Final Report

on

# PROPERTIES OF HYDROFORGED TYPE 316 STEEL PIPE AT HIGH TEMPERATURES

by

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# FINAL REPORT

# ON

# PROPERTIES OF HYDROFORGED TYPE 316 STAINLESS STEEL PIPE AT HIGH TEMPERATURES

An investigation was carried out to determine the properties at high temperatures of Type 316 (18-8+Mo) stainless steel pipe made by the Hydroforging process. Hydroforged pipe is made by expanding a hollow centrifugal casting using water under high pressure. The cold work is sufficient to cause recrystallization during subsequent heat treatment. This breaks up the coarse grains of the as-cast structure and produces a fine-equiaxed grain structure. From a metallurgical standpoint, the investigation covers the unique case of the influence on properties of producing a relatively fine-equiaxed grain structure in the alloy by cold working an as-cast structure and heat treatment without the usual hot working of an ingot.

Five pipes made under production conditions were investigated. Tensile tests up to 1500°F, rupture tests at 1100° to 1500°F with rupture up to 5000 to 6000 hours duration, and creep tests at 1000° to 1350°F of 5000 to 8000 hours duration were used to evaluate one pipe. Rupture at 1100° to 1500°F with testing times longer than 1000 hours and creep tests at 1100° to 1350°F of about 5000 hours duration were carried out for a second pipe. The other three pipes were tested at 1200°F. Tensile and impact tests at room temperature along with metallographic examinations were used to study the effect of exposure to temperature and stress on stability characteristics.

## CONCLUSIONS

The rupture and creep properties of the five large pipes made by the Hydroforging process were within the range of the properties to be expected for wrought Type 316 (18-8+Mo) stainless steel. The cold working of as-cast structures followed by complete recrystallization from annealing at 1950°F did not result in unusual properties. Yield strengths were on the low side of the range for the alloy but were normal for fully-annealed material. The properties were generally characteristic of those to be expected for cold worked and recrystallized Type 316 alloy. The heat-to-heat variations of the five pipes were the same as those commonly encountered for the alloy and the variations in properties were well within the range to be expected.

## EXPERIMENTAL MATERIAL

The tests were conducted using specimens furnished by the Steel and Tube Division of the United States Pipe and Foundry Company. The following information was supplied to describe the pipes from which the specimens were taken.

### Chemical Composition

The carbon content of the heats used for the investigation ranged from 0.049 to 0.063 percent (Table 1). Manganese ranged from 1.11 to 1.67 percent; silicon from 0.25 to 0.51 percent; chromium from 16.18 to 16.96 percent; nickel from 13.18 to 13.84 percent; and molybdenum from 2.36 to 2.55 percent. These compositions are within the range of current ASTM specifications for Type 316 pipe and are similar to the completely austenitic compositions generally used for producing seamless pipe.

### Processing

The heats were melted in 500 or 2000 pound induction furnaces (Table 2) in accordance with the production practices of United States Pipe and Foundry Company. The initial size of the centrifugal castings and the dimensions after expansion are detailed in Table 2. Three of the pipes were about 8 $^{5}/_{8}$ inches O. D. by about 0. 9-inch in wall thickness. One was 10 $^{3}/_{4}$ inches O. D. by 0. 9-inch in wall thickness, and one was 12 inches O. D. by 1. 44 inches in wall thickness.

All five pipes were cold expanded from centrifugal castings, annealed at 1950°F, and then cold expanded a second time. A final heat treatment at 1950°F for one hour and water quenching was then applied.

Normal production practices were used in making the pipe. The specimens tested, therefore, represent production material and are not experimental.

### Room-Temperature Properties

The results of tensile tests conducted at room temperature by the United States Pipe and Foundry Company on specimens cut from the five pipes are given in Table 3. The tensile properties were uniform both within a given pipe and between pipes. The level of properties was that to be expected for Type 316 steel heat treated at 1950°F in the section sizes involved.

### Structural Characteristics

The usual columnar radial grains extending through the wall thickness of the as-cast blank were shown by macroexamination. After Hydroforging and heat treating, macroetched rings cut from both ends of each pipe showed a relatively fine-equiaxed grain structure. There was no indication of inclusions or flaws in the macrostructures.

## EXPERIMENTAL PROCEDURE

Finished specimens machined from blanks cut from the pipes after final heat treatment were supplied for the investigation. Most of the tests were conducted on standard 0. 505-inch diameter by 2-inch gage length specimens prepared from coupons taken lengthwise from the pipes. These were obtained from rings cut from the pipes after discarding the 11 inches closest to the end to avoid influence from end effects. The center of the specimens coincided with the center of the pipe wall. A limited number of check tests were conducted on specimens taken transverse to the pipe axis from coupons cut tangentially. These specimens had a gage section 0.357-inch in diameter by 1.90-inches long.

The pipe from Heat 1072-73 was selected for the most extended testing primarily because it was expected that it would be experimentally installed in a steam line. Tensile tests sufficient to define a curve of tensile properties from room temperature to 1500°F were carried out. Sufficient rupture tests, varying from about 100 hours to 5000 to 6000 hours in duration, to define stress-rupture curves were conducted at 1100°, 1200°, 1350°, and 1500°F. Creep tests to define the stress for a creep rate of 0.00001-percent per hour were conducted at 1000°, 1100°, 1200°, and 1350°F. The procedure used to establish this creep strength was to use stresses which would result in minimum creep rates sufficiently close to 0.00001-percent per hour that the stress for that creep rate could be estimated without undue extrapolation. The tests generally had to be 3000 to 5000 hours or longer to obtain minimum creep rates. Unexpectedly low minimum creep rates for a given stress for Heat 1072-73 resulted in a number of tests with creep rates too low to be useful. For this heat, attempts were made to obtain two tests with minimum or sufficiently close to minimum creep rates so that a family of stress-creep rate curves could be defined.

For Heat 6454, tensile and rupture tests were conducted at 1100°, 1200°, 1350°, and 1500°F while creep tests were run at 1100°, 1200°, and 1350°F. The main objective of the tensile tests was to guide the selection of the first stress in the rupture tests. Because the objective of the rupture tests was to obtain data to compare with Heat 1072-73, the longest duration tests were 1000 to 2000 hours in duration.

Creep tests had to be 3000 to 5000 hours in duration to obtain minimum creep rates. Considerably more success was achieved in obtaining creep rates near 0.00001-percent per hour with single tests.

Tensile, rupture and creep tests were conducted at 1200°F on the pipes from Heats R5773 and R5855 to obtain comparative data for additional pipes. The tests on Heat R5854 were limited to tensile and rupture tests. The main objective of these tests was to obtain an indication of the heat-to-heat uniformity of the material.

In evaluating the creep characteristics, recourse was used to demonstrate equal or higher creep strengths than currently-used design strengths. If, for instance, the creep rate fell below 0.00001-percent per hour at a commonly-used design value, it was considered that the test demonstrated at least equivalent strengths for the Hydroforged pipe. In conducting creep tests, the measurement of creep rate becomes uncertain when the rates fall below 0.00001-percent per hour. For this reason, tests were terminated when rates fell below this value and it was evident that an exact minimum rate could not be established.

All tensile, rupture, and creep tests were conducted in accordance with ASTM Recommended Practices E21 and E139. The time of heating before tensile testing was one hour. For the rupture and creep tests, the specimens were brought up to temperature and held overnight before applying the load. For the creep tests, an optical extensometer with a sensitivity of 2.8 millionths of an inch per inch was used to measure creep strain.

