CONF-781219--3

TENSILE AND CREEP PROPERTIES OF TYPE 316 STAINLESS STEEL*

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A mechanical property characterization test program on type 316 stainless steel is in progress at ORNL to furnish information for (a) the formulation and verification of constitutive equations, (b) setting failure criteria, and (c) verification of ASME design stresses and rules. This characterization involves:

1. <u>Tensile testing of 16-mm plate of reference heat (8092297) of type 316 stainless steel</u>. Tests are in the temperature range of RT to 760°C and at strain rates from 3.3×10^{-3} to $8.3 \times 10^{-6} \text{sec}^{-1}$. Specimens were tested in both the mill-annealed (as-received) and laboratory-annealed (reannealed) conditions. The laboratory anneal was performed on machined specimens for 0.5 h at 1065°C. Tests on this product form provide base-line data as a function of both the test temperature and test strain rate. The strain rate effects on 0.2% yield, ultimate tensile strength, and reduction of area are shown in Figs. 1–3. These figures show the following:

   i) Yield strength is strain rate sensitive only at temperatures of ≤200°C.

   ii) Ultimate tensile strength has two regions of strain rate sensitivity. In one region ultimate tensile strength increased with decreasing strain rate (dynamic strain aging region), and in

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the other region it decreased with decreasing strain rate (creep region).

iii) Reduction of area shows drops in its values in the temperature range of 500-700°C. The temperature at which drop in reduction of area initiated decreased with decreasing strain rate. The ductility at the minimum point was also found to decrease with decreasing strain rate.

The reduction of area values are extended over a wider range of strain rates by combining tensile data with creep data (Fig. 4). Note that at ≥ 649°C, the reduction of area values started to increase from the minimum values followed by another decrease. Similar trends are becoming obvious at 538°C and 593°C. The reduction of area values hit 10% at the minimum point at 538°C. Figure 5 identifies four possible regions observed for the ductility of type 316 stainless steel. This figure also shows how a similar trend in ductility for two heats could displace with respect to each other and be responsible for a large variation in ductility observed for different heats.

2. Tensile testing of 10 different product forms (3 plates, 4 pipes, and 3 bars) of reference heat. Tests were conducted at RT and at 200°F intervals up to and including 1200°F. The test strain rate was $\dot{\varepsilon}$ $8.3 \times 10^{-5} \text{sec}^{-1}$. The product forms were tested in both the mill-annealed (as-received) and laboratory-annealed (reannealed) conditions. This work is completed and was published in ORNL-5348 (February 1978). Figures 6 and 7 present yield strength data on 10 product forms for both mill-annealed and laboratory-annealed conditions. These figures also list the average and standard deviation for yield strength values

at RT and 649°C. Note that laboratory annealing decreases average values and the standard deviation for yield strength at both RT and 649°C.

3. Creep and creep-rupture of 16-mm plate of reference heat of type 316 stainless steel. Both creep and long-term creep-rupture tests are in progress on the reference heat (8092297). Most of the creep tests are being conducted on mill-annealed specimens. The test temperatures are in the range of 482 to 760°C. The planned test times are >50,000 h. The current elapsed times for several tests are in the range of 15 to 20,000 h. The data are being monitored using averaging extensometers. The strain-time data will be used for verification of the currently accepted creep equation. The rupture data on this heat are compared with ASME Code Case minimum curve and also against the data from other heats for heat-to-heat variations. The long-term ductility data from these tests will be used to develop the strain limits and set some sort of failure criteria. Several long-term tests are currently in progress, and several additional tests are needed to complete the planned test matrix.

Figures 8 and 9 show the comparison of currently available rupture data on the reference heat with ASME Code Case minimum value curve. Note that only at 538°C the rutpure data appear to be quite close to the minimum. At other temperatures data are significantly above the minimum. It should also be pointed out that the stress-rupture data at 649°C are showing more curvature than reflected in the ASME minimum curve. If the same trend continues we may expect the experimental data to fall below the minimum ar rupture times >20,000 h. The creep ductility data on the reference heat have already been presented in Fig. 4. The effect of varying nitrogen content on ductility of type 316 is presented in Fig. 10. Note that increasing nitrogen decreases ductility at the ductility minimum point. Furthermore, the strain rate at which the minimum occurs also decreases with increasing nitrogen content.

4. Creep and creep-rupture properties of 10 different product forms of the reference heat. Short-term creep and creep-rupture tests are being conducted on 10 different product forms to obtain a measure of product-to-product variability for a single heat. One rupture test each has been completed on all product forms. The creep tests, of 1,000-h duration, have yet to be started.

5. Creep and creep-rupture tests on 10 different heats of type 316 stainless steel. These are planned to identify the heat-to-heat variations. Data will also be correlated with chemical composition to identify the elements responsible for the observed variations.

Elevated-temperature ultimate tensile strength (S_u) at the creep tests temperature has been shown to be a possible index for estimating the creep properties of types 304 and 316 stainless steel and associated weldments. Figure 11 shows the predicting capabilities of S_u-based model for a heat tested at HEDL. Figure 12 shows the capability of the model for long-term data available from NRIM (Japan). Predicting capabilities of the rupture model for 5 different heats tested at the University of Michigan are shown in Figs. 13 and 14. An example for type 16-8-2 weld metal data is shown in Fig. 15. All these figures illustrate that elevated-temperature ultimate tensile strength-based models can predict the rupture and minimum creep rate data of a given heat more accurately than models without an S_u term. Note, however, that the S_u models do not still solve the problem of extrapolation.

6. Complex behavior tests in support of design methods data requirements using 16-mm plate of reference heat (8092297). These tests include the following loading histories:

i) Creep tests on strain-cycle specimens. Several specimens were given ten strain cycles at total strain ranges of 0.2, 0.4, 0.6, 0.8, and 1.0%. In addition, for a given strain range (0.2 and 0.4%), the number of cycles were varied from 10 to 10,000. The results of creep tests on these strain-cycled specimens are now available at creep conditions of 593°C and 207 MPa. A report on these tests is being prepared. Two creep curves on strain-cycled specimens are presented in Figs. 16 and 17. Figure 16 shows slightly higher creep strain but essentially no effect of prior strain cycling on minimum creep rate and time to rupture. Results in Fig. 17 show that strain cycling at 1% strain range produces less creep strain, low creep rate, and longer time to rupture. The effect of strain cycling at various strain ranges on minimum creep rate is best summarized in Fig. 18. This figure illustrates that 10 strain cycles has negligible effect on minimum creep rate for total strain ranges of $\leq 0.8\%$. At higher strain ranges minimum creep rate decreases. Figure 18 also illustrates that strain cycling conditions which develop a fatigue crack will sharply increase the minimum creep rate.

ii) Creep tests at stresses with superimposed cycling. Several creep tests with superimposed cycling have been completed at 593°C on specimens removed from 16-mm plate. Results show (Fig. 19) a factor of 3-5 drop in rupture life as a result of stress oscillations. More long-term tests with superimposed cycling will be conducted to confirm these results.

iii) Compressive creep tests. These tests are in progress to check if strain-time response under tensile and compressive stress conditions is identical (as assumed by designers) or different. The tests completed thus far were run at 593°C with stresses in the vicinity of the proportional limit to minimize possible bending due to large plasticity on loading. The tests thus far show more primary creep strain during compressive loading than during tensile loading. A typical example is presented in Fig. 20. Testing in this area will continue for the next several months.

7. Tensile and creep tests on thermally-aged material. These tests are planned on material aged in-house and on material removed from service. Tensile results are now available on material aged in-house for 20,000 h. Data for material removed from service are available for aging time of 74,000 h. One short-term creep test each at 593 and 649°C is also available on material removed from service.

A few tensile tests are also available on material subjected to prior creep.

The changes in various tensile ductility quantities as a result of thermal aging are presented in Fig. 21. Figure 22 shows the plot of reduction of area as a function of thermal aging time. Note that reduction of area values remain unaffected by thermal aging at 482°C. Thermal aging at 593°C decreases reduction of area. The values drop from 66 to 57% after 10,000 h. At 649°C reduction of area values drop initially but show a substantial increase at longer aging time. Values increase from 49% to ∿70% after 10,000 h. At room temperature all ductility quantities decreased to an extent that increased with increasing aging temperature.

The increase in RA at 649°C due to thermal aging at 649°C without stress was also observed for aging under stress. For example, a specimen of type 316 stainless steel creep tested at 649°C and 124 MPa for 1983 h produced plasticity and creep strain of 17.32%. When tensile tested, this specimen showed a reduction of area value of 55.9%, as compared with 48.7% observed for the unaged material.

