is a member of the cobalt-base superalloy group and has an alternate designation of L-605. It is used for jet-engine parts such as turbine blades and afterburners, and as furnace muffles and liners in high-temperature kilns. The alloy is used extensively at temperatures up to 1367 K (2000° F). It is ductile, shows good resistance to oxidation, carburization, and corrosion, can be easily machined and welded, and is available in all forms.

Both of the heats of tubes tested were manufactured to the same specifications. Table I gives the heats and chemical analyses of Haynes Alloy No. 25. The weight percentages of the alloy constituents were within the tolerances of the Aeronautical Material Specification (AMS) 5537 for Haynes Alloy No. 25 sheet. The samples labeled heat L3-1637 and heat L1-1592 are tubes, while the remainder are sheet tensile specimens from references 6 and 7.

The two heats of drawn tubes were purchased commercially. They received the following heat treatment. The tubes were annealed in a cracked ammonia atmosphere for 2 to 4 minutes at 1465±14 K (2175°±25° F), followed by rapid cooling in air.

Test Specimens

Haynes Alloy No. 25 tube specimens were from 35.6 to 40.6 centimeters (14 to 16 in.) long, with a nominal outside diameter of 0.953 centimeter (0.375 in.) and a wall thickness of 0.064 centimeter (0.025 in.). Table II shows the measured outside diameter and wall thickness of each tube. The tube length was chosen so that the welded ends of the tube specimens remained outside the 30.5-centimeter- (12-in.-) long test section of the furnaces. The ratio of tube diameter to wall thickness was about 15, classifying these specimens as thick tubes.

Each tube test specimen (fig. 1) was assembled with gas tungsten arc welds. The materials were first ultrasonically cleaned and degreased. Then the hanger wire, the end plug, the inlet fitting, and the inlet tube with sleeve and sleeve nut, all made from 304 stainless steel, were welded in place. Finally, the completed tube specimens were tested with a mass spectrometer to ensure that the welds were helium tight.

Tests

Figure 2 is a schematic of the tube test rig. Four tubes at a time were tested in one of the electric resistance furnaces in an air atmosphere. The tubes were tested at constant temperatures and static internal helium pressures until failure. Three Chromel-Alumel thermocouples located at the middle and ends of the 5-centimeter- (2-in.-) long constant-temperature zone ($\pm$1.7 K ($\pm 3^{\circ}$ F)) measured the test temperatures, which were recorded on a 24-channel strip-chart recorder. The thermocouples were suspended from the top of the furnace and were not attached to the test specimens. The test pressures were monitored by a pressure transducer in each specimen's pressure circuit and were recorded continuously on a second 24-channel strip-chart recorder.

Before the test, the tubes were pressurized with helium to about 8.3 MN/m^2 (1200 psi), followed by a release of the pressure. Several cycles of this procedure purged the tubes of air. After this, the furnaces were brought up to the test temperatures. When the temperatures had stabilized, each tube was pressurized with helium to its test pressure, and was then sealed off by means of a valve. The pressures were monitored daily to check for minor leaks and tube failures. If the leaks caused loss of pressure, helium was added when necessary to maintain the test pressure. A pressure drop to 1/3 of the test pressure in less than 48 hours constituted failure.

The helium test pressures ranged from 4.1 to 12.4 MN/m^2 (600 to 1800 psi), the temperatures ranged from 1099 to 1200 K (1518° to 1200° F), and the test times varied from 144 to 4609 hours. The effective stresses at the tube bore were from 26.00 to 79.09 MN/m^2 (3.77 to 11.47 ksi). The tests were run in furnace air for a long duration to observe the effects of metallurgical changes and oxidation on life, and to reduce the errors in extrapolating creep data to long lifetimes, such as 10 000 hours.

Metallography

Sections of the tubes were taken both before and after testing, in both the longitudinal and transverse direction. For the post-test specimens, the sections were taken near the point of failure. The surfaces of the sections were etched electrolytically with chromic acid. Photomicrographs were then taken of the etched surfaces.

Accuracy

The uncertainty in the specimen temperature was about ±2.8 K (±5° F). The furnace controller sensitivity of ±2 microvolts and thermocouple variations contributed to the temperature uncertainty. The accuracy of the specimen pressures was estimated at ±0.07 MN/m^2 (±10 psi). This accuracy was affected by small leaks, by daily variation in the room temperature, and by expansion of the tube due to creep. The variation of the tube wall thickness was ±1.2 percent.

Analysis

The analysis of the tube test data was developed by Morris (ref. 3). His analysis of weld-drawn N-155 tubes was based on the following assumptions:

(1) The tube material is isotropic.

(2) The von Mises criterion for yielding is applicable to creep in the pressure tube wall.

(3) The principal strain rates are proportional to the reduced, or deviatoric, principal stresses (ref. 8).

(4) The axial strain rate is zero.

(5) The principal axes of stress and creep strain coincide.

(6) Norton and Bailey's exponential stress law, presented in reference 9, applies.

$$\dot{\epsilon} = B\bar{\sigma}^n \tag{1}$$

(7) The strain rate remains uniform over the life of the specimen; that is, primary and tertiary creep are negligible compared to secondary creep. Therefore, the diametral strain rate $\dot{\epsilon}_{\theta b}$ is equal to the strain measured on the outside diameter at rupture divided by the lifetime of the specimen.

On the basis of these assumptions, Morris used the following equations in his analysis. The equivalent stress at the bore of the tube is

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{n} \rho^{2/n}}{\rho^{2/n} - 1} p \qquad (2)$$

The diametral strain rate at the tube bore is related to the strain rate at the outside diameter by

$$\dot{\epsilon}_{\theta a} = \rho^2 \dot{\epsilon}_{\theta b} \qquad (3)$$

The equivalent strain rate at the bore of the tube is

$$\dot{\bar{\epsilon}}_a = \frac{2}{\sqrt{3}} \rho^2 \dot{\epsilon}_{\theta b} \qquad (4)$$

The analysis required a value for the stress exponent n in equation (1), which is temperature dependent. The values for n were determined by plotting the calculated equivalent bore strain rates as functions of the test pressure in each tube on log-log paper. This resulted in several straight lines, one for each test temperature. The reciprocal of the slope of each line was the value of n at the test temperature. A similar plot of stress against strain rate for the uniaxial data from references 6 and 7 gave the n values for bar and sheet. The results are shown in figure 3, which relates the value of the stress exponent n to the test temperature for both tubes and uniaxial test specimens.

The values of n determined by this method were used in this analysis, whereas Morris used a constant n, which was an average over the temperature range used in his tests. A second difference between this and Morris' analysis is that the actual wall thickness and tube diameters were used in the equations herein, whereas the nominal values supplied by the manufacturer were used by Morris.

Strain Measurement

The difference of the diameters of the failed and as-received tubes divided by the diameter of the as-received tube measured the circumferential strain at fracture. The outside diameters were measured, both before and after the test, with a micrometer at four points on each tube circumference spaced 45° apart. The measurements before the test were made at the middle of the tube. Following the tests, the tubes were measured at the point of fracture. Each set of four measurements was averaged to obtain the as-received and the strained diameters.

The diameters were also measured at a point 2.5 centimeters (1 in.) from the inlet end of the tube. Since this point was outside the furnace, no change was expected here. Comparison of measurements before and after the test show this to be so. This check was necessary because the tube wall thickness could not be measured before the test. Therefore, the tube was cut apart following the test and the wall thickness was measured with a caliper type micrometer at 2.5 centimeters (1 in.) from the inlet end at four places spaced 45° apart. The four measurements were averaged to obtain the tube wall thickness.

RESULTS AND DISCUSSION

Two heats of seamless Haynes Alloy No. 25 tubing was purchased commercially to make 66 test specimens. These were pressurized internally with helium and tested in an electric furnace at constant temperature in an air atmosphere at atmospheric pressure. The internal helium pressures ranged from 4.14 to 12.4 MN/m^2 (600 to 1800 psi), and the test temperatures ranged from 1099 to 1200 K (1518° to 1700° F). The effective stresses at the tube bore varied from 26.0 to 79.09 MN/m^2 (3.77 to 11.47 ksi). The lifetimes for the two heats were 385 to 4609 hours for heat L1-1592, and 144 to 1308 hours for heat L3-1637. The test results are listed in table III.

Correlation

The two heats of Haynes Alloy No. 25 showed a difference in the creep-rupture strengths. Heat L1-1592 had the same strength as the sheet tensile specimens from references 6 and 7, so that for this heat, the lifetime predictions could be based on uniaxial data. Heat L3-1637, however, had creep-rupture strengths 20 to 40 percent lower than both the sheet data and heat L1-1592, so that for this heat, predictions based on uniaxial data will not be correct.

The equivalent stresses and the Larson-Miller parameter (ref. 10) values are shown in table III and figures 4, 5, and 6 for the tubes, and in table IV and figures 6 and 7 for the sheet tensile test data. The equivalent stresses were calculated by using equation (2), which gives the equivalent stress at the tube bore by the distortion energy theory.

The value of the stress exponent n used in equation (2) is a function of temperature. The values used herein ranged from 6.0 at 1099 K (1518° F) to 2.2 at 1200 K (1700° F) for the heat L3-1637 tubes. Calculations for the stress exponent n for the uniaxial test specimens gave values ranging from 7.6 at 1089 K (1500° F) to 4.2 at 1256 K (1800° F). These are shown in figure 3. The value of $n = 4.28$ at 1200 K (1700° F) was the only one possible to calculate from the data for heat L1-1592. At other temperatures, $n = 4.8$ was assumed. The method used to calculate the stress exponent was described in the Analysis section.