All materials were examined microscopically in the as-received condition. Typical rupture and creep specimens were also examined. Tensile and impact tests were carried out at room temperature after creep testing to obtain an indication of the stability of the material.

# RESULTS

Tensile, rupture and creep tests were used to evaluate the properties of the pipes at elevated temperatures. Supplementary information was obtained by conducting tensile and impact tests at room temperature before and after creep testing and by metallographic examination of the specimens.

## Short Time Tensile Properties

The tensile properties of Heat 1072-73 were established from room-temperature to 1500°F (Table 4 and Fig. 1) These tests were conducted to provide tensile and yield strengths at the lower temperatures where short time properties govern design stresses.

Tensile strengths decreased to 500°F and then leveled off to 800° or 900°F. The tensile strength then fell off markedly with further increase in temperature. Yield strengths were reduced somewhat by increasing the test temperature to 500° or 600°F. The yield strengths were then nearly constant up to 1500°F. Ductility values were high and nearly constant between 300° and 1200°F. The values were somewhat higher for tests below 300° and above 1200°F.

The other four pipes were subjected to tensile tests at only room temperature and 1200°F with results given in Table 5. These data have been included in Figure 1 along with tensile data for Heat 6454 provided by the United States Pipe and Foundry Company. The tensile properties of the five pipes were in good agreement.

## Rupture-Test Properties

Rupture tests up to about 5000 hours in duration (Table 6) were used to establish stress-rupture time curves (Fig. 2) at 1100°, 1200°, 1350°, and 1500°F for the pipe from Heat 1072-73. Tests at the same temperature but limited to 1000 to 2000 hours duration (Table 7 and Fig. 3) were conducted on the pipe from Heat 6454 to obtain comparable data for another hydroforged pipe. Testing for the same purpose was carried out at 1200°F (Table 8 and Figs. 4 and 5) for the other three pipes. The rupture strengths defined by the stress-rupture time curves are given in Table 9 and shown graphically in Figure 6.

The following comments apply to the data for Heat 1072-73:

(1) The stress-rupture time curves at 1100° and 1200°F (Fig. 2) underwent definite increases in slope at about 2000 and 900 hours. The slope after the change is well established at 1200°F. Although there were only two points at 1100°F, a curve drawn through those two points had a slope consistent with the slope at 1200°F. This agreement in slope should occur if the curve is correct and lends a high degree of confidence in its extrapolation.

(2) The curves at 1350° and 1500°F do not show changes in slope. The slopes are, however, nearly the same as those for the curves at 1100° and 1200°F after the change in slope. The resulting "family-of-curves" indicates that the curves are correct and extrapolations are reliable.

(3) When the lowest stress tests at 1100° and 1200°F were selected, it was intended that the rupture times be of the order of 8000 to 10,000 hours. At the time, experience indicated that stress-rupture time curves for Type 316 steel were not subject to changes in slope. The unexpected changes in slope resulted in the tests rupturing at about 5000 hours. Considerable unpublished data for Type 316 steel, which has since been made available to the authors on a confidential basis, suggest that such changes in slope may frequently occur in the alloy when it is cold worked prior to heat treatment.

(4) A large amount of experience has demonstrated that if tests were now conducted at the indicated stresses for rupture in

10,000 hours, the rupture times would be so close to 10,000 hours that the curves would not be changed.

The comparative data for Heat 6454 show the following:

(1) A family of stress-rupture time curves (Fig. 3) with similar slopes from 1100° to 1500°F. Therefore, there is virtual certainty that the curves at 1100° and 1200°F do not have the changes in slope exhibited by the material from Heat 1072-73. The extrapolations to long time periods are, therefore, quite reliable.

(2) The curve at 1100°F is different than for Heat 1072-73 due to a steeper slope at short time periods and indicated less slope at prolonged time periods. There is less evidence of difference at higher temperatures although the curves all tend to have less slope than for Heat 1072-73. The result is somewhat lower short time rupture strengths and equal or slightly higher long time rupture strengths.

(3) Even though there are differences in the stress-rupture time curves, the differences in rupture strength at 100,000 hours (Table 9) indicated by the curves (Fig. 3) are relatively small.

(4) Ductility in the rupture tests was similar for the two heats.

The results of the comparative rupture tests at 1200°F on Heats R5773, R5854 and R5855 were as follows:

(1) There were only relatively small differences in rupture strength between pipes (Table 9 and Fig. 6).

(2) The shapes of the curves of the three heats, in comparison to Heat 1072-73 (Fig. 5), suggest that they are not subject to increases in slope at prolonged time periods as was the case for Heat 1072-73.

(3) Ductilities were similar except that Heat R5854 was somewhat lower and Heat R5773 somewhat higher than the others for equivalent rupture times.

Tests on single transverse specimens were conducted for Heat 6454 (Fig. 3) and for Heats R5773 and R5855 (Fig. 4). In each case, the transverse specimen had a slightly longer rupture time than the longitudinal specimens. With the possible exception of Heat R5773, the ductilities were similar to those of the longitudinal specimens.

## Creep Properties

Creep tests were conducted at 1000°, 1100°, 1200°, and 1350°F on Heat 1072-73 with the object of defining the stress for a creep rate of 0.00001 percent per 1000 hours without undue extrapolation. The results obtained are shown as stress-creep rate curves by Figure 7 and the indicated stresses for a creep rate of 0.00001 percent per hour are included in Table 9. The following comments apply to this data:

(1) The indicated creep strengths proved to be high and nearly equal in relation to the stresses for rupture in 100,000 hours (Table 9).

(2) High ratios of creep to rupture strength suggest that one or the other is not correct. The creep strength of 0.00001 percent per hour is commonly extrapolated as indicating the stress for 1-percent creep in 100,000 hours. When the ratios of the creep strength to the rupture strength approach 1.0, as they do in this case, it implies that rupture would occur with only about 1-percent elongation. Although this is a distinct possibility, it seems to be unlikely and suggests that either the creep strength is incorrectly high or the rupture strength incorrectly low. General experience indicates that where stress-rupture time curves are as well established as they are in this case, it is extremely rare for them to indicate a low value for 100,000-hour rupture strength. For this reason, the creep strengths are considered to be open to the most question.

(3) The determination of creep strengths for Type 316

steel is difficult. The creep rate usually decreases gradually for long time periods. Precipitation of carbides probably causes volume shrinkage. The major tests were continued until the creep rate appeared to be nearly constant (Figs. 8, 9, 10, and 11). The test at 1200°F under 10,000 psi attained a minimum creep rate in a comparatively short time period. In view of the apparent indicated creep strength being high in relation to the rupture strength, the test was continued to determine if the creep rate would increase. An increase was observed after 5000 hours. The creep rate again leveled off at about 7000 hours. This latter rate has also been plotted on Figure 7 and a dashed curve drawn through it to 0.00001-percent per hour. The indicated creep strength is about 8500 psi. The ratio to the 100,000 hour rupture strength of 9700 psi would be 0.88, which is still rather high.

(4) The results of the creep test at 1200°F under 10,000 psi are believed to be indicative of metallurgical changes in the alloy which lead to abnormally low creep rates in tests of 5000 to 10,000 hours duration. For this reason, it is considered that the creep rates would probably increase at longer time periods to rates consistent with the rupture strengths.