The effect of service exposure on various tensile ductility quantities is shown in Fig. 23. Note that in general the results are similar to those observed for the laboratory-aged material (Figs. 21 and 22). Table 1 lists the creep data available on service exposed material. Data shows that thermal aging increases both minimum creep rate and time to rupture. However, the fraction of time to onset of tertiary creep/time to rupture indicates that the longer time to rupture is obtained as a result of delayed fracture or longer tertiary creep stage.

<u>Future Plans</u> — Testing listed above will continue for the next few years to complete the program outlined in the test matrices. Data obtained will be analyzed both mathematically and microstructurally.

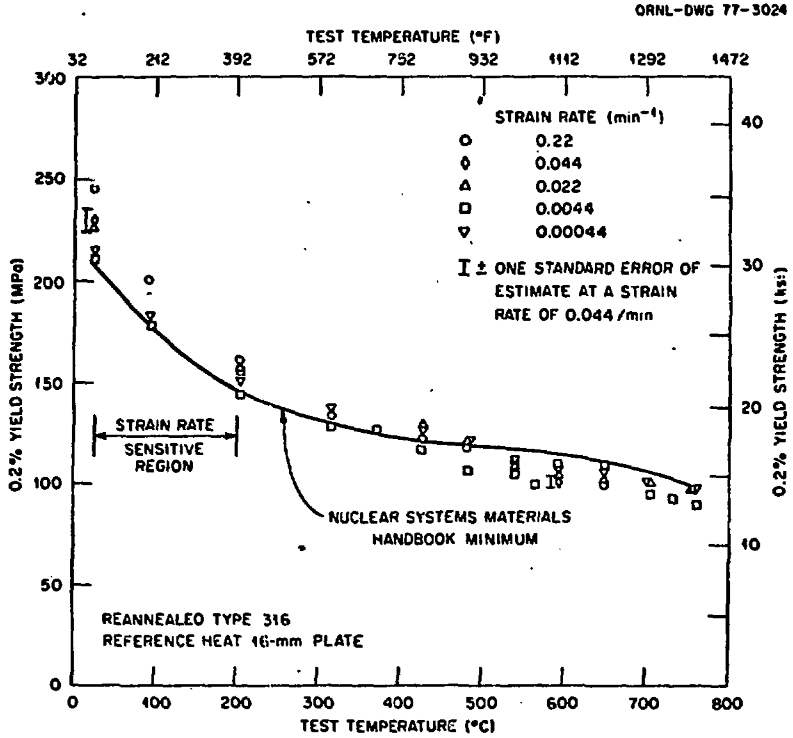

Fig. 1. The 0.2% Yield Strength as a Function of Test Temperature for 16-mm (5/8-in.) Plate of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at Several Strain Rates.

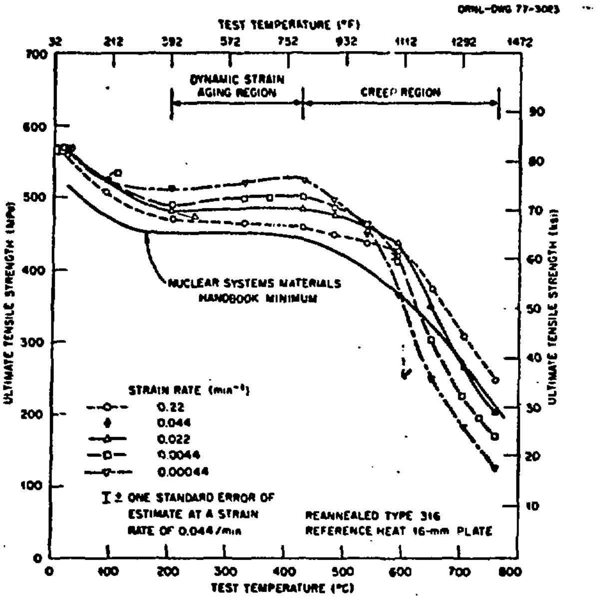

Fig. 2. The Ultimate Tensile Strength as a Function of Test Temperature for 16-mm (5/8-in.) Plate of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at Several Strain Rates.

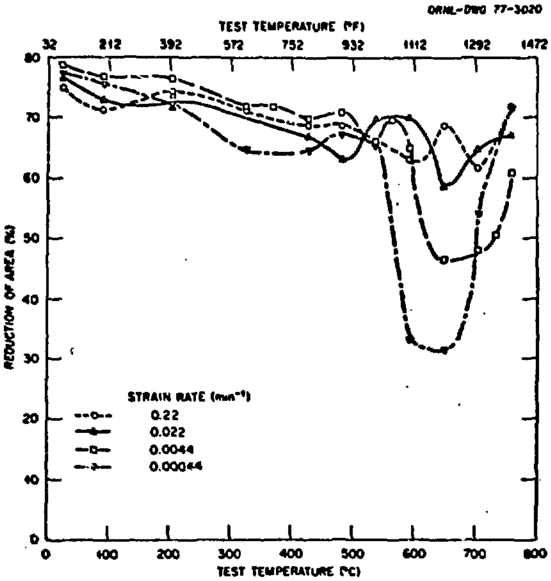

Fig. 3. The Reduction of Area as a Function of Test Temperature for 16-mm (5/8-in.) Plate of the Reference Heat (8092297) of Type 316 Stainless Steel in the Reannealed Condition at Several Strain Rates.

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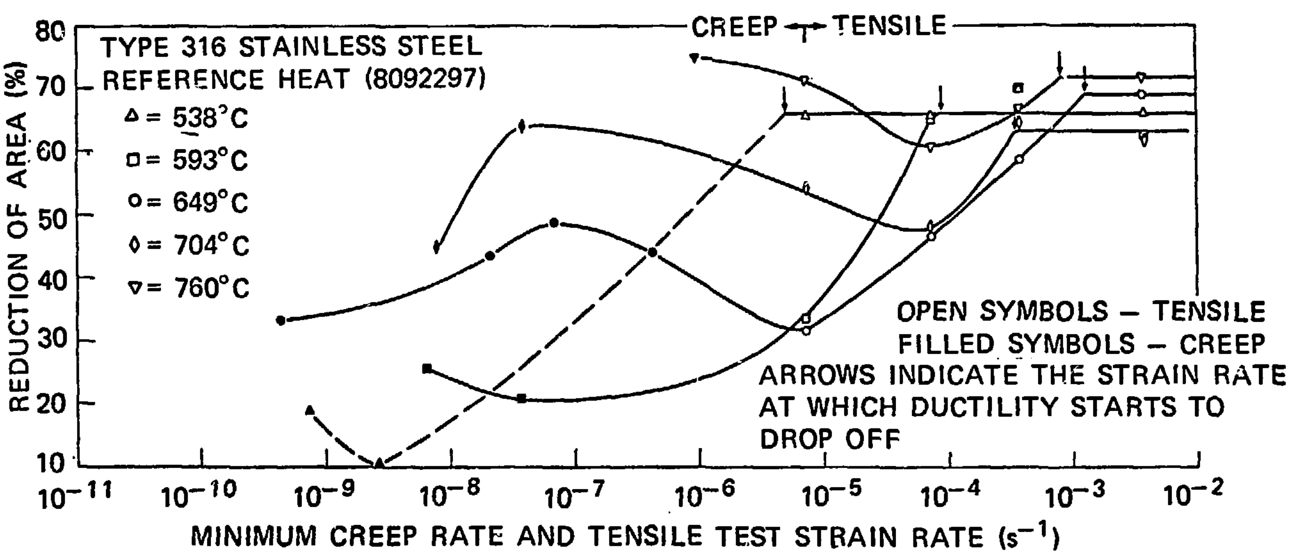


Fig. 4. Tensile and Creep Ductility of Type 316 (N = 0.034%) is Strongly Dependent on Temperature and Stress (Through Creep Rate). Note a minimum in ductility at each temperature.