The test data for both heats of the tubes and the data for the sheet tensile tests were used as input for the computer program of Mendelson, Roberts, and Manson (ref. 11). This program considers several parameters, but selected the Larson-Miller parameter for the best correlation of the stress, lifetime, and temperature data. The program also chose different constants to be used with the parameter for each of the two heats of tubes and the uniaxial test specimens. The results are plotted in figures 4, 5, and 7, which show the fitted Larson-Miller curves with ±1 standard deviation.

Since the constants for each parameter were different, the results could not be plotted on one graph for comparison. In order to make such a comparison, the test results and the uniaxial sheet test data were correlated by means of the Larson-Miller parameter by using a constant of 20.0. This is a commonly used value and therefore permits comparison with other published data also using this constant. The results of the computer calculations are listed in tables III and IV, and are shown in figure 6. This figure shows that the rupture strengths of the heat L1-1592 tubes and the uniaxial test specimens are nearly equal, and that the rupture strength of the heat L3-1637 tubes is from 20 to 40 percent less than that of the uniaxial test specimens.

A sample calculation to predict the lifetime of a tube under given temperature and pressure conditions based on the test results is shown in the appendix.

Creep Strain Rate

The creep strain rate was obtained by first measuring the diametral strain at rupture, then calculating the equivalent bore strain, and finally dividing the bore strain by the lifetime of the tube. The equivalent bore strain rates obtained by this method are listed in table III. It should be noted that this method assumes that the creep strain rates are uniform over the lifetime of the specimens, and that the primary and tertiary creep is negligible compared to secondary creep, so that the resultant creep strain rates are average values. Table IV lists the creep strain rates for the uniaxial test specimens calculated from the test results reported in references 6 and 7.

Figure 8 shows the equivalent stress as a function of the equivalent bore strain rate for the tubes. The graph is on log-log paper, so that the isothermal lines are straight, and have a slope equal to the reciprocal of the stress exponent n.

Fracture

Tube fracture occurred on planes parallel to the axis of each tube, propagating along grain boundaries. The fractures were very small, so that a bubble test was necessary to locate the failure spot. The pressure loss was gradual. The time to drop to 1/3 of the test pressure following the fracture ranged from 80 minutes to over 48 hours, with most of the tubes falling into the 300- to 700-minute range.

Metallography

Figures 9 to 12 are photomicrographs of tube specimens both before and after the tests, showing both longitudinal and transverse sections of heats L1-1592 and L3-1637. The original photomicrographs of the specimens were magnified 100 times.

Figures 9(a) and (b) show a tube made from heat L3-1637 in the as-received condition. Figure 9(a) shows many stringers running in the longitudinal direction, especially near the inside of the tube. A hardness test on the longitudinal section resulted in a Rockwell C hardness of 32 near the middle of the tube wall, and 27 near the outside diameter.

Figures 10(a) and (b) show specimen 29 following the test. This tube was made from heat L3-1637, and was tested at 1150 K (1610° F) and 6.89 MN/m^2 (1000 psi) for 1308 hours. The grain size did not change, and considerable precipitation is evident. This precipitate probably consists of M_6C carbides at the grain boundaries (ref. 12) as well as Laves phase (Co_2W) at the grain boundaries and within the grains (ref. 13). The outside surface of the specimen shows some depletion.

Figures 11(a) and (b) are photomicrographs of a heat L1-1592 tube as received. This heat had larger grains and fewer and less dense stringers than heat L3-1637. Also, this tube had a Rockwell C hardness of 22 near the middle of the tube wall.

Figures 12(a) and (b) show specimen 2 (heat L1-1592) which was tested at 1144 K (1600° F) and 0.65 MN/m^2 (1400 psi) for 2279 hours. This specimen also shows no change in grain size following the test. Precipitates at the grain boundaries and within the grains are evident, although the amount is smaller than in heat L3-1637. The intergranular fractures are clearly visible.

Comparison of the photomicrographs shows several differences between the two heats. These differences most likely account for the difference in creep-rupture strengths. The stringers, whose composition has not been determined, are much more prominent in heat L3-1637 than in the other heat. These stringers contribute to the anisotropy of the material and probably tend to weaken the material. The smaller grain size of this heat also reduces the creep strength of this heat.

CONCLUDING REMARKS

Sixty-six seamless tubes of Haynes Alloy No. 25 pressurized internally with helium were tested in an electric resistance furnace until failure. The tests in an air atmosphere ranged from 144 to 4609 hours. The test temperatures ranged from 1099 to 1200 K (1518° to 1700° F), and the pressures ranged from 4.1 to 12.4 MN/m^2 (600 to 1800 psi). The pressures resulted in equivalent stresses at the tube bore from 26.00 to 79.09 MN/m^2 (3.77 to 11.47 ksi). The pressures were converted to equivalent stresses and correlated to the test temperatures and lifetimes by the Larson-Miller parameter. The parameter constant for the two heats of tubes and for the sheet tensile specimens was selected by a computer program. A graph is shown for each correlation. All three sets of data are also correlated by the Larson-Miller parameter using a constant of 20.0, which permits all three sets to be presented on one graph for comparison.

Analysis of the test data and the photomicrographs of the specimens produced the following results and conclusions:

1. Tests of two heats of Haynes Alloy No. 25 tubes showed the creep-rupture strengths for one heat to be as high as the strength of the uniaxial tensile test specimens, while the other heat was 20 to 40 percent weaker.

2. The difference in the creep-rupture strength of the two heats is apparently due to (a) the stringers which produce anisotropy, and (b) different grain sizes. Since the two heats were fabricated to the same specifications, the differences are presumed to be due to the tolerances in the specifications.

3. Predictions of creep-rupture lifetimes for Haynes Alloy No. 25 tubes should not be based on uniaxial tensile test data. Rather, the predictions should be based on tests made with tubes of the same heat.

4. Tube failures propagated radially along the grain boundaries.

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National Aeronautics and Space Administration,
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126-15.

APPENDIX - APPLICATION OF DATA

One example of the application of the creep-rupture data is the calculation of the service lifetime for tubes in a heat exchanger at a constant temperature and internal pressure. The following are the pertinent specifications and conditions for a heat L1-1592 tube used in the sample calculations:

Material	Haynes Alloy No. 25, seamless tubing
Tube size:	
Outside diameter, cm (in.)	0.635 (0.250)
Wall thickness, cm (in.)	0.076 (0.030)
Ratio of outside diameter to inside diameter	1.3158
Pressure, MN/m^2 (psi)	10.3 (1500)
Temperature, K (^{o}F)	1089 (1500)
Stress exponent n	4.8
Safety factor N	1.5

The equivalent stress is calculated by equation (2):

$$\bar{\sigma} = \frac{\frac{\sqrt{3}}{4.8}(1.3158)^{2/4.8}}{(1.3158)^{2/4.8} - 1.0} p = 3.34 p = 34.40 \text{ MN/m}^2 \text{ (5009 psi)}$$

The ultimate equivalent strength $\bar{\sigma}_u$ is calculated by

$$\bar{\sigma}_u = N\bar{\sigma} = 1.5\,\bar{\sigma} = 51.60 \text{ MN/m}^2 \text{ (7514 psi)}$$

From figure 4, read the parameter value of 39.3 for the equivalent stress of 51.60 MN/m^2 (7514 psi), and solve for the lifetime t:

$$t = \text{antilog}\left[\frac{1000\ P}{1.8\ T} - 15.567\right] = 30\ 500 \text{ hours}$$

where temperature T is in kelvins. Thus, for the given conditions, the service lifetime is 30 500 hours. The calculated lifetime for a tube without the safety factor is 132 000 hours.

Performing a similar calculation for a heat L3-1637 tube under identical conditions results in a service lifetime of 5 850 hours, or 17 400 hours if the safety factor is omitted.

Since the results of heat L1-1592 are similar to the sheet tensile test results, calculations of tube lifetimes based on sheet tensile data will give similar lifetimes for this heat.

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TABLE I. - CHEMICAL COMPOSITION OF SPECIMENS OF

HAYNES ALLOY NO. 25

[Composition in weight percent.]

Component	Aeronautical material specification, AMS 5537 A	Specimen				
		Heat L1-1592 (a)	Heat L3-1637 (a)	HSD040 (b)	GE-062 (b)	CAL067 (b)
Cobalt	Balance	51.68	51.13	51.0	49.17	53.
Nickel	9.0 to 11.0	9.67	9.61	10.0	10.80	10.
Chromium	19.0 to 21.0	19.65	19.94	20.0	21.11	20.
Tungsten	14.0 to 16.0	15.21	15.23	15.0	15.54	15.
Iron	0 to 3.0	1.85	1.94	2.0	1.60	-----
Carbon	0.05 to 0.15	.046	.052	.09	.08	.13
Silicon	0 to 1.0	.45	.57	.40	.61	.4
Manganese	1.0 to 2.0	1.44	1.53	1.50	1.64	1.5

[a]Analysis by an independent laboratory.
[b]Sheet tensile specimens from references 6 and 7.