(5) A number of creep tests were started and then discontinued when the creep rates fell below 0.00001-percent per hour before attainment of minimum rates. The rates were becoming too low to be measured reliably. The stresses for these tests were selected before it was determined that Heat 1072-73 had such high ratios of creep to rupture strength. The creep rate for the test at 1100°F under 24,000 psi resulted from a test initially selected for a prolonged rupture test and later judged to have a rupture time too long to be included in this investigation. A curve drawn through its minimum creep rate and the test at 17,500 psi were consistent in slope with the data at 1200°F.

(6) The tests at 1350°F were an exception in that tests at

3300 and 4000 psi attained apparent minimum creep but did not agree. A short duration check test at 4000 psi gave essentially the same creep as the first test at 4000 psi. This indicated that for some unknown reason the test at 3300 psi had an abnormally high creep rate. Due to the uncertainty, another test was run at 5500 psi. The stress-creep rate curve indicated by the tests at 4000 and 5500 psi was somewhat steeper than the curves indicated by the data at lower temperatures. This is believed due to the metallurgical reactions occurring faster at 1350°F with a closer approach to true minimum creep.

Single creep tests were conducted at 1100° and 1350°F and two tests at 1200°F on Heat 6454 with the results shown in Table 9 and Figure 7. The time-creep rate curves for the tests are included in Figures 9, 10, and 11. The test at 1100°F was discontinued after 1500 hours when the creep rate fell below 0.00001-percent per hour. This demonstrated a creep strength higher than 10,500 psi at 1100°F. A stress for a creep rate of 0.00001-percent per hour was estimated for 1100°F from this test by judging the probable minimum creep rate of the test and drawing a line back to 0.00001-percent per hour at the proper slope. Both tests at 1200°F apparently attained minimum creep rates and therefore define the creep strength quite well. The test at 1350°F was discontinued at 3000 hours before attaining a minimum creep rate. The time was sufficient so that it must have been near minimum at the time it was discontinued and not much error was involved in the estimated creep strength. The following additional comments apply to the creep data for Heat 6454:

(1) The creep resistance was considerably lower than that of Heat 1072-73 for the time periods of the tests.

(2) The ratios of the creep to rupture strength were lower and more nearly normal.

(3) Evidently, Heat 6454 was not subject to the reactions

causing the abnormally low creep rates (high creep strength) for Heat 1072-73. The slope of the stress creep rate curve at 1200°F was consistent with that for Heat 1072-73 at 1350°F, again suggesting freedom from such reactions.

A creep test at 1200°F on Heat R5773 at 10,000 psi apparently attained minimum creep rate (Fig. 10). A test at 7500 psi was discontinued when the creep rate decreased to 0.00001-percent per hour (Fig. 10) and it was judged that several thousand hours additional testing would be required to attain minimum creep rate with a rate so low that it could not be measured accurately. The stress for a creep rate of 0.00001-percent per hour was estimated by drawing a line (Fig. 12) through the point for the 10,000 psi test at the proper slope. One test was conducted on Heat R5855 at 1200°F under 8000 psi. It was judged that this test was near minimum creep rate at 4000 hours (Fig. 10) and that not much error was involved in estimating the creep strength with the curve shown in Figure 12. The indicated creep strengths for both heats are included in Table 9.

Both Heats R5773 and R5855 had creep resistance at 1200°F approaching that of Heat 1072-73 (Table 9) and considerably above that of Heat 6454. Moreover, the ratios of the creep strength to the rupture strengths were low enough so that the creep strengths appeared to be reasonably consistent with the rupture strengths.

The reported creep rates were measured from working time-elongation curves plotted to the proper time scale. Because these plots were so long for the prolonged tests, curves plotted to a condensed time scale to reduce the size for inclusion in the report were prepared as Figures 18 through 23. Figures 24 through 27 show creep curves for the rupture tests. The following comments are offered concerning these curves:

(1) As the previously discussed creep rate time curves

showed all the creep tests decreased in creep rate as testing time increased for long time periods as is typical for Type 316 alloy.

(2) The creep curves for Heat 1072-73 at 1200° and 1350°F under the lowest stresses (Figs. 20 and 21) indicate decreases in length early in the tests. This is generally due to a volume decrease from precipitation of excess phases. More volume decrease probably occurred in all the tests than is readily evident from the creep curves. It was probably responsible for the extension immediately after loading being small in comparison to creep tests on most materials. In most cases, positive creep offsets the volume decrease. Either such reactions were stronger in Heat 1072-73 or it had higher creep resistance so that the volume decrease was more evident. Such effects occur generally in the alloy and are not unique to the cast, cold worked and solution treated material investigated.

(3) The large deformation during loading for the higher stress tests at 1000° and 1100°F on Heat 1072-73 reflects the yielding during application of the stress for the creep tests.

(4) Unlike the creep tests, the creep curves for the rupture tests underwent very little, if any, decrease in creep rate. In most cases, the creep rates increased with testing time from the start of the tests. In some cases, there were periods of nearly constant creep rate prior to the increase in rate leading to fracture. In all cases, the creep rates increased gradually with time. Probably the yielding which occurred during application of the stress for the rupture tests in conjunction with precipitation reactions so strengthened the material that so-called "first-stage" creep was practically eliminated.

## Mechanical Properties at Room Temperature after Creep Testing

Tensile and impact tests (Tables 10 and 11) were conducted at room temperature on part of the specimens after creep testing to obtain data on the changes induced by exposure to creep, with the following results:

(1) Tensile and yield strengths increased and ductility decreased.

(2) Creep at 1100° and 1200°F caused the most increase in strength with the increase being larger the higher the stress. The most marked increase in strength, however, occurred in the specimen of Heat 1072-73 (Table 10) creep tested under 24,000 psi, apparently due to the yielding which occurred during application of the stress.

(3) Ductility decreased with increasing temperature of testing from 1000° to 1350°F.

(4) All of the heats had similar properties after creep testing under similar conditions. Such small differences as were present could have been due to differences in creep exposure conditions.

(5) Impact strengths (Tables 10 and 11) were reduced by creep testing, except at 1000°F. Testing at 1100°F resulted in a loss of one foot-pound in 4067 hours and 10 foot-pounds in 6790 hours at a higher stress from an original value of 90 foot-pounds. The reductions from testing at 1200°F varied from approximately 15 foot-pounds for Heat R5773 to 36 foot-pounds for Heat 6454. Apparently, Heat 6454 was most subject to reduction in impact strength because the creep exposure time was only about half that of Heat 1072-73 with a greater reduction in impact strength. Heats R5773 and R5855 were considerably less subject to change. Heat 1072-73 exhibited a further reduction when creep tested at 1350°F with impact strengths of 40 foot-pounds in comparison to the original value of 90. The 3300 psi specimen which had an abnormally high creep rate suffered somewhat less loss than the other specimens creep tested at 1350°F. Such reductions in impact strength are to be expected for Type 316 alloy made by any process. It will be noted that there apparently was a considerable difference between heats in these characteristics. The lowest values

measured still exhibited a rather high level of impact strength and the observed reductions at 1200° and 1350°F would be of no concern unless the impact strength of Type 316 alloy continues to fall off with further exposure times under creep conditions.