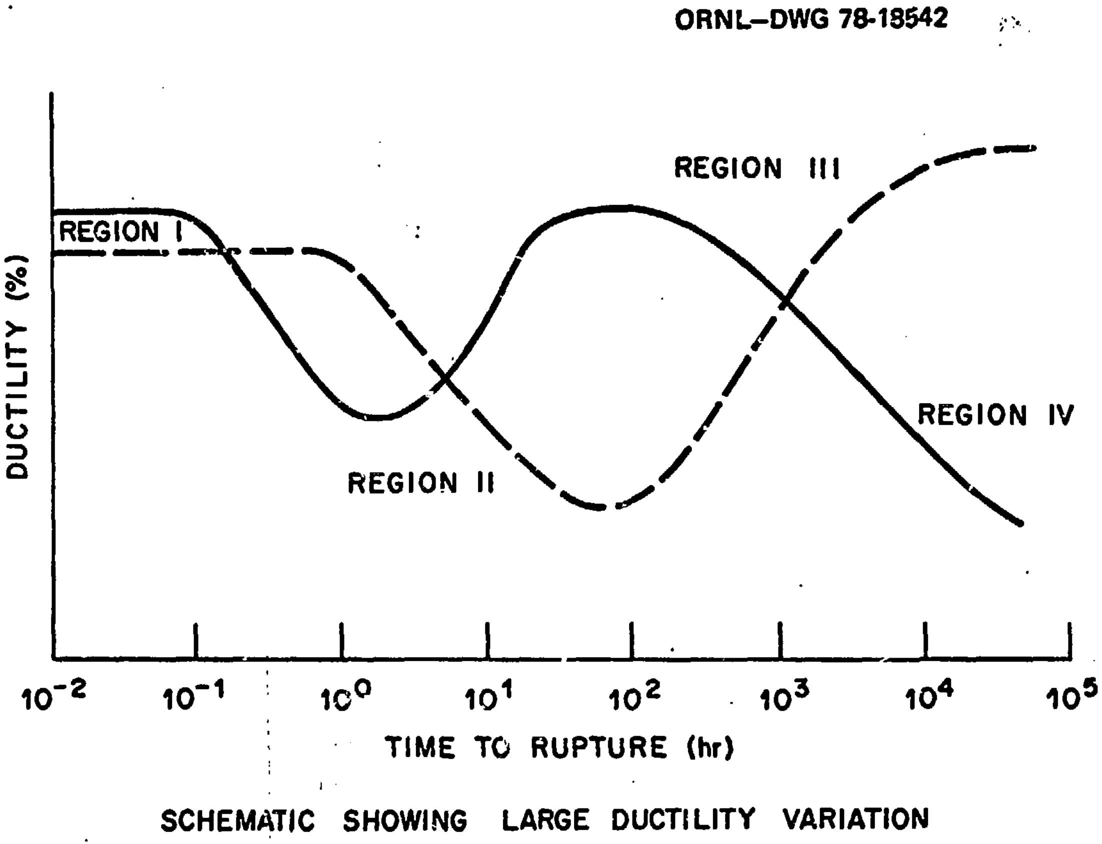
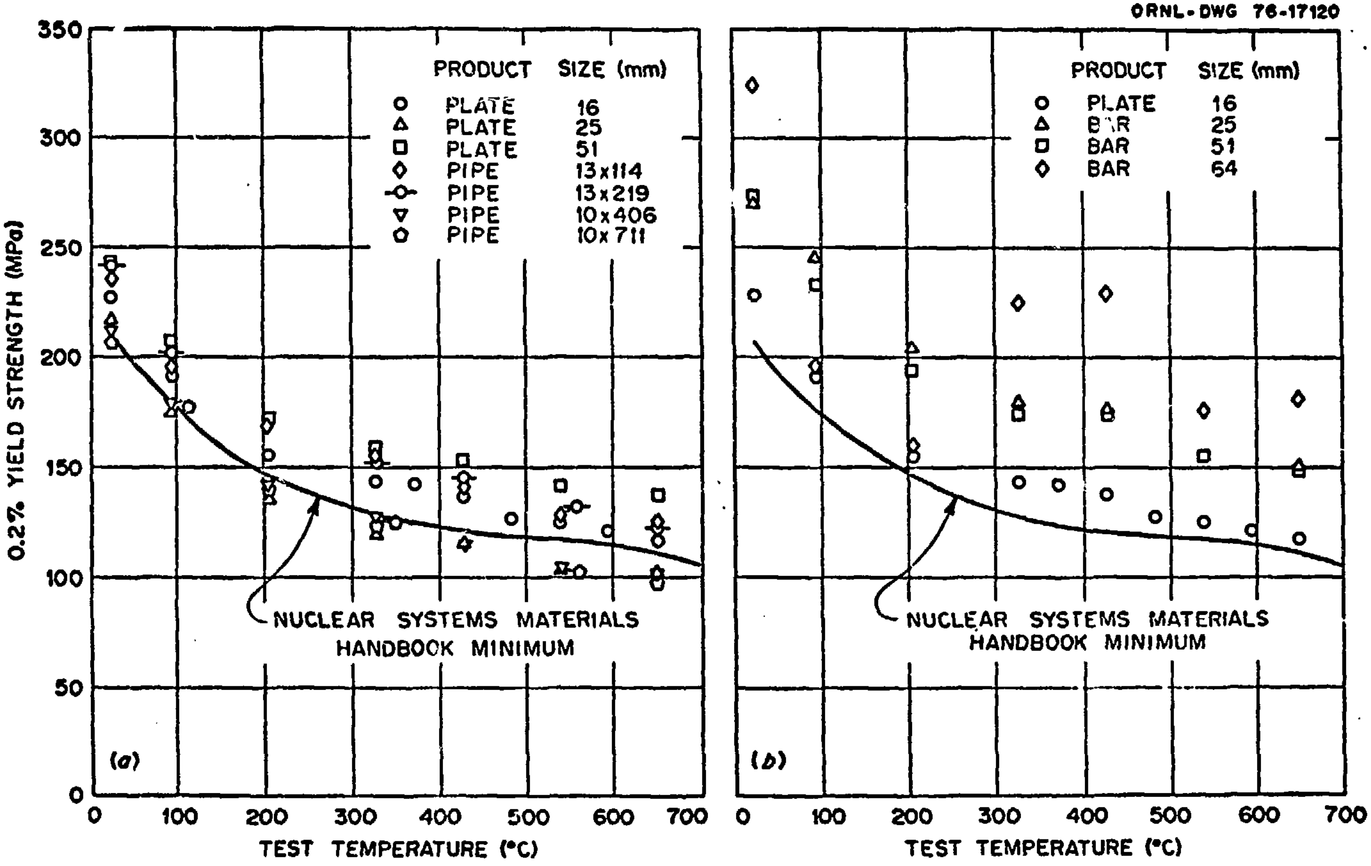


Fig. 5. Tensile and Creep Ductility Data Available Over a Range of Test Conditions can be Schematically Represented. The exact location and width of various regions depend on: test temperature, stress, grain size, chemical composition, and material condition.

Fig. 6. LARGE VARIATIONS ARE OBSERVED IN YIELD STRENGTH OF VARIOUS PRODUCTS OF A GIVEN HEAT (8092297) OF TYPE 316 STAINLESS STEEL

TEMPERATURE	AVERAGE YS OF 10 PRODUCTS (ksi)	SD (ksi)
RT	35.49	±5.22
649°C	18.59	±3.82



Temperature	Average YS of All Products (ksi)	SD (ksi)
RT	30.64	±1.20
649°C	14.63	±1.67

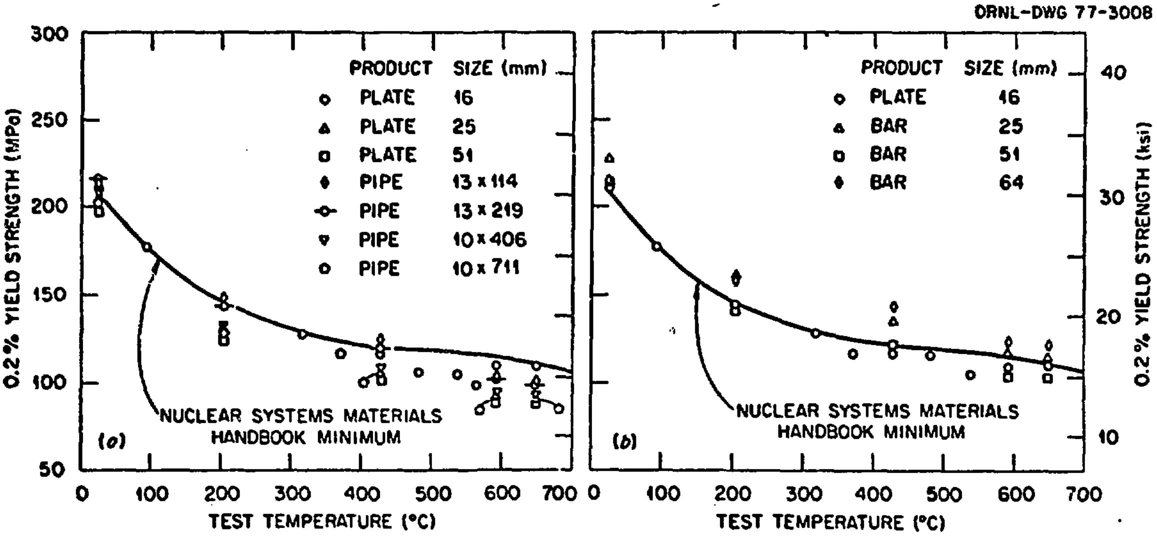


Fig. 7. Laboratory Annealing Decreases the Scatter, but it Brings the Yield Strength Below the NSMH Minimum Curve (Heat 8092297).