TABLE II. - TEST DATA FOR SEAMLESS TUBES OR HAYNES ALLOY NO. 25

Heat	Speci- men	Temperature, T		Pressure, p		Lifetime, hr	Outside diameter				Wall thickness		Stress exponent, n
							Before test		After test				
		K	^{o}F	MN/m^2	ksi		cm	in.	cm	in.	cm	in.	
L1-1592	1	1144.3	1600.0	9.65	1.40	2173.0	0.9604	0.3781	0.9964	0.3923	0.0648	0.0255	4.80
	2	1144.3	1600.0	9.65	1.40	2279.0	0.9604	0.3781	0.9972	0.3926	0.0643	0.0253	4.80
	3	1172.0	1650.0	6.21	0.90	2412.0	0.9601	0.3780	0.9954	0.3919	0.0640	0.0252	4.80
	4	1199.8	1700.0	4.14	0.60	4609.0	0.9601	0.3780	1.0089	0.3972	0.0635	0.0250	4.28
	5	1199.8	1700.0	4.14	0.60	4084.0	0.9604	0.3781	0.9947	0.3916	0.0638	0.0251	4.28
	6	1199.8	1700.0	5.52	0.80	1826.0	0.9601	0.3780	0.9906	0.3900	0.0632	0.0249	4.28
	7	1199.8	1700.0	5.52	0.80	2056.0	0.9611	0.3784	1.0018	0.3944	0.0638	0.0251	4.28
	8	1199.8	1700.0	6.21	0.90	1053.0	0.9611	0.3784	1.0023	0.3946	0.0638	0.0251	4.28
	9	1199.8	1700.0	6.21	0.90	1082.0	0.9611	0.3784	1.0013	0.3942	0.0638	0.0251	4.28
	10	1199.8	1700.0	6.89	1.00	759.0	0.9604	0.3781	1.0018	0.3944	0.0640	0.0252	4.28
	11	1199.8	1700.0	6.89	1.00	770.0	0.9601	0.3780	1.0046	0.3955	0.0643	0.0253	4.28
	12	1199.8	1700.0	8.27	1.20	434.0	0.9609	0.3783	1.0244	0.4033	0.0635	0.0250	4.28
	13	1199.8	1700.0	8.27	1.20	335.0	0.9609	0.3783	1.0071	0.3965	0.0635	0.0250	4.28
L3-1637	14	1098.7	1518.0	12.41	1.80	1053.0	0.9611	0.3784	0.9830	0.3870	0.0638	0.0251	5.97
	15	1098.7	1518.0	12.41	1.80	957.0	0.9619	0.3787	0.9792	0.3855	0.0638	0.0251	5.97
	16	1098.7	1518.0	12.41	1.80	1025.0	0.9614	0.3785	0.9835	0.3872	0.0640	0.0252	5.97
	17	1098.7	1518.0	12.41	1.80	952.0	0.9606	0.3782	0.9761	0.3843	0.0638	0.0251	5.97
	18	1122.0	1560.0	12.41	1.80	532.0	0.9629	0.3791	0.9876	0.3888	0.0635	0.0250	5.21
	19	1122.0	1560.0	12.41	1.80	513.0	0.9619	0.3787	0.9822	0.3867	0.0632	0.0249	5.21
	20	1122.0	1560.0	10.34	1.50	1150.0	0.9632	0.3792	0.9789	0.3854	0.0632	0.0249	5.21
	21	1122.0	1560.0	10.34	1.50	1047.0	0.9627	0.3790	0.9812	0.3863	0.0632	0.0249	5.21
	22	1133.1	1580.0	10.34	1.50	581.0	0.9627	0.3790	0.9863	0.3883	0.0640	0.0252	4.11
	23	1133.1	1580.0	10.34	1.50	454.0	0.9616	0.3786	0.9840	0.3874	0.0638	0.0251	4.11
	24	1133.1	1580.0	12.41	1.80	254.0	0.9614	0.3785	0.9886	0.3892	0.0638	0.0251	4.11
	25	1133.1	1580.0	12.41	1.80	297.0	0.9616	0.3786	0.9883	0.3891	0.0638	0.0251	4.11
	26	1138.7	1590.0	8.27	1.20	921.0	0.9614	0.3785	0.9802	0.3859	0.0643	0.0253	3.96
	27	1138.7	1590.0	8.27	1.20	900.0	0.9614	0.3785	0.9820	0.3866	0.0640	0.0252	3.96
	28	1144.3	1600.0	8.96	1.30	498.0	0.9611	0.3784	0.9837	0.3873	0.0635	0.0250	3.79
	29	1144.3	1600.0	8.96	1.30	478.0	0.9609	0.3783	0.9842	0.3875	0.0638	0.0251	3.79
	30	1144.3	1600.0	9.65	1.40	459.0	0.9614	0.3785	0.9845	0.3876	0.0632	0.0249	3.79
	31	1144.3	1600.0	9.65	1.40	419.0	0.9614	0.3785	0.9771	0.3847	0.0638	0.0251	3.79
	32	1144.3	1600.0	9.65	1.40	536.0	0.9616	0.3786	0.9853	0.3879	0.0635	0.0250	3.79
	33	1144.3	1600.0	9.65	1.40	520.0	0.9604	0.3781	0.9825	0.3868	0.0630	0.0248	3.79
	34	1144.3	1600.0	9.65	1.40	479.0	0.9622	0.3788	0.9815	0.3864	0.0635	0.0250	3.79
	35	1144.3	1600.0	9.65	1.40	550.0	0.9604	0.3781	0.9820	0.3866	0.0632	0.0249	3.79
	36	1144.3	1600.0	11.03	1.60	292.0	0.9614	0.3785	0.9865	0.3884	0.0635	0.0250	3.79
	37	1144.3	1600.0	11.03	1.60	312.0	0.9622	0.3788	0.9817	0.3865	0.0638	0.0251	3.79
	38	1149.8	1610.0	6.89	1.00	936.0	0.9616	0.3786	0.9865	0.3884	0.0635	0.0250	3.56
	39	1149.8	1610.0	6.89	1.00	1338.0	0.9614	0.3785	0.9792	0.3855	0.0635	0.0250	3.56
	40	1149.8	1610.0	12.41	1.80	187.0	0.9632	0.3792	0.9919	0.3905	0.0635	0.0250	3.56
	41	1149.8	1610.0	12.41	1.80	215.0	0.9616	0.3786	0.9893	0.3895	0.0635	0.0250	3.56
	42	1160.9	1630.0	8.27	1.20	1030.0	0.9611	0.3784	0.9883	0.3891	0.0638	0.0251	3.26
	43	1160.9	1630.0	8.27	1.20	1105.0	0.9611	0.3784	0.9837	0.3873	0.0635	0.0250	3.26
	44	1160.9	1630.0	10.34	1.50	192.0	0.9614	0.3785	0.9881	0.3890	0.0640	0.0252	3.26
	45	1160.9	1630.0	10.34	1.50	200.0	0.9611	0.3784	0.9924	0.3907	0.0635	0.0250	3.26
	46	1172.0	1650.0	5.52	0.80	946.0	0.9624	0.3789	0.9817	0.3865	0.0630	0.0248	2.94
	47	1172.0	1650.0	5.52	0.80	730.0	0.9616	0.3786	0.9817	0.3865	0.0638	0.0251	2.94
	48	1172.0	1650.0	5.52	0.80	1305.0	0.9622	0.3788	0.9782	0.3851	0.0635	0.0250	2.94
	49	1172.0	1650.0	5.52	0.80	1135.0	0.9627	0.3790	0.9794	0.3856	0.0632	0.0249	2.94
	50	1172.0	1650.0	6.21	0.90	653.0	0.9611	0.3784	0.9817	0.3865	0.0640	0.0252	2.94
	51	1172.0	1650.0	6.21	0.90	716.0	0.9609	0.3783	0.9835	0.3872	0.0643	0.0253	2.94
	52	1172.0	1650.0	6.21	0.90	737.0	0.9606	0.3782	0.9809	0.3862	0.0648	0.0255	2.94
	53	1172.0	1650.0	6.89	1.00	400.0	0.9619	0.3787	0.9835	0.3872	0.0638	0.0251	2.94
	54	1172.0	1650.0	6.89	1.00	430.0	0.9614	0.3785	0.9797	0.3857	0.0635	0.0250	2.94
	55	1172.0	1650.0	8.27	1.20	358.0	0.9616	0.3786	0.9815	0.3864	0.0632	0.0249	2.94
	56	1172.0	1650.0	8.27	1.20	347.0	0.9619	0.3787	0.9883	0.3891	0.0635	0.0250	2.94
	57	1188.7	1680.0	5.52	0.80	476.0	0.9611	0.3784	0.9815	0.3864	0.0635	0.0250	2.52
	58	1188.7	1680.0	5.52	0.80	434.0	0.9614	0.3785	0.9825	0.3868	0.0635	0.0250	2.52
	59	1188.7	1680.0	5.52	0.80	454.0	0.9619	0.3787	0.9837	0.3873	0.0638	0.0251	2.52
	60	1188.7	1680.0	5.52	0.80	478.0	0.9614	0.3785	0.9827	0.3869	0.0638	0.0251	2.52
	61	1199.8	1700.0	6.21	0.90	340.0	0.9604	0.3781	0.9903	0.3899	0.0635	0.0250	2.20
	62	1199.8	1700.0	6.21	0.90	315.0	0.9611	0.3784	0.9842	0.3875	0.0635	0.0250	2.20
	63	1199.8	1700.0	6.89	1.00	196.0	0.9614	0.3785	0.9860	0.3882	0.0632	0.0249	2.20
	64	1199.8	1700.0	6.89	1.00	136.0	0.9616	0.3786	0.9845	0.3876	0.0635	0.0250	2.20
	65	1199.8	1700.0	8.27	1.20	144.0	0.9616	0.3786	0.9858	0.3881	0.0630	0.0248	2.20
	66	1199.8	1700.0	8.27	1.20	148.0	0.9609	0.3783	0.9845	0.3876	0.0638	0.0251	2.20