## Microstructural Characteristics

Original microstructures for the five heats are shown in Figures 28 through 32. The cold expansion from Hydroforging plus heat treatment resulted in equiaxed grains. As would be expected, the heat treatment resulted in clear austenitic grains with the following grain sizes:

| Heat | ASTM Grain Size |
|---|---|
| 1072-73 | 0-2 |
| 6454 | 2-4 |
| R5773 | 1-4 |
| R5854 | 0-4 |
| R5855 | 1-4 |

Heat 6454, in addition to having a somewhat finer grain size than the other heats, contained small particles of an excess phase. The particles were not dissolved by heat treating at 2150°F so that it is unlikely that they were carbides. The heat had the lowest ratio of austenite to ferrite forming elements so the probability is that it was ferrite. However, no magnetic response could be detected.

During testing, fine carbides precipitated within the grains and at the grain boundaries as is typical of Type 316 alloy. The precipitate particle size increased with test temperature and with testing time as would be expected. After the longer tests at 1500°F, the particles were comparatively large, while they were very fine after testing at the lower temperatures. The precipitates tended to be in patches, a characteristic of Type 316 alloy, a tendency more evident with increasing test temperature. The path of fracture of rupture specimens was both intergranular and transgranular. Intergranular cracking occurred adjacent to the actual fracture with fracture probably starting at such locations. The extent of this type of cracking increased with test temperature and time for rupture. Those specimens with high elongation in the rupture tests contained severely elongated grains near the fracture, as would be expected.

Photomicrographs of the most prolonged test specimens for Heat 1072-73 are included in this report as Figures 33 through 48. A previous report [1] included photomicrographs for the other heats after testing and photomicrographs of specimens with shorter testing times. The photomicrographs for Heat 1072-73 are reasonably typical. The general precipitation in Heat 1072-73 was apparently somewhat more uniform and extensive than for the other heats. The precipitates within the grains after creep testing at 1000°F under 25,000 psi were largely on the slip planes (Fig. 33) developed by yielding during loading of the tests. Also, there was evidence of precipitation along the fracture and intergranular cracks of the most prolonged rupture specimens from Heat 1072-73 tested at 1500°F (Fig. 43) due to nitrogen pick-up from the atmosphere. This is a common phenomena in all stainless steels during tests at 1500°F or higher. It is mainly confined to the areas with cracks and seems to be made possible by the fracture mechanism. Very little, if any, occurs at only a short distance from the fracture.

No difference was found in structure between the creep specimen at 1350°F under 3300 psi which gave an abnormally high creep rate from the other specimens (Figs. 39, 40, and 41).

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[1] Progress Report on Properties of Hydroforged Type 316 Steel Pipe at High Temperatures - February 28, 1961.

The only other difference not shown by the included photomicrographs was the changes in the excess phase originally present in Heat 6454. As was shown in the previous report[1], the particles etched rapidly. During testing at 1100°F, extensive precipitation took place within the particles. The particles tended to break down to numerous smaller particles during testing at the higher temperatures and to string out along the grain boundaries. This behavior would be expected for small particles of ferrite originally present.

## DISCUSSION

The ranges in measured rupture and creep strengths of the five Hydroforged pipes of Type 316 austenitic steel are normal. The rupture strengths, in particular, were in good agreement. The creep strengths varied somewhat more as would be expected for this structure sensitive property.

The high ratios of creep to rupture strength are not at all unusual for stainless steels. Some heats are apparently subject to metallurgical reactions which cause abnormally low creep rates in tests of several thousand hours duration. As was previously pointed out, these probably do not last very long and the creep rates probably increase up to values consistent with the rupture strengths. This type of creep occurs in Type 316 made by other processes and is not unique to the Hydroforging process.

The comparison of the rupture strengths at 10,000 and 100,000 hours of the Hydroforged pipes with the published values for Type 316 austenitic steel in ASTM STP Number 124 (Figs. 13 and 14) shows:

(1) The strengths are within the range for the alloy.

(2) They tend to be on the low side of the range particularly at 1100° and 1200°F. The strengths being on the low side of the range is almost certainly a characteristic of cold worked and re-

crystallized Type 316 alloy made by any process rather than a characteristic of the Hydroforging process.

A similar comparison of the creep strengths for a creep rate of 0.00001-percent per hour in Figure 15 shows:

(1) All heats of Hydroforged pipe except Heat 6454 had creep strengths on the high side of the range for the alloy.

(2) The creep strengths of Heat 6454 were well within the range.

It should be recognized that many of the creep strengths from STP Number 124 were based on relatively short time tests. Therefore, they do not reflect the increase in apparent creep strength arising from the gradual decrease in creep rate with prolonged testing time characteristic of Type 316 alloy. For this reason, it is expected that comparison with data for other prolonged tests would result in the creep strengths of the Hydroforged pipe being shifted towards the lower side of the range. The lower side of the range should represent cold worked and recrystallized material made by any process.

In the use of alloys, design stresses are usually based on a fraction of the tensile or yield strengths up to the temperature where such values become larger than rupture or creep strengths. Because yield strengths of Type 316 alloy are low in comparison to tensile strengths, and would govern the shift from short time to long time strengths for design purposes, the yield strengths have been included in Table 9 for comparison with the creep and rupture strengths. It will be noted that the yield strengths do not exceed the creep and rupture strengths until the temperature exceeds 1100°F.

The tensile and yield strengths of the Hydroforged pipes are compared in Figures 16 and 17 with the ranges of values in ASTM STP Number 124 for Type 316 austenitic steel. As would be expected, the values for the Hydroforged pipes are on the low side but within the range for the alloy. Type 316 material when cold worked and recrystallized by heat treating at 1950°F should have the lower values, regardless of the manufacturing process. This type of treatment produces a material free from cold work and, therefore, with the strengths on the low side of the range. The high values in the range almost certainly reflect residual cold work or cold work arising from cold strengthening.

The Hydroforged pipes exhibited the high level of ductility to be expected for Type 316 alloy in both tensile and rupture tests.

In summary, the results of the investigation of the tensile, creep and rupture properties did not result in unusual properties for specimens from Hydroforged Type 316 stainless steel. The properties were generally at the level and exhibited the characteristics to be expected for the alloy when cold worked and then heat treated to cause recrystallization and solution of carbides. The variations between heats encountered are to be expected for the alloy.

Table 1

Chemical Composition of Five Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes

| Heat No. | Chemical Composition (Percent) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | Cr | Ni | Mo | P | S |
| R5773 | 0.053 | 1.18 | 0.31 | 16.18 | 13.44 | 2.36 | 0.016 | 0.015 |
| 6454 | 0.049 | 1.11 | 0.51 | 16.96 | 13.84 | 2.55 | low | low |
| R5854 | 0.063 | 1.67 | 0.35 | 16.70 | 13.49 | 2.50 | 0.010 | 0.014 |
| R5855 | 0.053 | 1.59 | 0.36 | 17.76 | 13.52 | 2.39 | 0.010 | 0.014 |
| 1072-73 | 0.061 | 1.38 | 0.25 | 16.70 | 13.18 | 2.36 | 0.016 | 0.019 |