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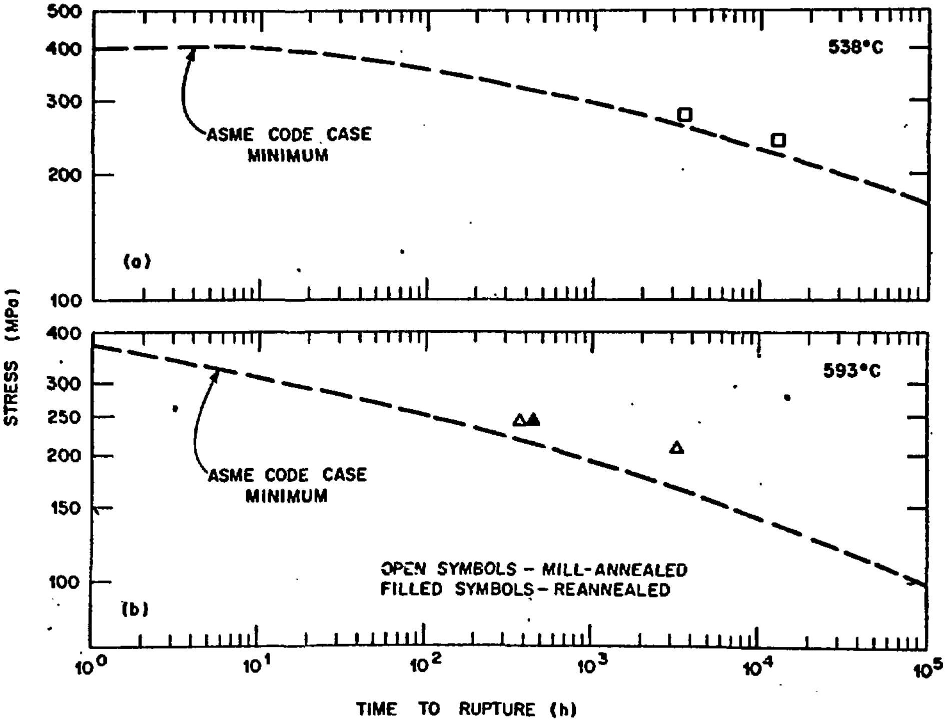

Fig. 8. Currently Available Reference Heat Rupture Data are Evaluated Against ASME Code Case Minimum.

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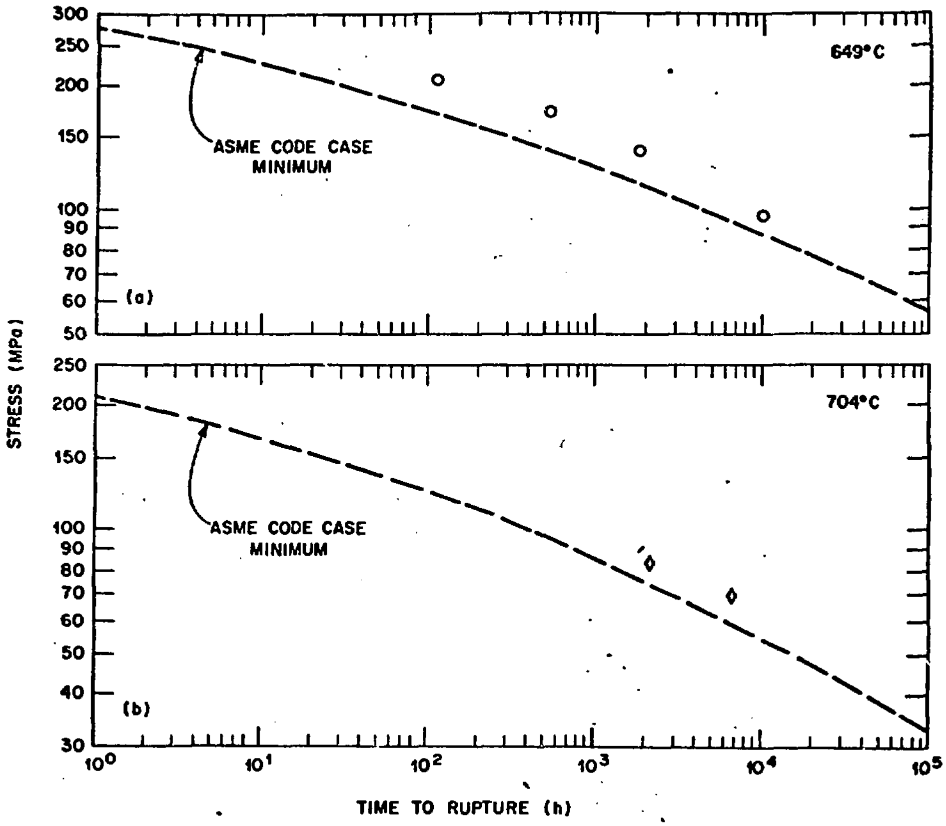

Fig. 9. Currently Available Reference Heat Rupture Data are Evaluated Against ASME Code Case Minimum.

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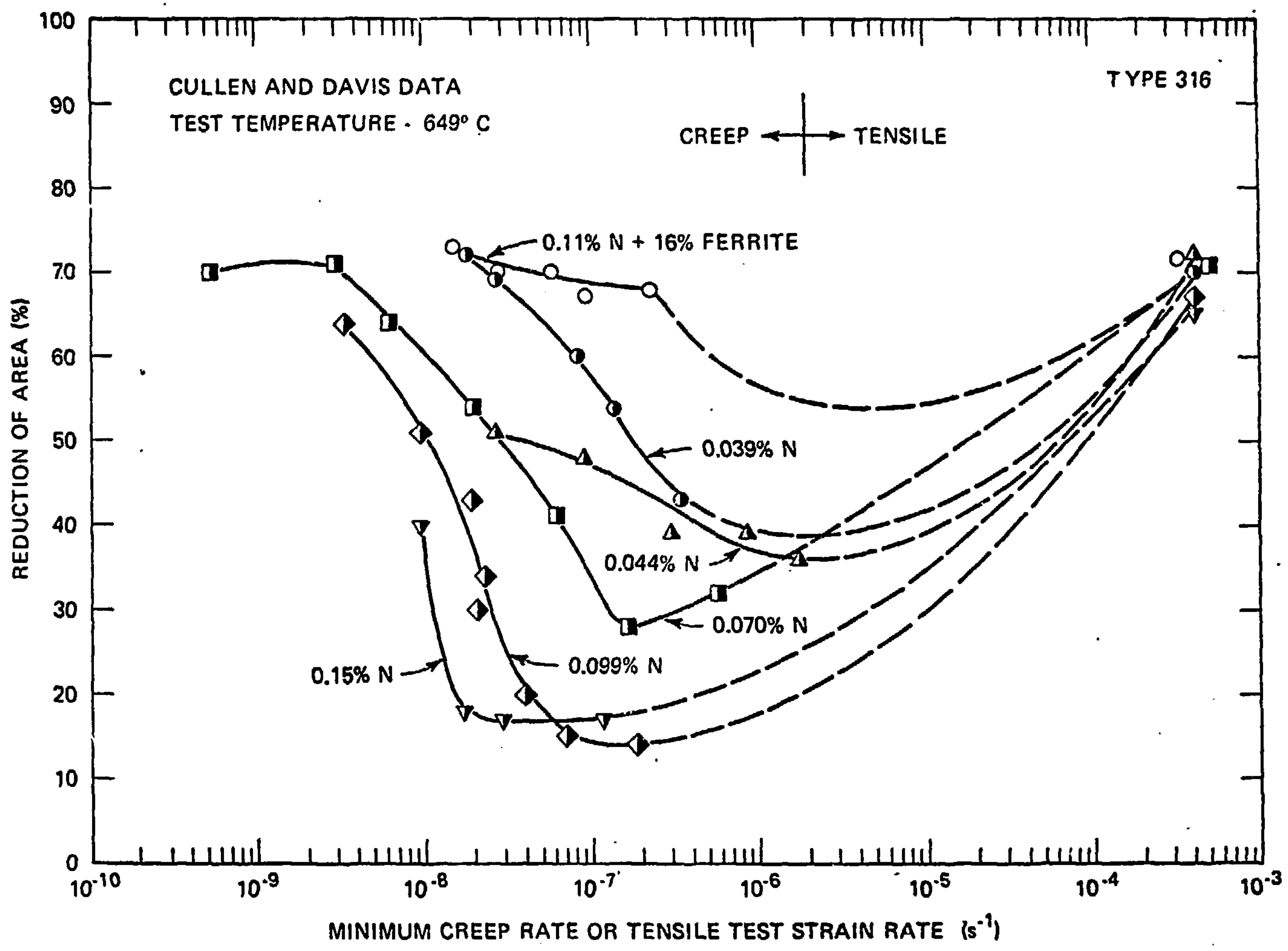


Fig. 10. The Drop in Reduction of Area at a Given Temperature and Strain Rate is Affected by the N_2 Content of the Steel.