TABLE III. - TEST RESULTS FOR TUBES OF HAYNES ALLOY NO. 25

Heat	Specimen	Equivalent stress, σ		Larson-Miller parameter, P (a)	Strain	Ultimate equivalent bore strain	Equivalent bore strain rate, ϵ_a, hr^{-1}
		MN/m^2	ksi				
L1-1592	1	59.45	8.62	48.07	0.3756E-01	0.5794E-01	0.2667E-04
	2	59.94	8.69	48.12	0.3835E-01	0.5902E-01	0.2590E-04
	3	38.68	5.61	49.34	0.3677E-01	0.5653E-01	0.2344E-04
	4	26.10	3.79	51.11	0.5079E-01	0.7790E-01	0.1690E-04
	5	26.00	3.77	51.00	0.3570E-01	0.5482E-01	0.1342E-04
	6	34.94	5.07	50.24	0.3175E-01	0.4863E-01	0.2663E-04
	7	34.69	5.03	50.36	0.4228E-01	0.6490E-01	0.3157E-04
	8	39.03	5.66	49.74	0.4281E-01	0.6571E-01	0.6182E-04
	9	39.03	5.66	49.75	0.4175E-01	0.6409E-01	0.5923E-04
	10	43.15	6.26	49.43	0.4311E-01	0.6627E-01	0.8618E-04
	11	42.96	6.23	49.43	0.4630E-01	0.7126E-01	0.9254E-04
	12	52.24	7.58	48.90	0.5609E-01	0.1013E+00	0.2335E-03
	13	52.24	7.58	48.78	0.4811E-01	0.7376E-01	0.1916E-03
L3-1537	14	77.33	11.22	45.55	0.2273E-01	0.3489E-01	0.3282E-04
	15	77.39	11.22	45.46	0.1796E-01	0.2756E-01	0.2879E-04
	16	77.03	11.17	45.52	0.2299E-01	0.3532E-01	0.3446E-04
	17	77.29	11.21	45.46	0.1613E-01	0.2476E-01	0.2574E-04
	18	78.07	11.32	45.99	0.2559E-01	0.3920E-01	0.6736E-04
	19	78.31	11.36	45.87	0.2112E-01	0.3234E-01	0.6304E-04
	20	65.35	9.48	46.59	0.1635E-01	0.2502E-01	0.2157E-04
	21	65.31	9.47	46.50	0.1926E-01	0.2948E-01	0.2816E-04
	22	64.97	9.42	46.44	0.2454E-01	0.3769E-01	0.6488E-04
	23	65.17	9.45	46.24	0.2324E-01	0.3567E-01	0.7688E-04
	24	78.18	11.34	45.74	0.2827E-01	0.4339E-01	0.1644E-03
	25	78.20	11.34	45.84	0.2773E-01	0.4256E-01	0.1433E-03
	26	51.76	7.51	47.08	0.1955E-01	0.3008E-01	0.3266E-04
	27	51.97	7.54	47.06	0.2140E-01	0.3289E-01	0.3654E-04
	28	56.85	8.24	46.76	0.2352E-01	0.3606E-01	0.7241E-04
	29	56.60	8.21	46.72	0.2432E-01	0.3733E-01	0.7810E-04
	30	61.49	8.92	46.70	0.2404E-01	0.3681E-01	0.7849E-04
	31	60.98	8.84	46.60	0.1638E-01	0.2514E-01	0.6000E-04
	32	61.25	8.88	46.77	0.2456E-01	0.3765E-01	0.7441E-04
	33	61.68	8.95	46.79	0.2301E-01	0.3520E-01	0.6769E-04
	34	61.29	8.89	46.72	0.2006E-01	0.3075E-01	0.6419E-04
	35	61.42	8.91	46.85	0.2248E-01	0.3443E-01	0.6260E-04
	36	69.98	10.15	46.28	0.2616E-01	0.4010E-01	0.1373E-03
	37	69.75	10.12	46.34	0.2033E-01	0.3119E-01	0.9997E-04
	38	43.86	6.36	47.55	0.2588E-01	0.3968E-01	0.4239E-04
	39	43.84	6.36	47.85	0.1849E-01	0.2835E-01	0.2167E-04
	40	79.07	11.47	46.10	0.2980E-01	0.4566E-01	0.2441E-03
	41	78.94	11.45	46.23	0.2879E-01	0.4413E-01	0.2053E-03
	42	52.57	7.63	48.14	0.2828E-01	0.4340E-01	0.4019E-04
	43	52.79	7.66	48.16	0.2352E-01	0.3606E-01	0.3263E-04
	44	65.47	9.49	46.57	0.2774E-01	0.4263E-01	0.2220E-03
	45	65.99	9.57	46.61	0.3251E-01	0.4983E-01	0.2492E-03
	46	35.70	5.18	48.48	0.2006E-01	0.3066E-01	0.3241E-04
	47	35.23	5.11	48.24	0.2087E-01	0.3202E-01	0.4387E-04
	48	35.40	5.13	48.77	0.1663E-01	0.2549E-01	0.1953E-04
	49	35.56	5.16	48.69	0.1741E-01	0.2665E-01	0.2249E-04
	50	39.45	5.72	48.14	0.2141E-01	0.3290E-01	0.5038E-04
	51	39.28	5.70	48.22	0.2353E-01	0.3620E-01	0.5056E-04
	52	38.96	5.65	48.25	0.2115E-01	0.3263E-01	0.4428E-04
	53	44.05	6.39	47.69	0.2245E-01	0.3444E-01	0.8611E-04
	54	44.21	6.41	47.76	0.1902E-01	0.2916E-01	0.6782E-04
	55	53.28	7.73	47.61	0.2060E-01	0.3154E-01	0.8571E-04
	56	53.08	7.70	47.56	0.2746E-01	0.4209E-01	0.1213E-03
	57	35.64	5.17	48.53	0.2114E-01	0.3241E-01	0.6809E-04
	58	35.65	5.17	48.55	0.2193E-01	0.3362E-01	0.6945E-04
	59	35.52	5.15	48.49	0.2271E-01	0.3485E-01	0.7676E-04
	60	35.50	5.15	48.53	0.2219E-01	0.3406E-01	0.7126E-04
	61	40.38	5.86	48.67	0.3121E-01	0.4786E-01	0.1408E-03
	62	40.41	5.86	48.60	0.2405E-01	0.3687E-01	0.1170E-03
	63	45.10	6.54	48.15	0.2563E-01	0.3924E-01	0.2002E-03
	64	44.93	6.52	48.10	0.2377E-01	0.3644E-01	0.1959E-03
	65	54.35	7.88	47.86	0.2509E-01	0.3837E-01	0.2665E-03
	66	53.66	7.78	47.89	0.2458E-01	0.3774E-01	0.2550E-03

[a] Larson-Miller parameter $P = \begin{cases} 1.8\,T(\log t + 20.0)\times 10^{-3} & \text{for } T \text{ in K} \\ T(\log t + 20.0)\times 10^{-3} & \text{for } T \text{ in } ^{\circ}\text{R} \end{cases}$

TABLE IV. - TENSILE TEST DATA FOR SHEET SPECIMENS OF HAYNES ALLOY NO. 25

[From refs. 6 and 7.]