Table 2

Description of Hydroforged Type 316 (18-8+Mo) Pipes Investigated

| Heat | Furnace Size (lbs) | As-Cast Dimensions O. D. (in.) | As-Cast Dimensions I. D. (in.) | As-Cast Dimensions Length (in.) | Finished Dimensions O. D. (in.) | Finished Dimensions Wall Thickness (in.) | Number of Expansions | Number of Intermediate Anneals at 1950°F |
|---|---|---|---|---|---|---|---|---|
| R5773 | 500 | 7-5/16 | 3-3/16 | 50 | 8-21/32 | 0.890 | 2 | 1 |
| R5854 | 500 | 7-3/8 | 3-3/32 | 50-3/16 | 8-5/8 | 0.906 | 2 | 1 |
| R5855 | 500 | 7-3/8 | 3-3/32 | 50-1/4 | 8-5/8 | 0.906 | 2 | 1 |
| 6454 | 2000 | 9-1/2 | 5-3/8 | 74-3/4 | 10-3/4 | 0.906 | 2 | 1 |
| 1072-73 | 2000 | 10-3/4 | 5-3/8 | 162 | 12 | 1.44 | 2 | 1 |

Table 3

Tensile Properties of Five Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes at Room Temperature. (Data Reported by Steel and Tube Division, United States Pipe and Foundry Company)

| Test Location | Heat No. | Tensile Strength (psi) | 0.2% Offset Yield Strength (psi) | Elongation (%) | Reduction of Area (%) |
|---|---|---|---|---|---|
| -- | R5773 | 79,200 | 35,600 | 57.1 | 71.4 |
| -- | R5773 | 79,100 | 36,150 | 55.7 | 73.7 |
| -- | 6454 | 79,500 | 37,200 | 57.5 | 69.7 |
| -- | 6454 | 80,400 | 36,850 | 60.0 | 69.2 |
| Pouring End | R5854 | 82,800 | 40,000 | 57.8 | 71.7 |
| Pouring End | R5854 | 82,400 | 39,200 | 59.2 | 72.9 |
| Back End | R5854 | 81,300 | 37,750 | 59.2 | 72.3 |
| Back End | R5854 | 82,300 | 37,500 | 62.8 | 73.7 |
| Pouring End | R5855 | 80,400 | 34,600 | 65.0 | 74.3 |
| Pouring End | R5855 | 80,300 | 35,100 | 57.8 | 72.3 |
| Back End | R5855 | 81,600 | 35,100 | 56.4 | 72.6 |
| Back End | R5855 | 81,600 | 36,000 | 58.5 | 73.2 |
| "Stem" End | 1072-73 | 80,350 | 37,500 | 61.0 | 75.3 |
| "Stem" End | 1072-73 | 80,290 | 36,750 | 61.5 | 75.3 |
| "A" End | 1072-73 | 79,050 | 35,500 | 63.0 | 75.5 |
| "A" End | 1072-73 | 79,850 | 36,000 | 61.0 | 73.9 |

Table 4

Tensile Properties for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73

| Temperature (°F) | Tensile Strength (psi) | Offset Yield Strength(psi) 0.1% | 0.2% | Elongation (% in 2 inches) | Reduction of Area (%) |
|---|---|---|---|---|---|
| 80 | 79,000 | 30,500 | 33,000 | 66.0 | 70.0 |
| 80 | 79,250 | 29,750 | 32,500 | 64.0 | 65.5 |
| 500 | 67,000 | 19,750 | 21,750 | 49.0 | 63.0 |
| 500 | 67,250 | 20,250 | 22,000 | 48.0 | 61.5 |
| 700 | 67,500 | 19,750 | 21,500 | 53.0 | 62.5 |
| 700 | 67,500 | 19,500 | 21,000 | 50.0 | 63.0 |
| 800 | 68,250 | 18,500 | 20,000 | 50.0 | 59.5 |
| 800 | 67,500 | 19,000 | 20,500 | 50.0 | 60.0 |
| 1000 | 61,750 | 15,250 | 16,500 | 48.5 | 62.5 |
| 1000 | 63,500 | 16,250 | 17,500 | 49.0 | 59.0 |
| 1100 | 57,500 | 15,250 | 16,250 | 48.0 | 61.5 |
| 1100 | 58,000 | 15,000 | 16,250 | 46.5 | 62.5 |
| 1200 | 47,750 | 15,000 | 16,000 | 53.0 | 62.5 |
| 1200 | 48,750 | 15,250 | 16,250 | 52.0 | 62.5 |
| 1350 | 34,000 | 14,000 | 15,250 | 57.0 | 61.5 |
| 1350 | 34,500 | 14,250 | 15,250 | 57.0 | 57.0 |
| 1500 | 22,000 | 13,250 | 14,250 | 71.0 | 72.0 |
| 1500 | 21,500 | 13,750 | 14,750 | 78.0 | 73.5 |

Table 5

Tensile Data for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes

| Heat No. | Temp (°F) | Tensile Strength (psi) | Offset Yield Strength(psi) 0.1% | Offset Yield Strength(psi) 0.2% | Elongation (% in 2 inches) | Reduction of Area(%) |
|---|---|---|---|---|---|---|
| 6454 | 80 | 79,500 | 31,500 | 34,000 | 68.5 | 72.0 |
| R5773 | 80 | 79,750 | 32,000 | 34,750 | 71.0 | 72.0 |
| 1072-73 | 80 | 79,000 | 30,500 | 33,000 | 66.0 | 70.0 |
| 1072-73 | 80 | 79,250 | 29,750 | 32,500 | 64.0 | 65.5 |
| 6454 | 1200 | 49,500 | 18,500 | 20,000 | 47.5 | 64.0 |
| R5773 | 1200 | 49,500 | 15,750 | 17,000 | 48.0 | 63.0 |
| R5854 | 1200 | 50,500 | 16,000 | 17,000 | 47.5 | 56.0 |
| R5855 | 1200 | 49,250 | 15,500 | 16,750 | 50.0 | 58.0 |
| 1072-73 | 1200 | 47,750 | 15,000 | 16,000 | 53.0 | 62.5 |
| 1072-73 | 1200 | 48,750 | 15,250 | 16,250 | 52.0 | 62.5 |

Table 6

Stress-Rupture Time Data at 1100°, 1200°, 1350°, and 1500°F for the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73

| Temperature (°F) | Stress (psi) | Rupture Time (hours) | Elongation (% in 2 inches) | Reduction of Area (%) |
|---|---|---|---|---|
| 1100 | 57,500 | STTT | 48.0 | 61.5 |
| 1100 | 58,000 | STTT | 46.5 | 62.5 |
| 1100 | 36,000 | 171 | 19.5 | 26.5 |
| 1100 | 33,500 | 1158 | 28.0 | 31.5 |
| 1100 | 30,000 | 3568 | 23.5 | 28.0 |
| 1100 | 28,000 | 4882 | 20.5 | 25.5 |
| 1200 | 47,750 | STTT | 53.0 | 62.5 |
| 1200 | 48,750 | STTT | 52.0 | 62.5 |
| 1200 | 30,000 | 76 | 68.5 | 60.0 |
| 1200 | 27,500 | 155 | 66.0 | 64.0 |
| 1200 | 25,000 | 448 | 47.5 | 59.0 |
| 1200 | 22,000 | 1172 | 39.0 | 42.5 |
| 1200 | 20,000 | 2067 | 34.5 | 38.5 |
| 1200 | 18,000 | 3183 | 27.5 | 28.0 |
| 1200 | 16,500 | 5516 | 25.0 | 25.0 |
| 1350 | 34,000 | STTT | 57.0 | 61.5 |
| 1350 | 34,500 | STTT | 57.0 | 57.0 |
| 1350 | 15,000 | 217 | 73.0 | 62.0 |
| 1350 | 12,500 | 588 | 38.5 | 37.5 |
| 1350 | 11,000 | 1082 | 40.0 | 41.5 |
| 1350 | 8,000 | 4707 | 10.5 | 15.0 |
| 1500 | 22,000 | STTT | 71.0 | 72.0 |
| 1500 | 21,500 | STTT | 78.0 | 73.5 |
| 1500 | 8,000 | 236 | 72.0 | 52.0 |
| 1500 | 6,500 | 625 | 40.0 | 40.0 |
| 1500 | 5,000 | 2576 | 23.0 | 24.0 |
| 1500 | 4,200 | 4975 | 25.5 | 25.5 |