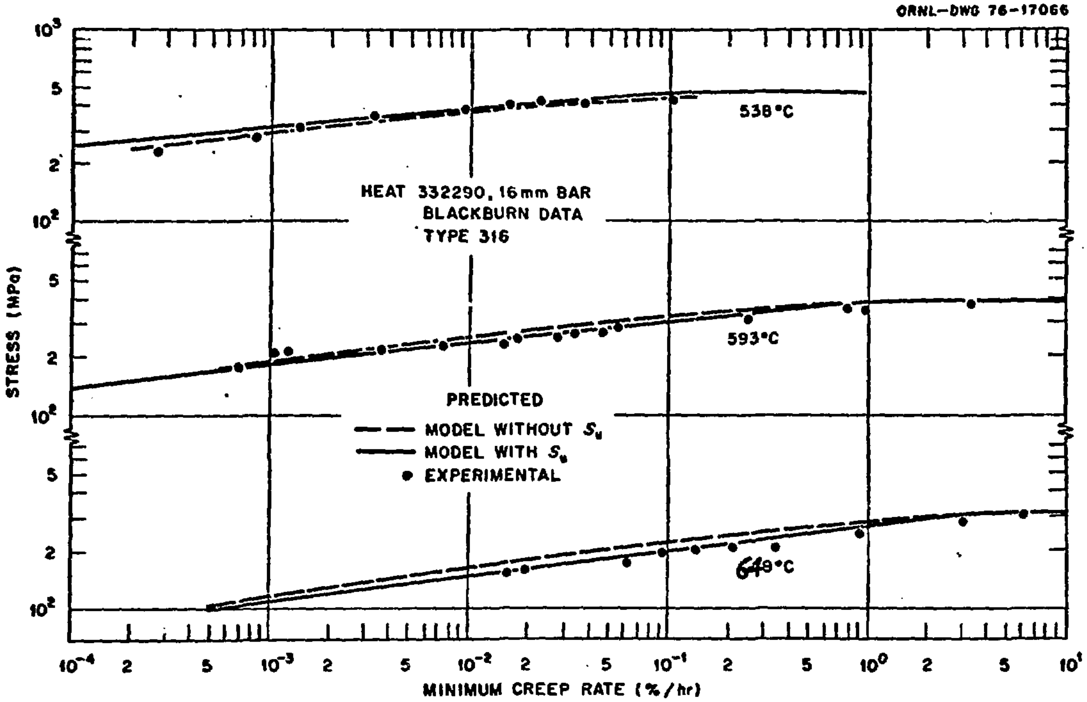


Fig. 11. Comparison of Experimental Minimum Creep-Rate Data with Values Computed from Models With and Without Elevated-Temperature Ultimate Tensile Strength (S_u) for Blackburn Data on Heat 332290 of Type 316 Stainless Steel.

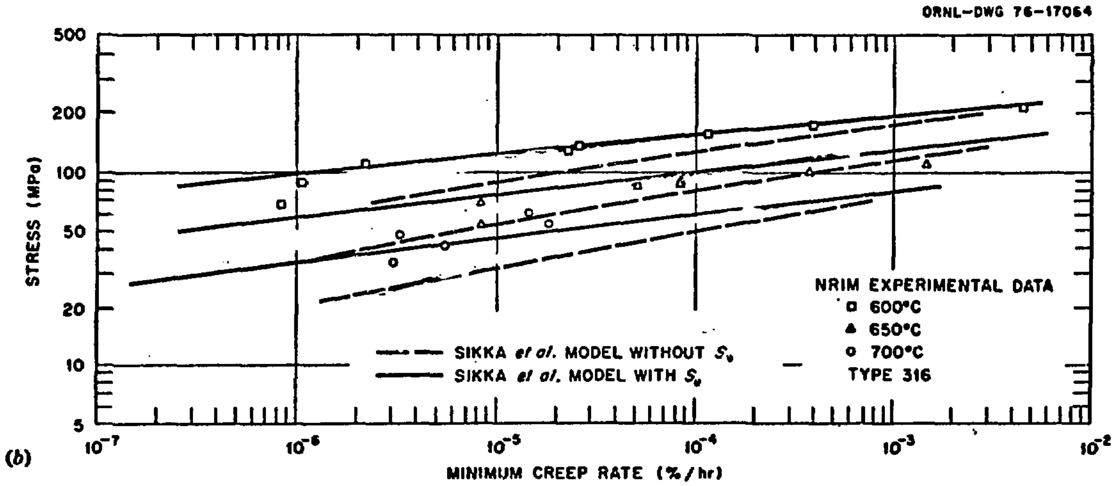


Fig. 12. Comparison of Experimental Minimum Creep-Rate Data with Values Computed from Models With and Without Elevated-Temperature Ultimate Tensile Strength (S_u) for Long-Term Data Obtained from NRIM on Type 316 Stainless Steel.

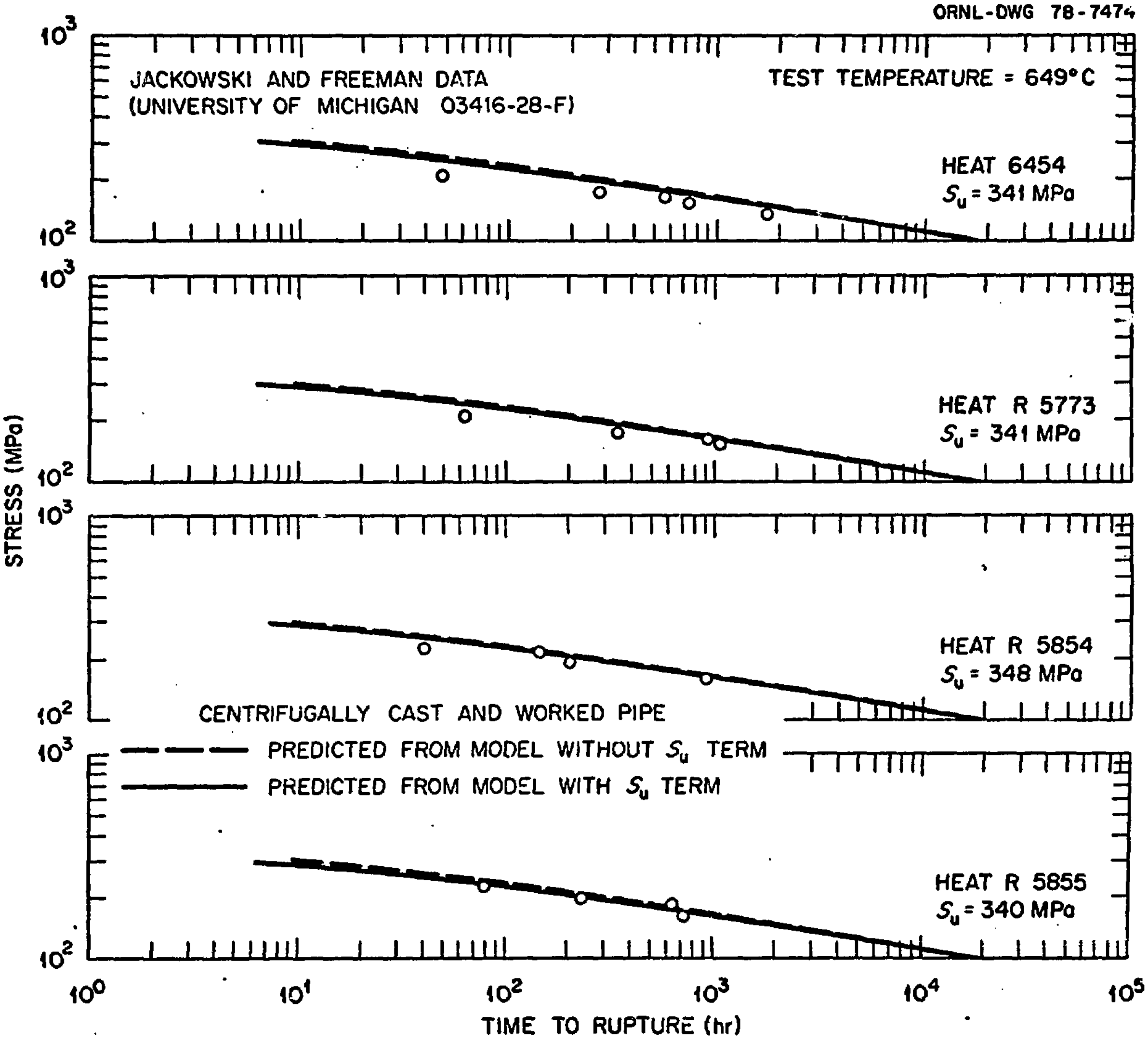


Fig. 13. Comparison of Experimental Time to Rupture Data with Values Computed from Models With and Without Elevated-Temperature Ultimate Tensile Strength (S_u) for the University of Michigan Data on Four Heats of Type 316 Stainless Steel at 649°C.