Specimen	Temperature, T		Stress		Lifetime, hr	Strain	Strain rate, $\bar{\epsilon}$, hr^{-1}	Larson-Miller parameter, P (a)
	K	°F	MN/m^2	ksi				
HSD040	1088.7	1500.0	96.53	14.00	2850.0	0.4000E-01	0.1404E-04	45.97
	1088.7	1500.0	124.11	18.00	339.0	0.1500E+00	0.3856E-03	44.28
	1088.7	1500.0	124.11	18.00	324.0	0.1100E+00	0.3395E-03	44.12
	1088.7	1500.0	131.00	19.00	431.0	0.2000E+00	0.4640E-03	44.36
	1088.7	1500.0	148.24	21.50	259.0	0.1700E+00	0.6320E-03	43.96
	1088.7	1500.0	165.47	24.00	109.0	0.1700E+00	0.1560E-02	43.19
	1144.3	1600.0	55.16	8.00	1671.0	0.6000E-01	0.3591E-04	47.84
	1144.3	1600.0	68.95	10.00	532.0	0.1000E+00	0.1718E-03	46.90
	1144.3	1600.0	82.74	12.00	506.0	0.7600E-01	0.1502E-03	46.77
	1144.3	1600.0	96.53	14.00	186.0	0.1000E+00	0.5376E-03	45.88
	1144.3	1600.0	103.42	15.00	139.0	0.1900E+00	0.1367E-02	45.61
	1144.3	1600.0	124.11	18.00	52.0	0.1750E+00	0.3365E-02	44.73
	1199.8	1700.0	41.37	6.00	569.0	0.6000E-01	0.1054E-03	49.15
	1199.8	1700.0	55.16	8.00	233.0	0.1300E+00	0.4594E-03	48.50
	1199.8	1700.0	68.95	10.00	123.0	0.1300E+00	0.1057E-02	47.71
	1199.8	1700.0	82.74	12.00	76.0	0.1000E+00	0.1316E-02	47.26
	1255.4	1800.0	27.58	4.00	686.0	0.4000E-01	0.5831E-04	51.61
	1255.4	1800.0	34.47	5.00	259.0	0.4000E-01	0.1487E-03	50.69
	1255.4	1800.0	41.37	6.00	198.0	0.7000E-01	0.3535E-03	50.39
GE-062	1088.7	1500.0	137.90	20.00	438.0	0.1500E+00	0.3425E-03	44.38
	1088.7	1500.0	172.37	25.00	128.0	0.2100E+00	0.1641E-02	43.33
	1088.7	1500.0	241.32	35.00	9.0	0.2800E+00	0.3111E-01	41.07
	1172.0	1650.0	68.95	10.00	324.0	0.6000E-01	0.1852E-03	47.50
	1172.0	1650.0	103.42	15.00	36.0	0.1600E+00	0.4444E-02	45.48
	1172.0	1650.0	137.90	20.00	11.0	0.2000E+00	0.1818E-01	44.40
	1172.0	1650.0	172.37	25.00	2.0	0.2400E+00	0.1200E+00	42.84
CAL067	1088.7	1500.0	103.42	15.00	752.0	0.5000E-01	0.6649E-04	44.84
	1088.7	1500.0	137.90	20.00	90.0	0.6000E-01	0.6667E-03	43.03
	1088.7	1500.0	172.37	25.00	20.0	0.7500E-01	0.3750E-02	41.75
	1088.7	1500.0	206.84	30.00	5.0	0.1050E+00	0.2100E-01	40.57
	1255.4	1800.0	34.47	5.00	420.0	0.3500E-01	0.8333E-04	51.13
	1255.4	1800.0	41.37	6.00	155.0	0.4000E-01	0.2424E-03	50.21
	1255.4	1800.0	55.16	8.00	30.0	0.9000E-01	0.3000E-02	48.54
	1255.4	1800.0	68.95	10.00	12.0	0.9000E-01	0.7500E-02	47.64
	1255.4	1800.0	89.63	13.00	2.0	0.1350E+00	0.6750E-01	45.88
NAA050	1255.4	1800.0	31.03	4.50	970.0	0.2500E+00	0.2577E-03	51.95
CANNON--MUSK.	1088.7	1500.0	165.47	24.00	57.0	0.1200E+00	0.2105E-02	42.64
	1088.7	1500.0	165.47	24.00	25.0	0.1700E+00	0.6800E-02	41.94
MISC. SHEET.	1088.7	1500.0	165.47	24.00	58.0	0.1300E+00	0.2241E-02	42.66
	1088.7	1500.0	165.47	24.00	38.0	0.3200E+00	0.8421E-02	42.30

[a]Larson-Miller parameter $P = \begin{cases} 1.8T(\log t + 20.0)\times10^{-3} & \text{for } T \text{ in K} \\ T(\log t + 20.0)\times10^{-3} & \text{for } T \text{ in } {}^{o}R \end{cases}$

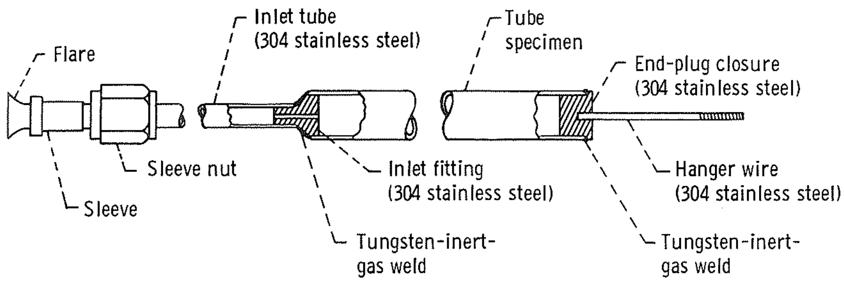


Figure 1. - Test specimen tube of Haynes Alloy No. 25.

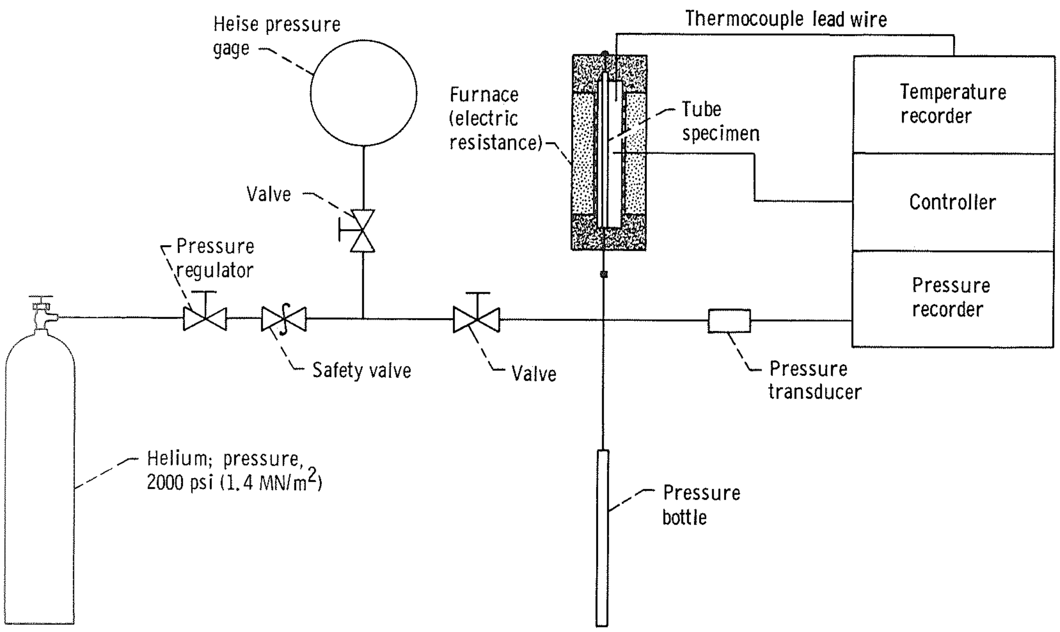


Figure 2. - Heat-exchanger-tube test rig. Maximum test temperature, 1200 K (1700° F); maximum test pressure, 12.41 MN/ m^2 (1800 psi).

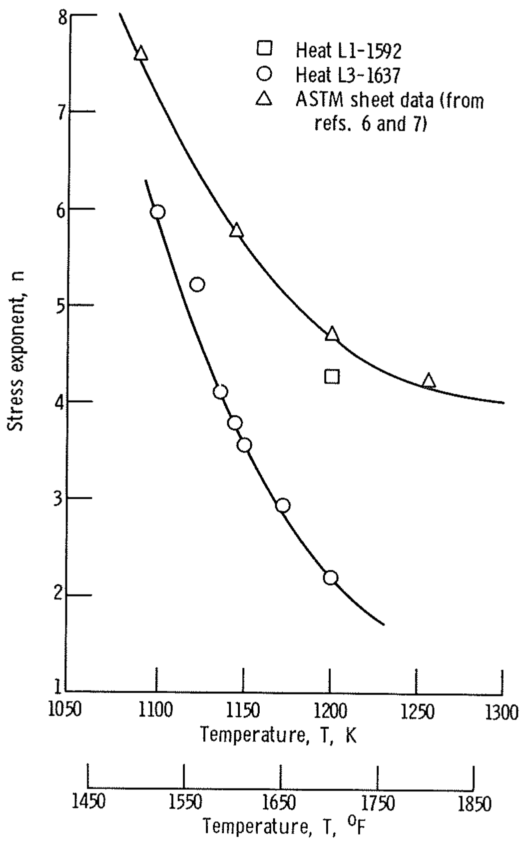


Figure 3. - Stress exponent as a function of temperature for Haynes Alloy No. 25.

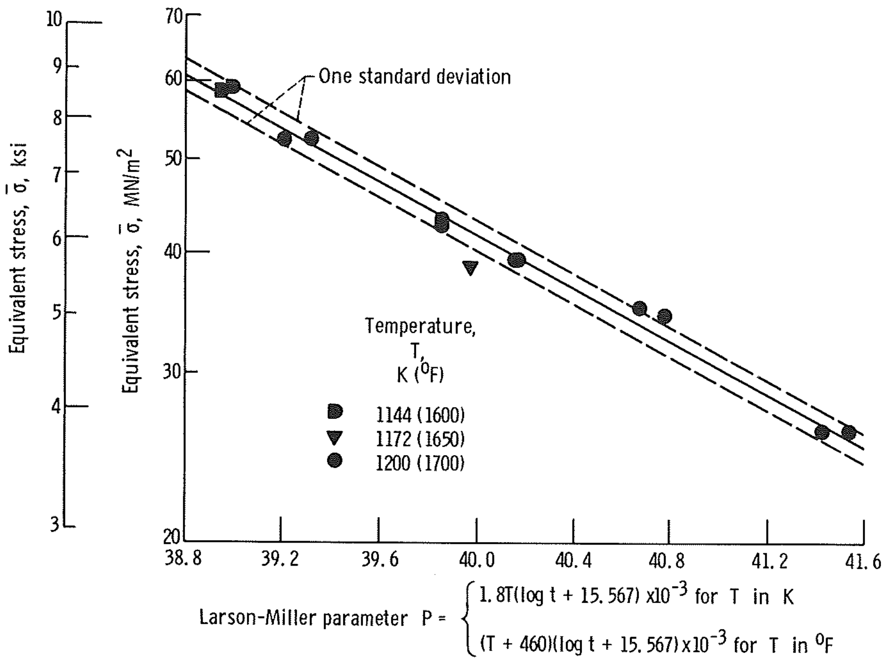


Figure 4. - Equivalent stress as a function of the Larson-Miller parameter for tube specimens of Haynes Alloy No. 25. Heat L1-1592.