STTT - Data from short time tensile test

Table 7

Stress-Rupture Time Data at 1100°, 1200°, 1350°, and 1500°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe

Heat 6454

| Temperature (°F) | Stress (psi) | Rupture Time (hours) | Elongation (% in 2 inches) | Reduction of Area (%) |
|---|---|---|---|---|
| 1100 | 45,000 | 23.3 | 39.0 | 43.0 |
| 1100 | 37,000 | 124 | 20.5 | 27.5 |
| 1100 | 32,000 | 416 | 24.0 | 29.5 |
| 1100 | 29,000 | 1060 | 18.0 | 26.5 |
| | | | | |
| 1200 | 49,500 | STTT | 47.5 | 64.0 |
| 1200 | 30,000 | 48.7 | 47.0 | 48.5 |
| 1200 | 25,000 | 278 | 47.0 | 48.5 |
| 1200 | 23,500 | 564 | 47.0* | 47.0 |
| 1200 | 22,000 | 728 | 53.5 | 52.0 |
| 1200 | 19,500 | 1714 | 31.5 | 39.0 |
| | | | | |
| 1350 | 19,000 | 39.8 | 45.5 | 46.5 |
| 1350 | 16,500 | 67.4 | 44.0 | 46.0 |
| 1350 | 14,000 | 198 | 44.0 | 42.0 |
| 1350 | 11,000 | 1045 | 39.5 | 40.5 |
| | | | | |
| 1500 | 11,000 | 43.7 | 41.0 | 41.0 |
| 1500 | 8,500 | 117 | 41.0 | 39.0 |
| 1500 | 6,000 | 759 | 32.0 | 31.0 |

* Transverse specimen - elongation in 1.5 inches

Table 8

Stress-Rupture Time Data at 1200°F for Three Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes

| Heat Number | Stress (psi) | Rupture Time (hours) | Elongation (% in 2 inches) | Reduction of Area (%) | Specimen Location |
|---|---|---|---|---|---|
| R5773 | 49,500 | STTT | 48.0 | 63.0 | Longitudinal |
| | 30,000 | 63.3 | 44.0 | 52.5 | Longitudinal |
| | 25,000 | 343 | 59.0 | 62.0 | Longitudinal |
| | 23,500 | 929 | 58.5 | 59.0 | Transverse |
| | 22,000 | 1056 | 87.0 | 62.0 | Longitudinal |
| R5854 | 50,500 | STTT | 47.5 | 56.0 | Longitudinal |
| | 33,000 | 41.3 | 23.0 | 28.0 | Longitudinal |
| | 31,000 | 145 | 34.5 | 38.0 | Longitudinal |
| | 28,000 | 204 | 32.0 | 39.5 | Longitudinal |
| | 23,000 | 928 | 30.5 | 37.5 | Longitudinal |
| R5855 | 49,250 | STTT | 50.0 | 58.0 | Longitudinal |
| | 32,000 | 77.7 | 40.0 | 44.0 | Longitudinal |
| | 28,000 | 234 | 47.0 | 52.0 | Longitudinal |
| | 26,000 | 632 | 51.0 | 60.0 | Transverse |
| | 23,000 | 713 | 49.0 | 55.0 | Longitudinal |

STTT - Short-Time Tensile Test

(Note: Elongations of Transverse Specimens are % in 1.5 inches)

Table 9

Rupture and Creep Strengths of Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes

| Heat | Temp (°F) | Rupture Strengths (psi) 100-hr | 1000-hr | 10,000-hr | 100,000-hr | Stress(psi) for a Creep Rate of 0.00001% per hr. | Ratio Creep Strength to 100,000-hr Rupture Strength | 0.2% Offset Yield Strength (psi) |
|---|---|---|---|---|---|---|---|---|
| 1072-73 | 1000 | -- | -- | -- | --- | 24,500 | -- | 17,000 |
| 1072-73 | 1100 | 37,000 | 34,000 | 25,000 | 16,500 | 15,500 | 0.94 | 16,250 |
| 6454 | 1100 | 38,000 | 29,000 | 22,000 | 17,000 | (>11,000) | (0.65) | -- |
| 1072-73 | 1200 | 29,000 | 22,500 | 15,000 | 9,700 | (9,600)-(8,400) | (0.99)-(0.86) | 16,125 |
| 6454 | 1200 | 28,000 | 21,000 | 15,000 | 10,500 | 6,500 | 0.62 | 20,000 |
| R5773 | 1200 | 29,000 | 22,000 | 17,000 | 12,750 | 8,600 | 0.68 | 17,000 |
| R5854 | 1200 | 32,000 | 22,500 | 16,000 | 11,000 | -- | -- | 17,000 |
| R5855 | 1200 | 32,000 | 22,000 | 15,000 | 10,500 | 9,000 | 0.85 | 16,750 |
| 1072-73 | 1350 | 17,500 | 11,000 | 7,000 | 4,200 | 4,200 | 1.00 | 15,250 |
| 6454 | 1350 | 15,500 | 11,000 | 7,800 | 5,400 | ( 2,500) | (0.46) | -- |
| 1072-73 | 1500 | 9,600 | 6,000 | 3,700 | 2,300 | -- | -- | 14,500 |
| 6454 | 1500 | 9,000 | 5,800 | 3,700 | 2,400 | -- | -- | -- |

Table 10

Tensile and Impact Properties at Room Temperature after Creep Testing for Type 316 (18-8+Mo) Stainless Steel Hydroforged Pipe from Heat 1072-73

| Creep Test Conditions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Temp (°F) | Stress (psi) | Test Duration (hours) | Tensile Strength (psi) | Offset Yield Strength (psi) (0.1%) | Offset Yield Strength (psi) (0.2%) | Elongation (% in 2 inches) | Reduction of Area (%) | Modified Izod Impact (a) (ft-lbs) |
| Original | | | 79,000 | 30,500 | 33,000 | 66 | 70 | 90, 91 |
| | | | 79,250 | 29,750 | 32,500 | 64 | 65.5 | |
| 1000 | 25,000 | 6887 | -- | -- | -- | -- | -- | 94, 96 |
| 1000 | 20,000 | 3334 | 79,500 | 38,750 | 39,250 | 57.5 | 67.0 | -- |
| 1100 | 24,000 | 2807 | 93,500 | 53,000 | 53,750 | 39.0 | 52.0 | -- |
| 1100 | 17,500 | 6790 | -- | -- | -- | -- | -- | 78, 80 |
| 1100 | 14,000 | 4067 | -- | -- | -- | -- | -- | 89, 89 |
| 1100 | 10,400 | 3175 | 85,000 | 38,000 | 40,250 | 47.0 | 57.0 | -- |
| 1200 | 10,000 | 8499 | -- | -- | -- | -- | -- | 62, 58 |
| 1200 | 8,500 | 4753 | 88,500 | 38,250 | 39,750 | 44.5 | 51.0 | -- |
| 1200 | 6,800 | 2666 | 86,500 | 35,750 | 37,750 | 42.5 | 49.0 | -- |
| 1350 | 5,500 | 5272 | -- | -- | -- | -- | -- | 40, 39 |
| 1350 | 4,000 | 1819 | 85,000 | 34,000 | 36,250 | 35.0 | 32.0 | -- |
| 1350 | 4,000 | 3745 | -- | -- | -- | -- | -- | 45, 49 |
| 1350 | 3,300 | 4646 | -- | -- | -- | -- | -- | 51, 51 |
| 1350 | 2,700 | 2666 | 84,500 | 33,000 | 35,000 | 34.0 | 33.0 | -- |