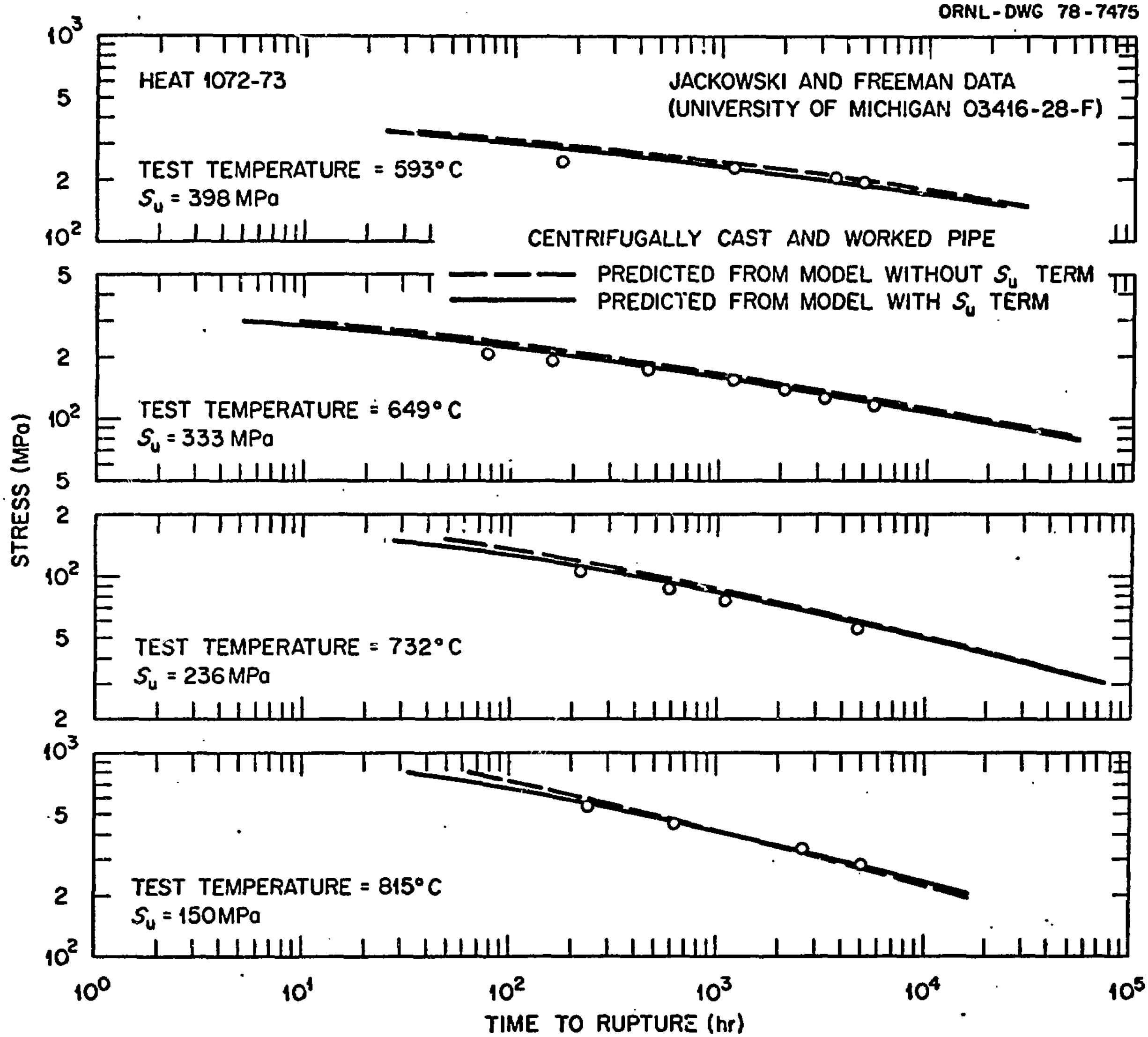


Fig. 14. COmparison of Experimental Time to Rupture Data with Values Computed from Models With and Without Elevated-Temperature Ultimate Tensile Strength (S_u) for the University of Michigan Data on a Single Heat of Type 316 Stainless Steel at Four Different Test Temperatures.

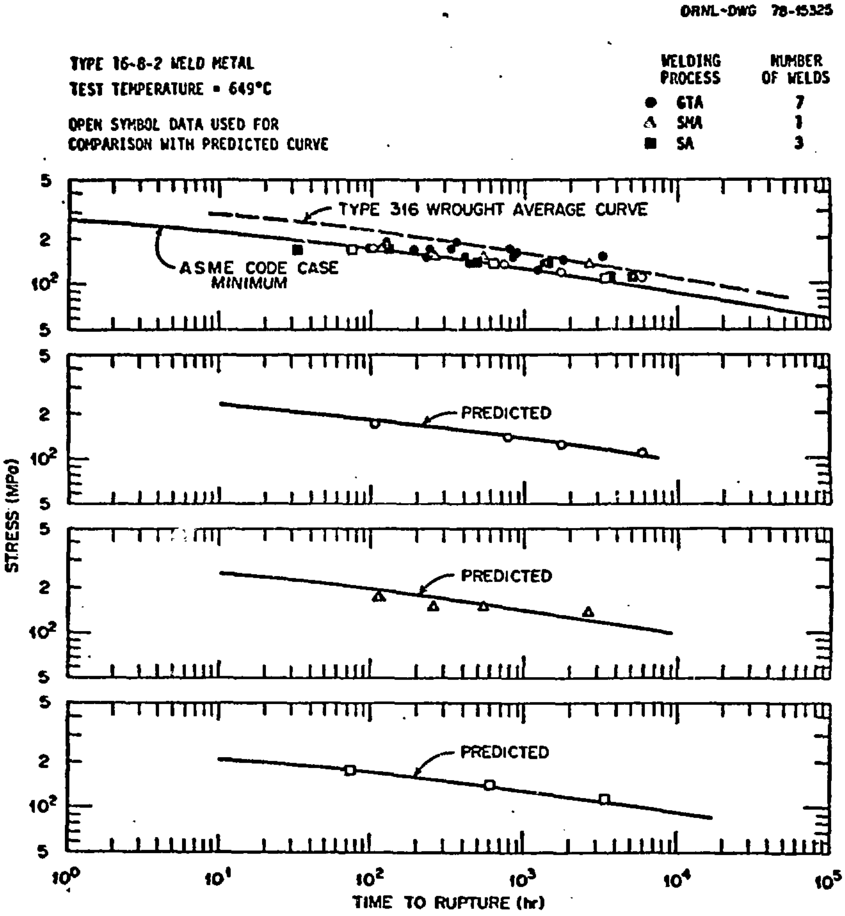
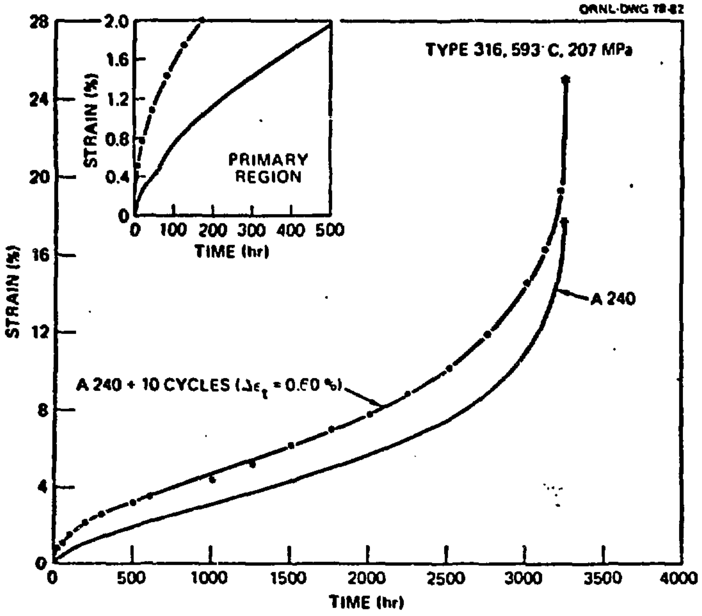


Fig. 15. Weld Metal Shows a Range of Creep-Rupture Values, But They are now Predictable by the Knowledge of Their Elevated-Temperature Ultimate Tensile Strength.