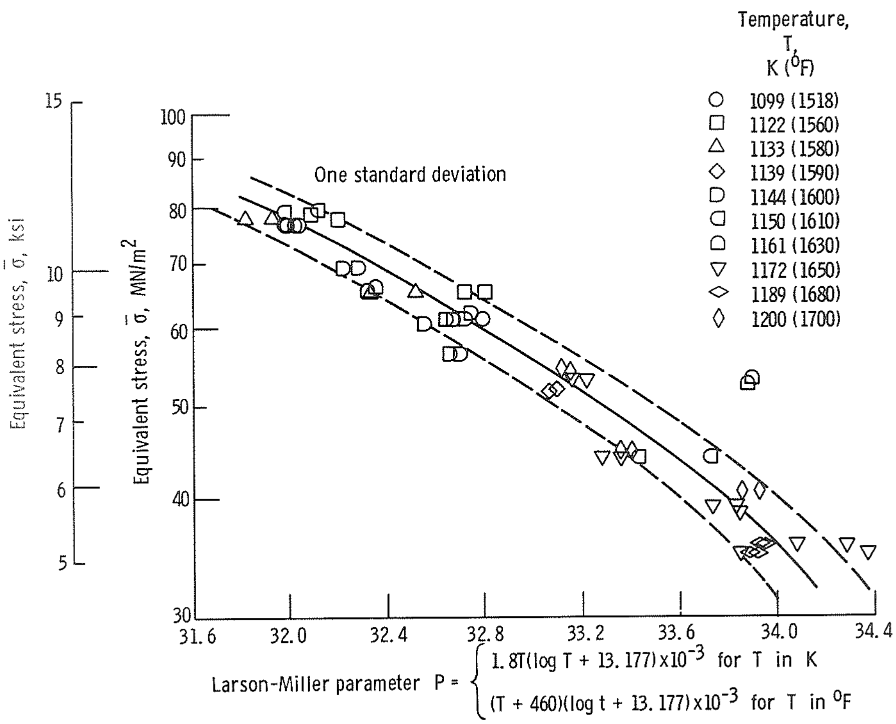


Figure 5. - Equivalent stress as a function of the Larson-Miller parameter for tube specimens of Haynes Alloy No. 25. Heat L3-1637.

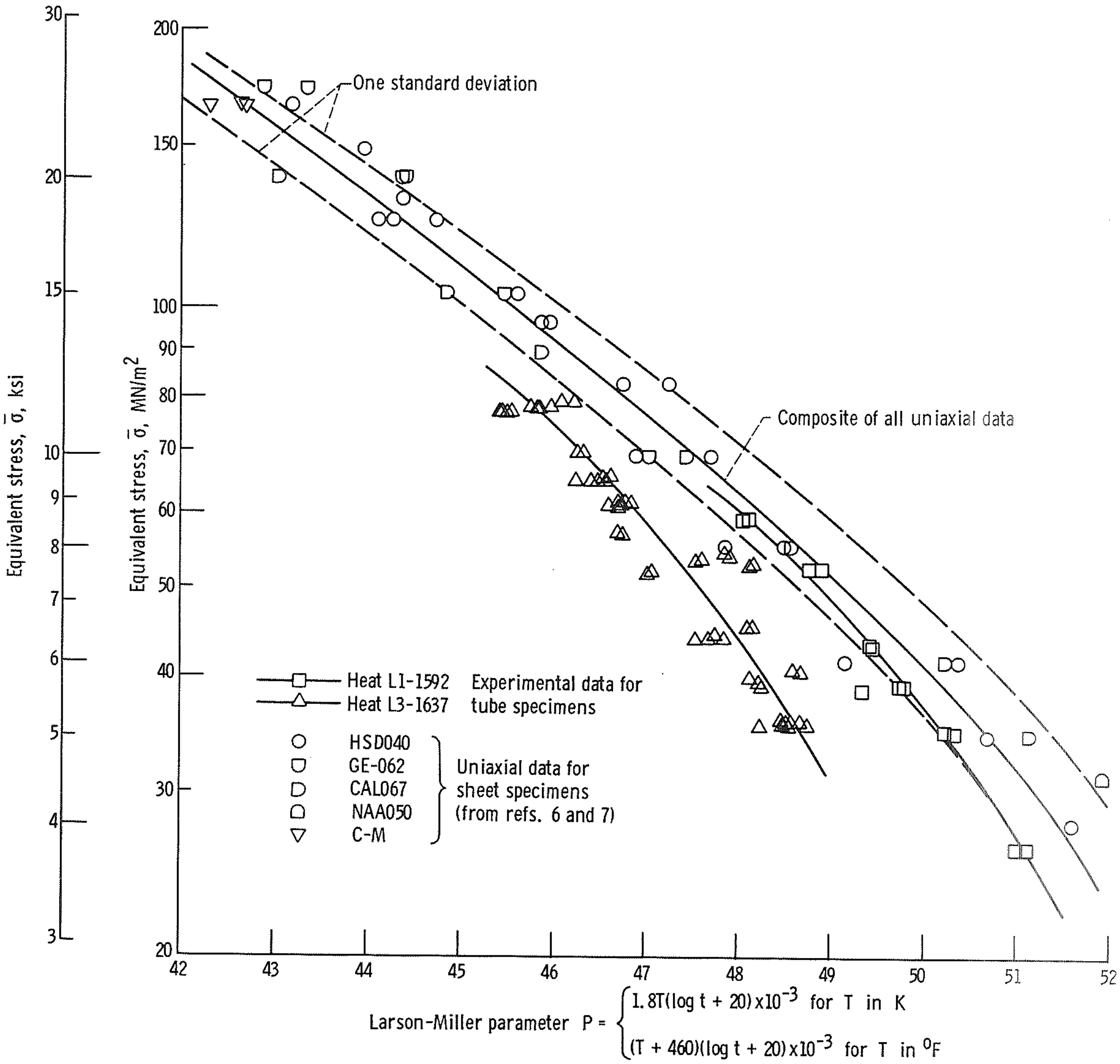
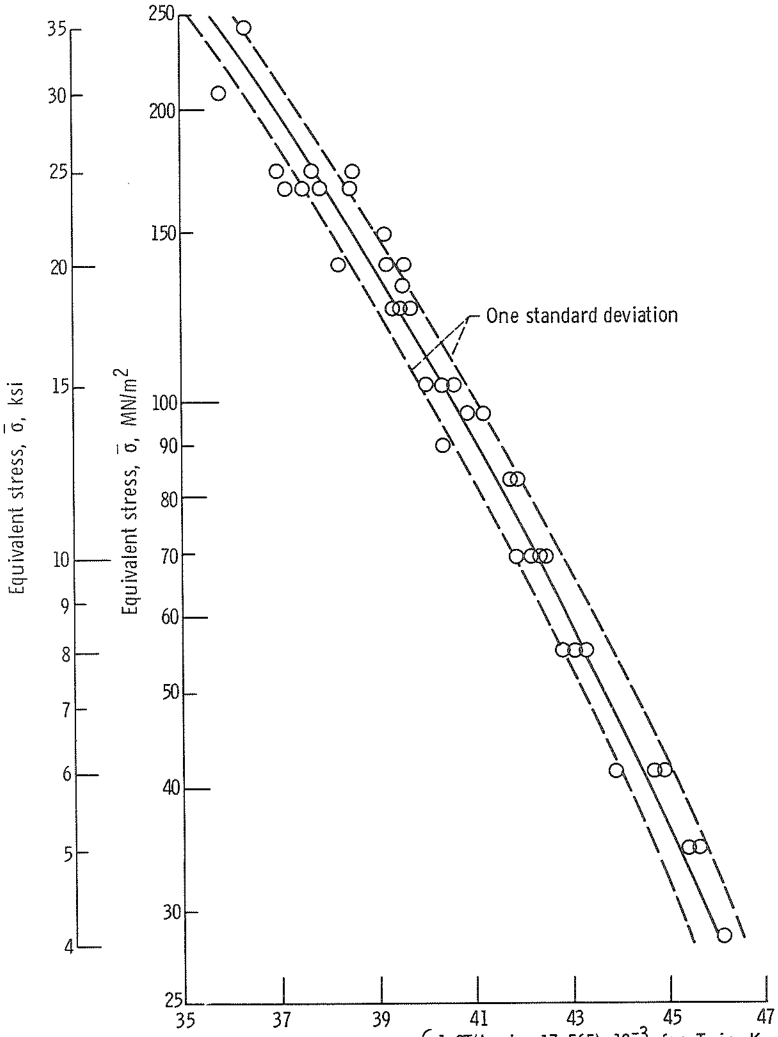


Figure 6. - Equivalent stress as a function of the Larson-Miller parameter for sheet and tube specimens of Haynes Alloy No. 25.



Larson-Miller parameter $P = \begin{cases} 1.8T(\log t + 17.565)\times10^{-3} & \text{for } T \text{ in K} \\ (T + 460)(\log t + 17.565)\times10^{-3} & \text{for } T \text{ in } ^{o}F \end{cases}$

Figure 7. - Equivalent stress as a function of the Larson-Miller parameter for sheet specimens of Haynes Alloy No. 25. (From refs. 6 and 7.)