(a) From modified Izod Impact Specimen (0.365-inch square with a 0.050-inch deep V notch

Table 11

Tensile and Impact Properties of Type 316 (18-8+Mo) Hydroforged Pipes at Room Temperature After Creep Testing

| Creep Test Conditions | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Heat No. | Temp (°F) | Stress (psi) | Test Duration (hours) | Tensile Strength (psi) | Offset Yield Strength(psi) 0.1% | Offset Yield Strength(psi) 0.2% | Elongation (% in 2 in.) | Reduction of Area(%) | Modified Izod Impact* (ft-lbs) | |
| R5773 | | Original | | 79,750 | 32,000 | 34,750 | 71.0 | 72.0 | 94 | 97 |
| R5773 | 1200 | 7,500 | 2883 | 86,000 | 35,250 | 37,000 | 52.0 | 57.5 | -- | -- |
| R5773 | 1200 | 10,000 | 4369 | -- | -- | -- | -- | -- | 80 | 78 |
| 6454 | | Original | | 79,500 | 31,500 | 34,000 | 68.5 | 72.0 | 90 | 94 |
| 6454 | 1100 | 10,400 | 1746 | 83,000 | 35,500 | 37,750 | 59.0 | 63.0 | -- | -- |
| 6454 | 1200 | 6,800 | 4707 | 88,750 | 36,000 | 38,250 | 46.5 | 50.5 | -- | -- |
| 6454 | 1350 | 2,700 | 3559 | 86,250 | 30,750 | 33,500 | 38.0 | 33.0 | -- | -- |
| 6454 | 1200 | 10,000 | 4395 | -- | -- | -- | -- | -- | 53 | 59 |
| R5855 | | Original | | -- | -- | -- | -- | -- | 94 | 95 |
| R5855 | 1200 | 8,000 | 4539 | -- | -- | -- | -- | -- | 74 | 72 |

* From Modified Izod Impact Specimen (0.365-inch square with a 0.050-inch deep V notch)

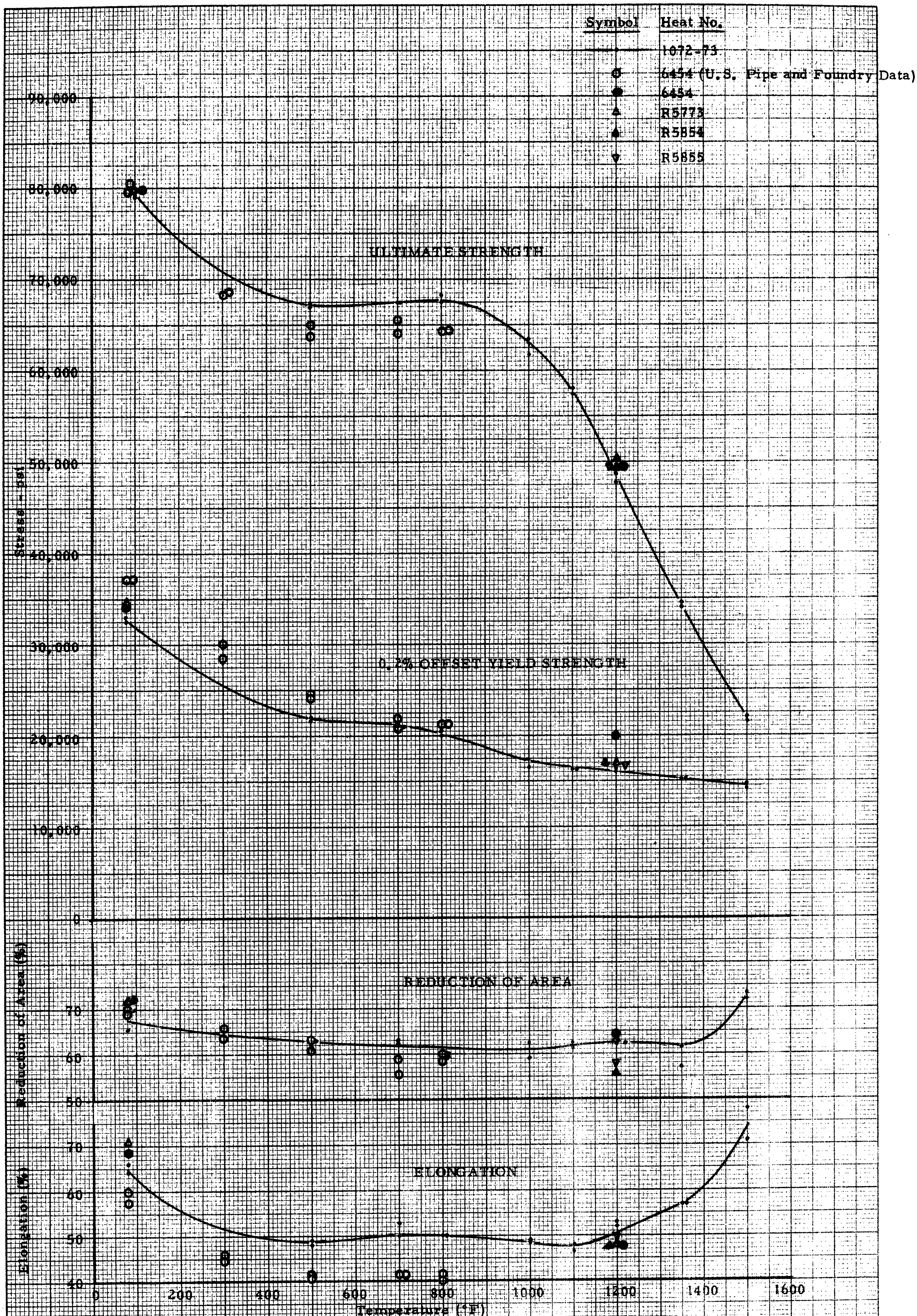
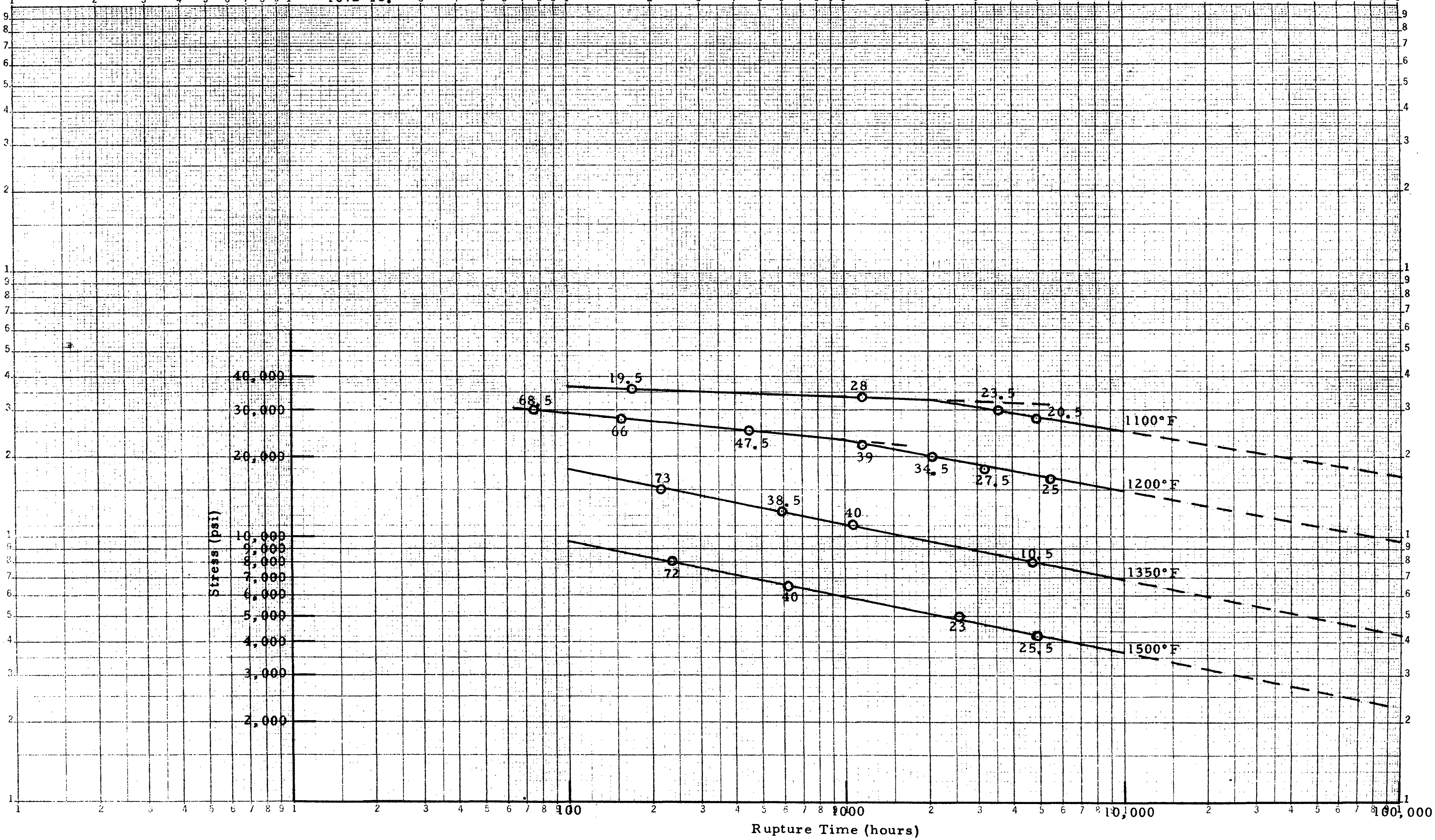