Fsg. 16. Prior Strain Cycling (10 cycles at 0.60%) has Relatively Small Effect on the Creep Deformation and Fracture Behavior of Type 316 Stainless Steel.

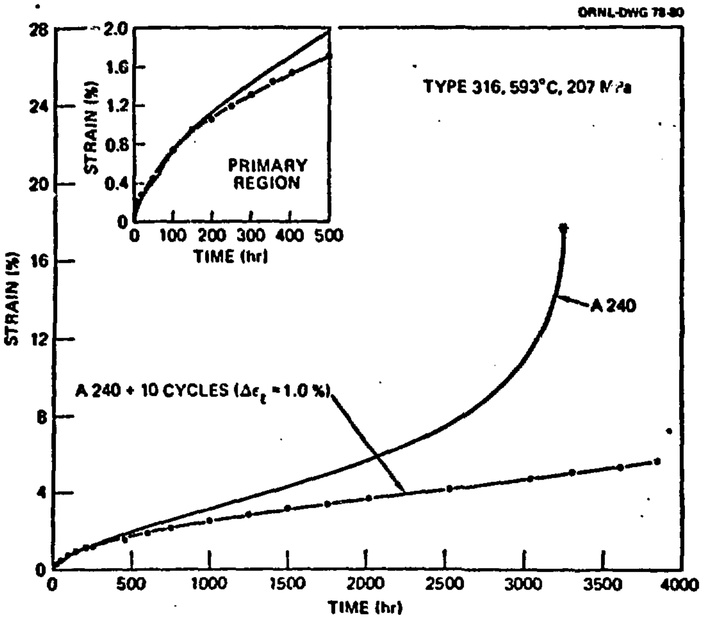


Fig. 17. Prior Strain Cycling at a High Strain Range (10 cycles at 1.0%) Can Introduce a Strengthening Effect in the Creep Behavior of Type 316 Stainless Steel.

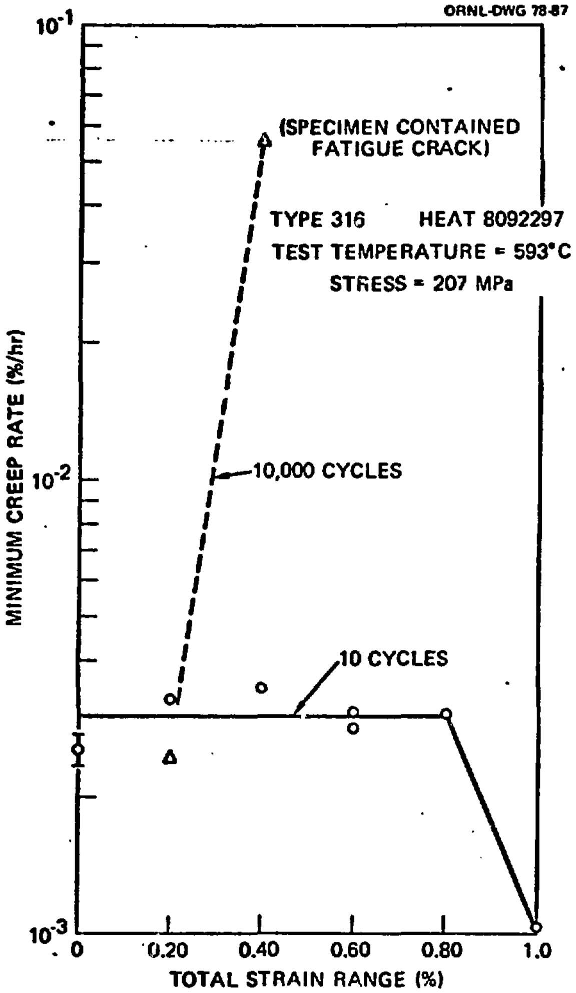


Fig. 18. Effect of 10 Strain Cycles at Various Strain Ranges on Minimum Creep Rate can be Illustrated.

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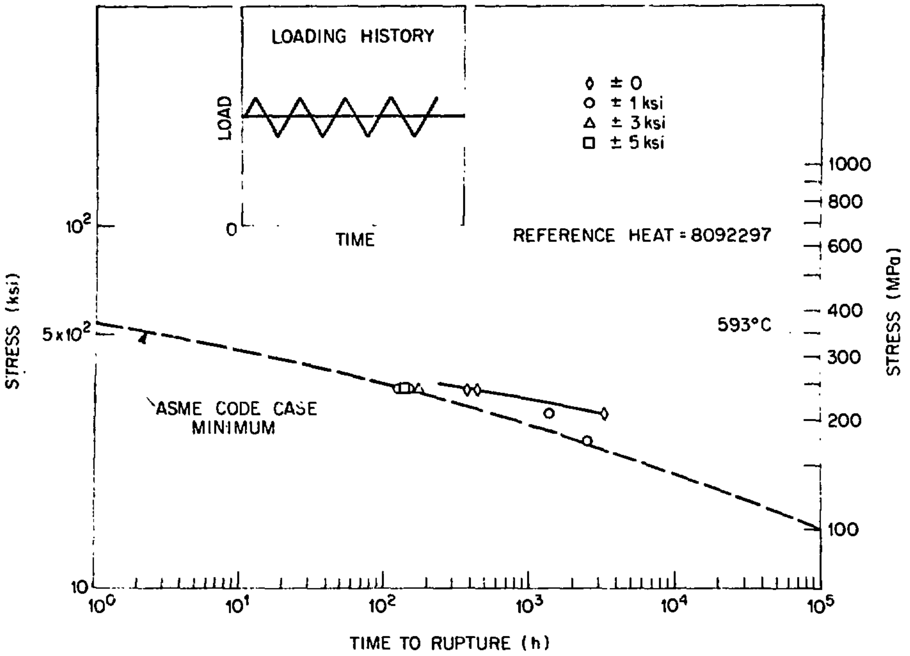

Fig. 19. Loading History (Especially Superimposed Cycling) Appears to Have a Strong Effect on the Rupture Behavior of the Reference Heat. Note that the rupture time may be lower by a factor of 3-5.

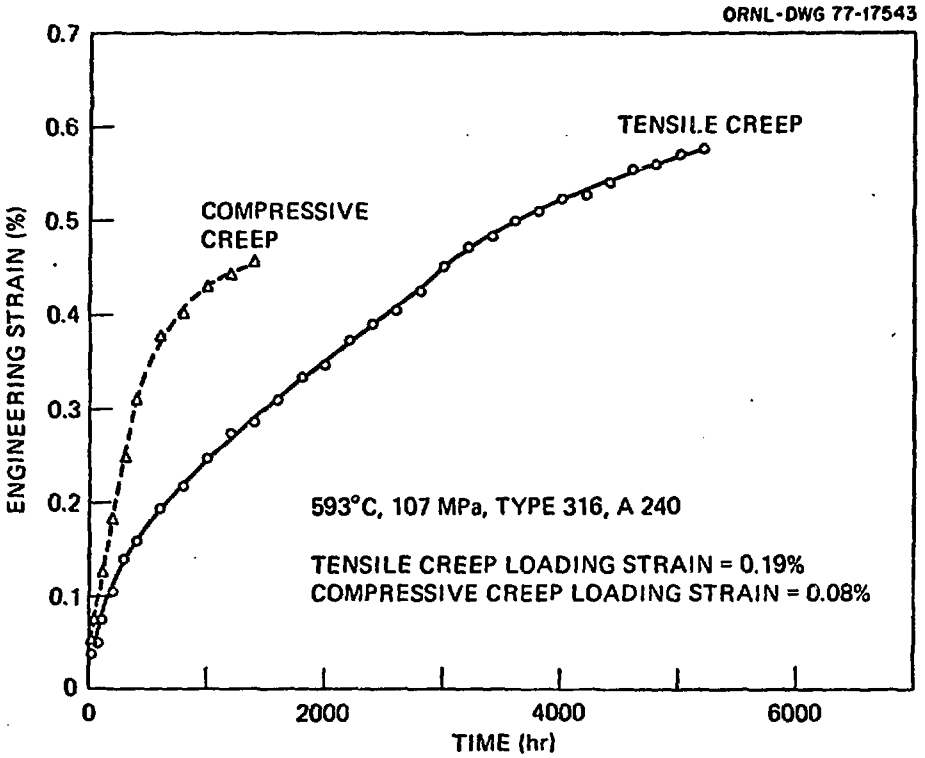

Fig. 20. Comparison of Tensile and Compressive Creep Curves at 593°C and 107 MPa for 16-mm Plate of the Reference Heat of Type 316 Stainless Steel. Both specimens are tested in the A 240 condition.