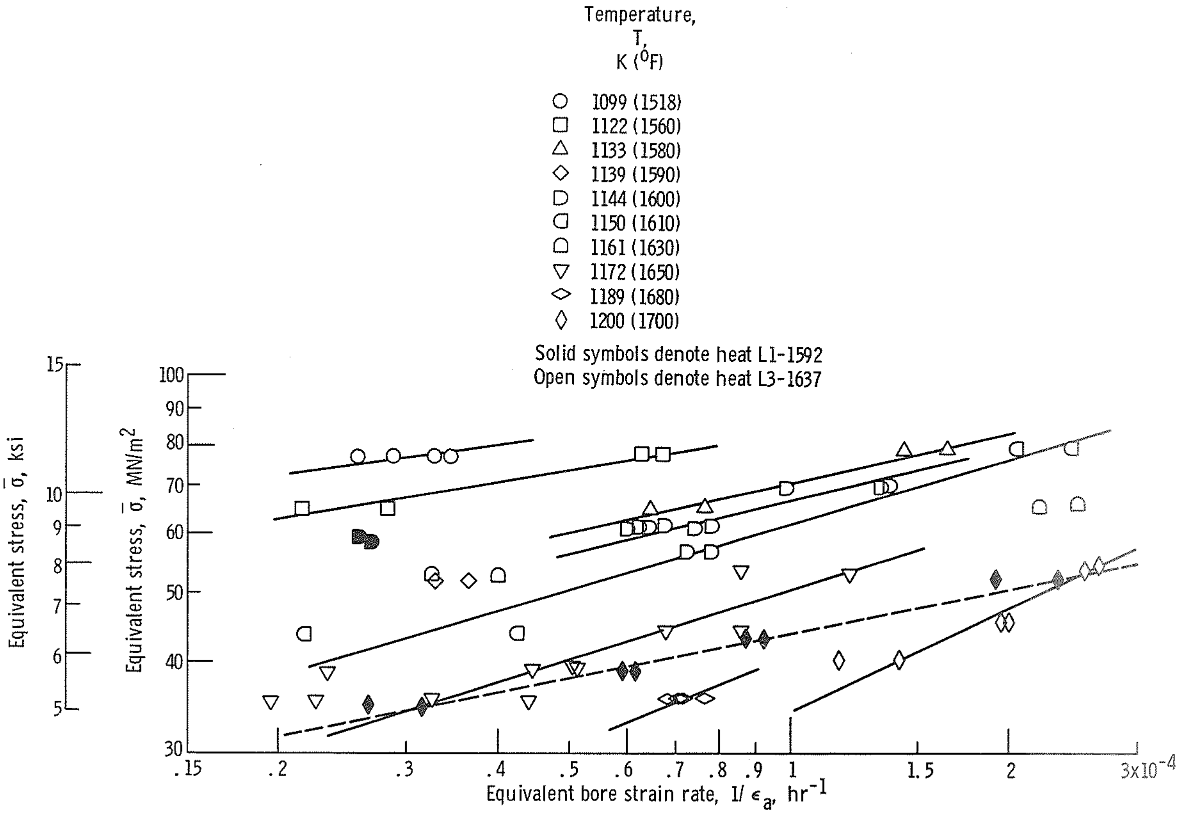
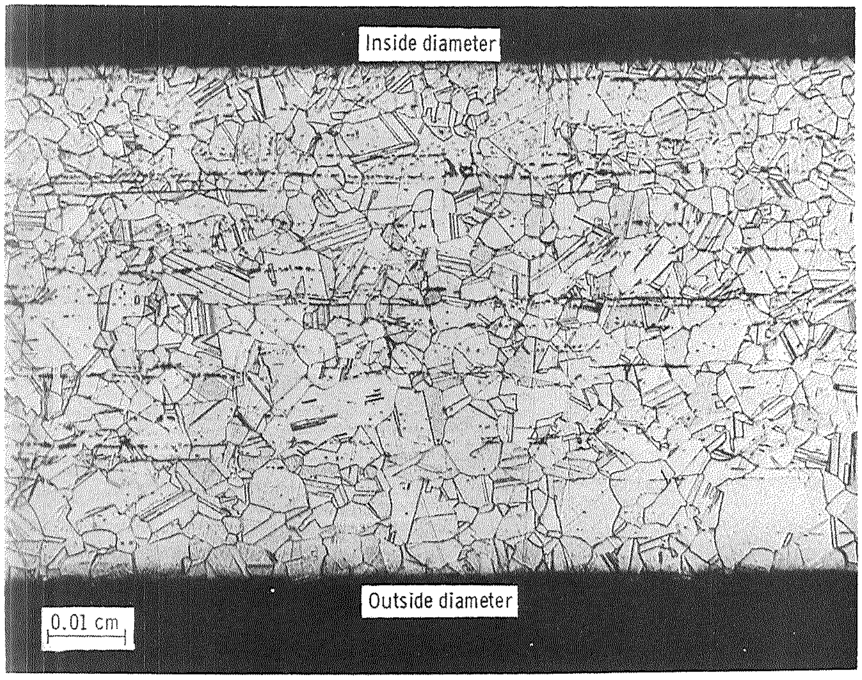
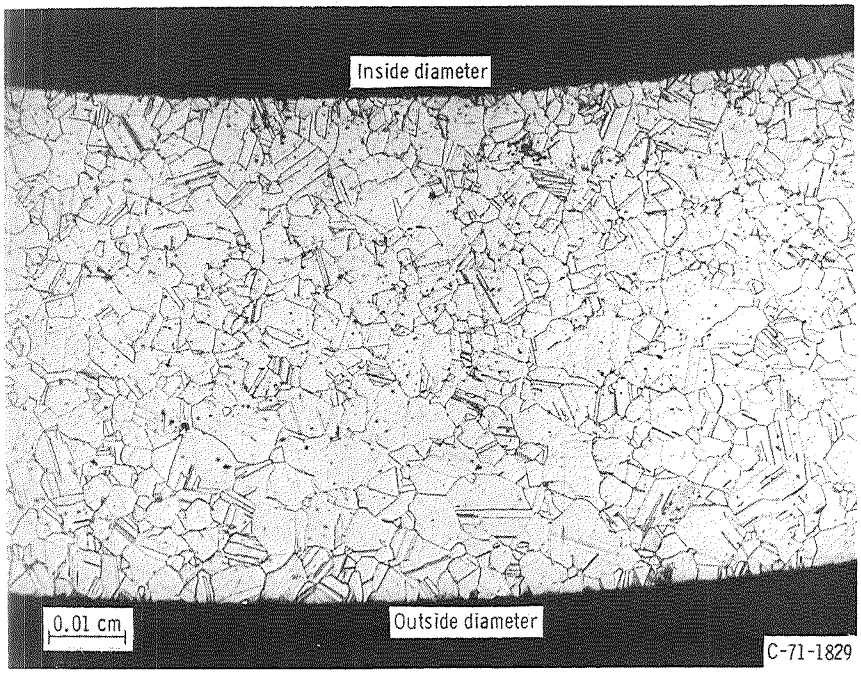


Figure 8. - Equivalent stress as a function of the equivalent bore strain rate for tube specimens of Haynes Alloy No. 25.

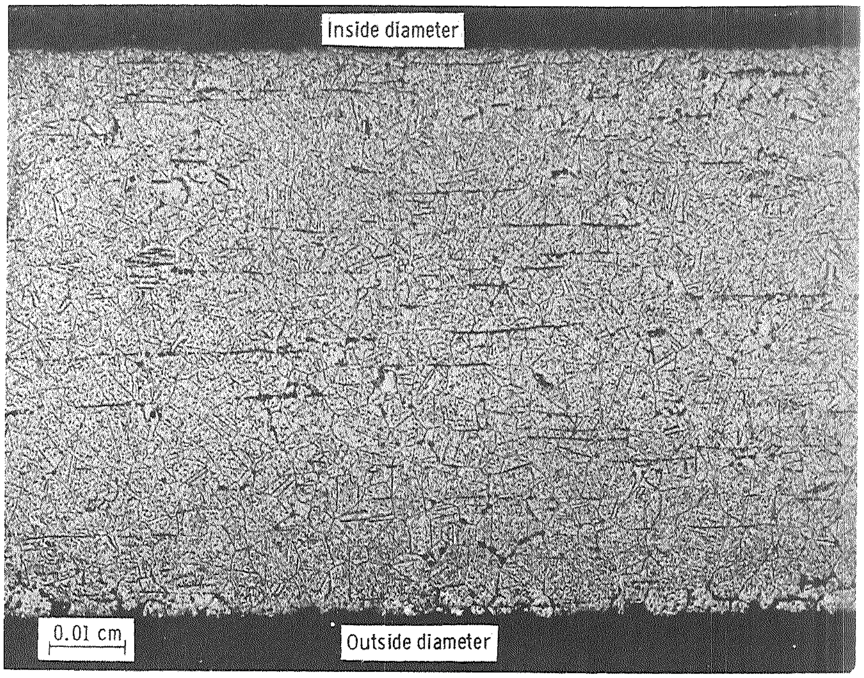


(a) Longitudinal section.

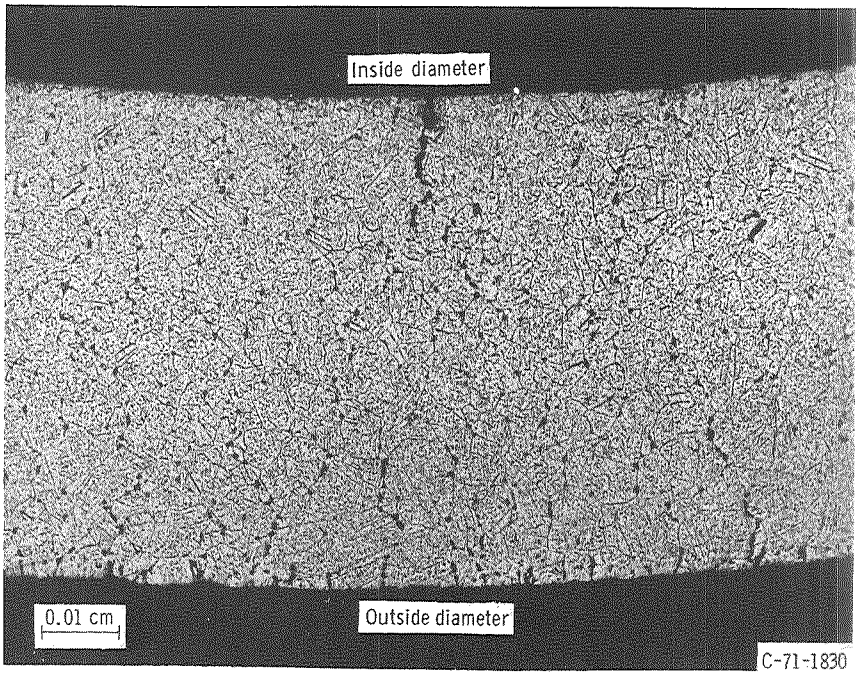


(b) Transverse section.

Figure 9. - Sections of as-received tube specimens of Haynes Alloy No. 25, from heat L3-1637. Etched. X100.

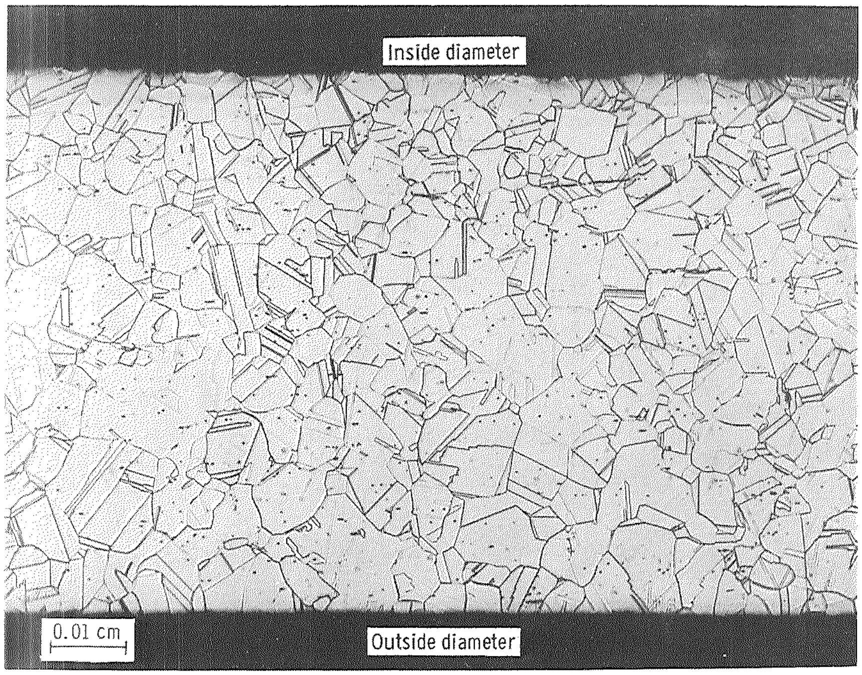


(a) Longitudinal section.

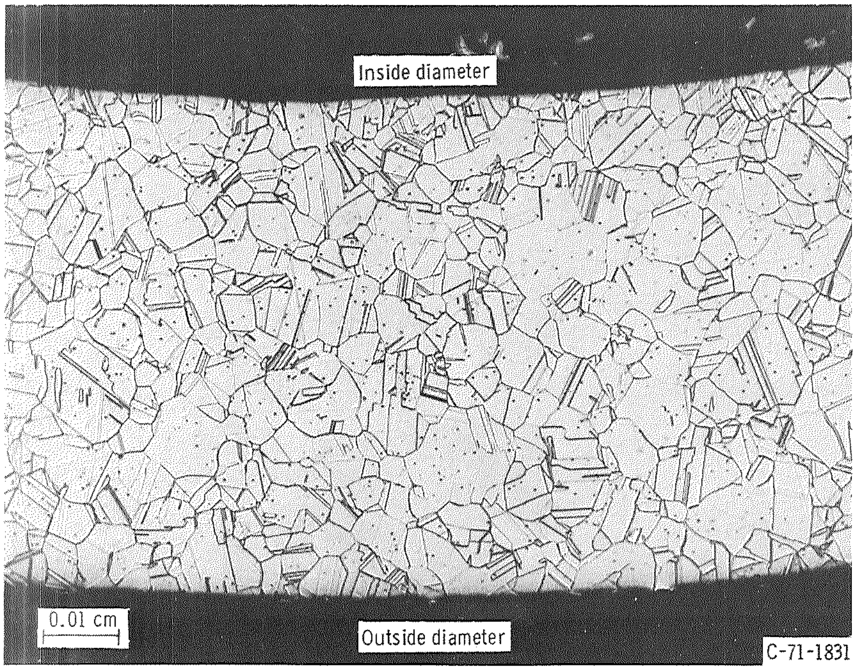


(b) Transverse section.

Figure 10. - Sections of failure area of tube specimen 29, from heat L3-1637, after 1308 hours at 1150 K (1610° F) and 6.89 MN/m^2 (1000 psi). Etched. X100.

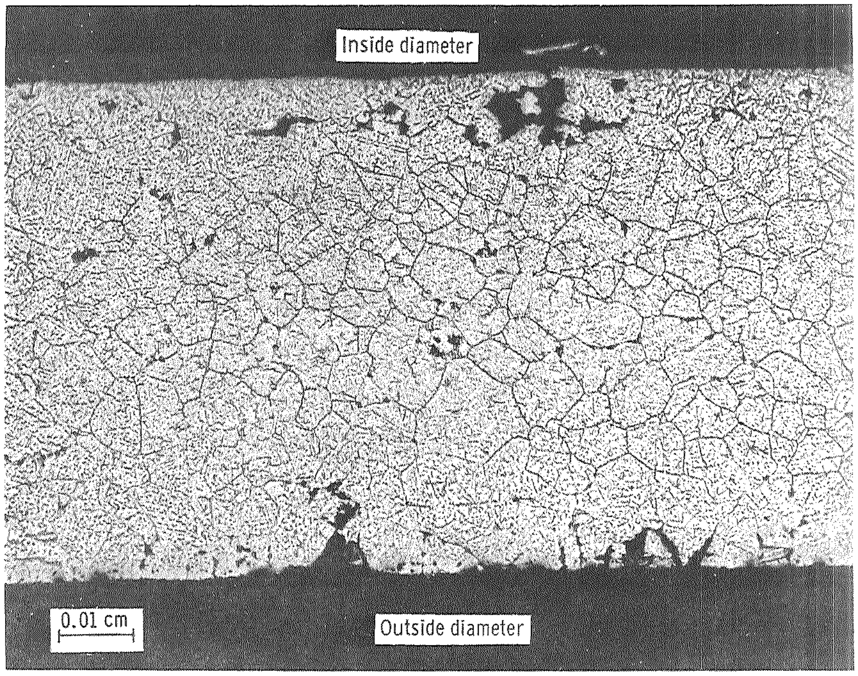


(a) Longitudinal section.

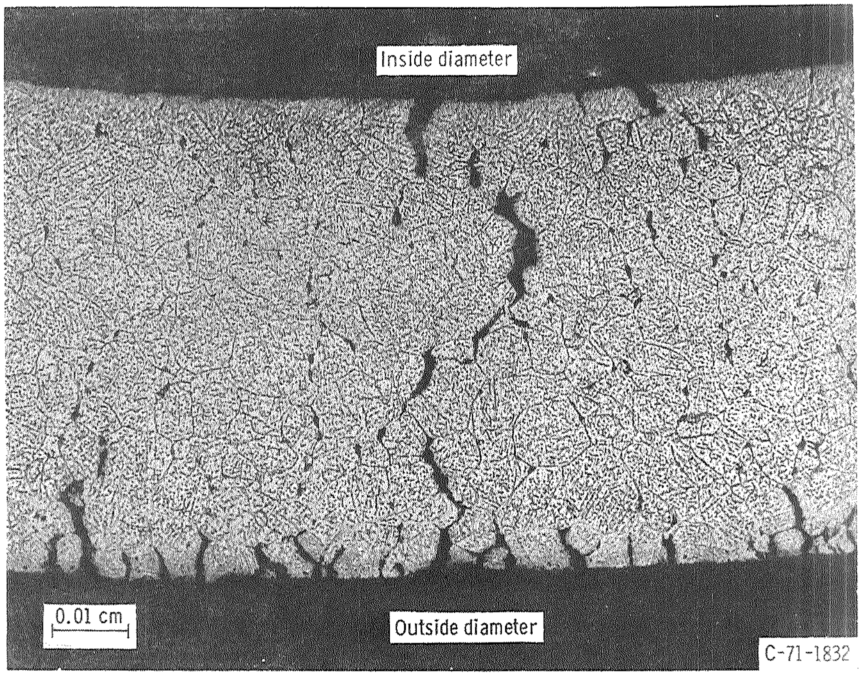


(b) Transverse section.

Figure 11. - Sections of as-received tube specimen of Haynes Alloy No. 25, from heat L1-1592. Etched. X100.



(a) Longitudinal section.



(b) Transverse section.

Figure 12. - Sections of failure area of tube specimen 2, from heat L1-1592, after 2279 hours at 1144 K (1600° F) and 9.65 MN/m^2 (1400 psi). Etched. X100.

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