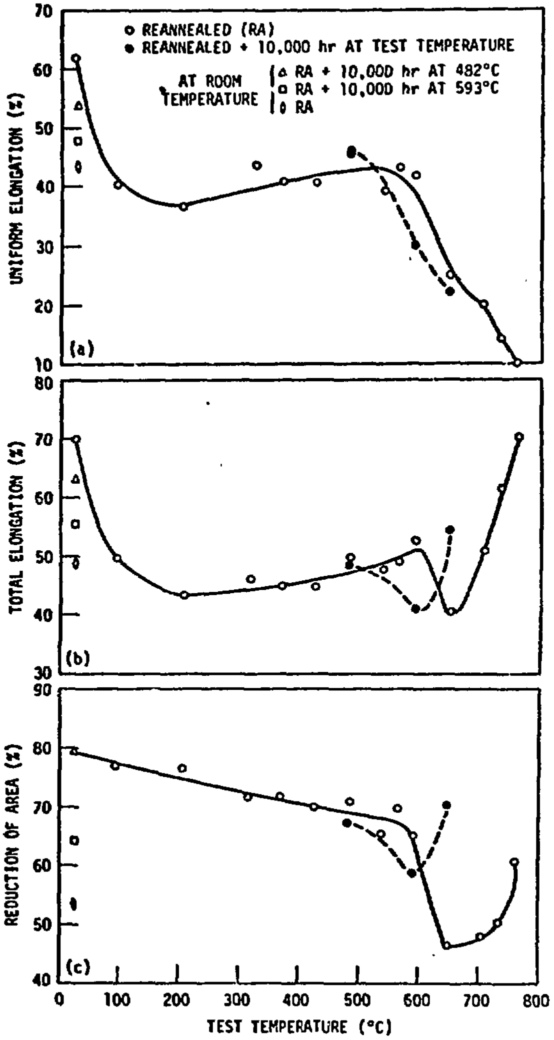

Fig. 21. Comparison of Ductility Properties of Aged and Reannealed Reference Heat of Type 316 Stainless Steel. (a) Uniform elongation. (b) Total elongation. (c) Reference heat.

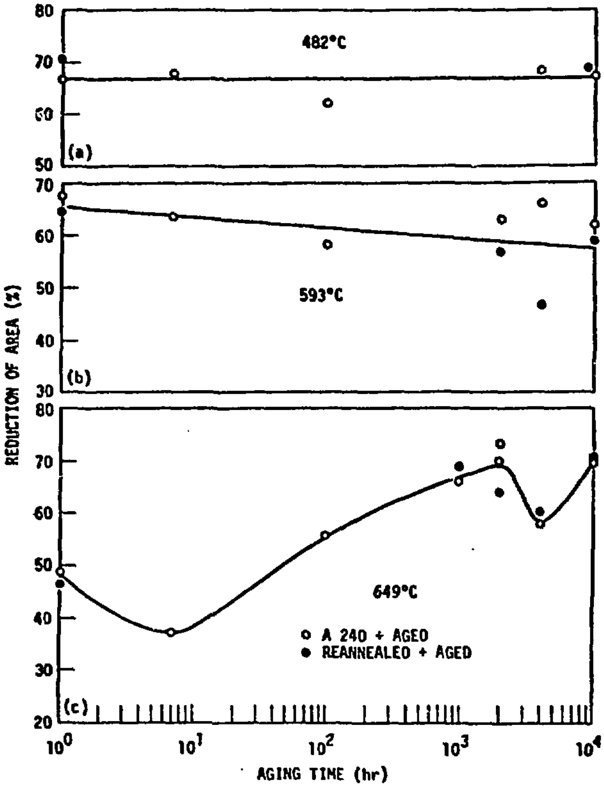

Fig. 22. Reduction of Area as a Function of Aging Time for the Reference Heat (8092297) of Type 316 Stainless Steel. Specimens were aged and tested at (a) 482, (b) 593, and (c) 649°C.

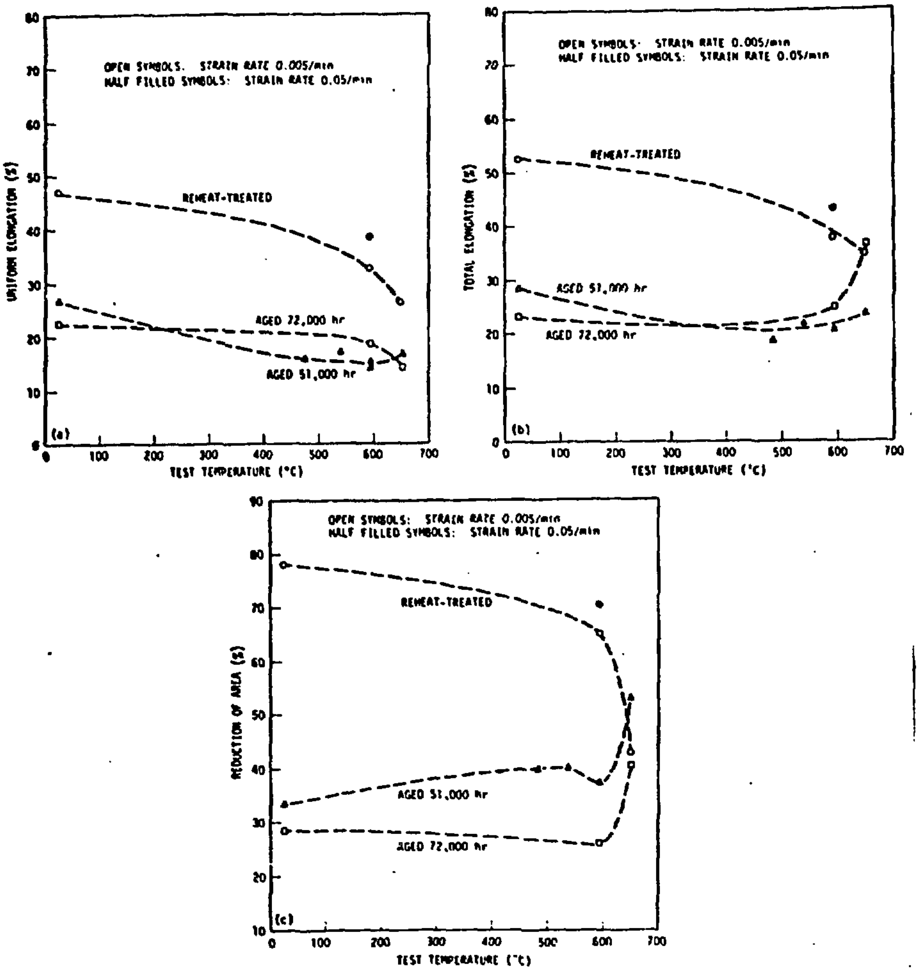

Fig. 23. Ductility as a Function of Test Temperature for Type 316 Stainless Steel Specimens Taken from the Header. (a) Uniform elongation. (b) Total elongation. (c) Reduction of area. Reheat-treated (0.5 h at 1065°C), as-removed from service (51,000-h exposure), and additionally aged (total aging time 72,000 h).

Table 1

THE 8-YEAR THERMAL AGING AT 621°C SHOWS AN INCREASE IN CREEP-DEFORMATION RATE WITH A SIGNIFICANT DELAY IN THE RUPTURE (AS INDICATED BY THE RATIO OF t_2/t_r). NOTE ALSO THE IMPROVEMENT IN DUCTILITY

MATERIAL CONDITION	LOADING STRAIN (%)	TIME TO RUPTURE (h)	MINIMUM CREEP RATE (%/h)	TOTAL ELONGATION (%)	REDUCTION OF AREA (%)	$\left(\frac{t_2}{t_r}\right)$
			<u>593°C AND 30 ksi</u>			
SOLUTION-ANNEALED	8.70	408.3	0.00495	12.63	29.32	0.735
AGED 74000 h at 621°C	0.78	812.0	0.0185	27.19	40.65	0.339
			<u>649°C AND 25 ksi</u>			
SOLUTION-ANNEALED	4.75	229.6	0.0428	25.19	41.48	0.403
AGED 74000 h at 621°C	0.48	183.4	0.0988	47.43	45.34	0.218