Figure 1. Comparative Tensile Properties Versus Temperature for Five Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes.

Figure 2 Stress-Rupture Time Curves at 1100°, 1200°, 1350°, and 1500°F for the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.



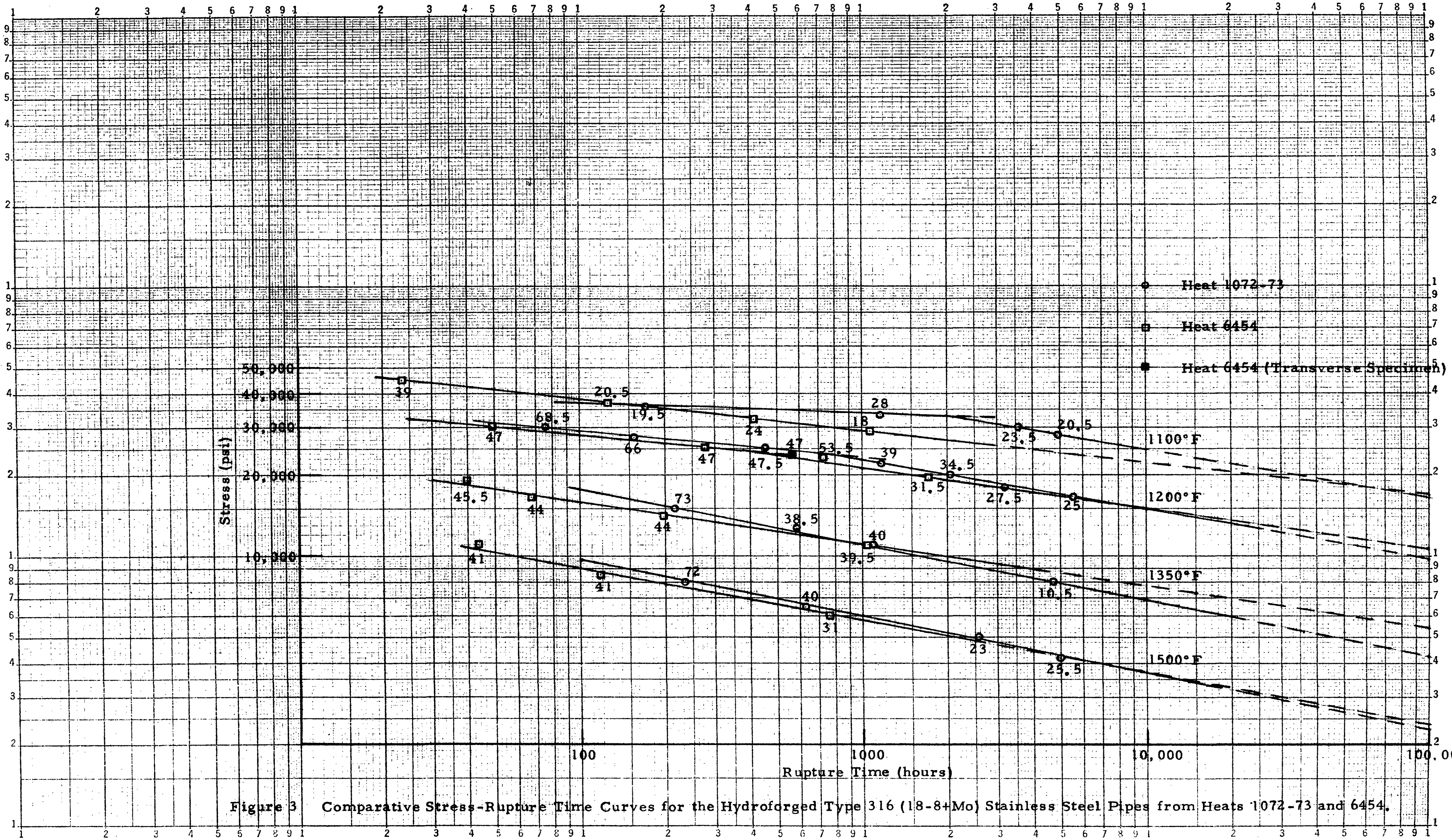
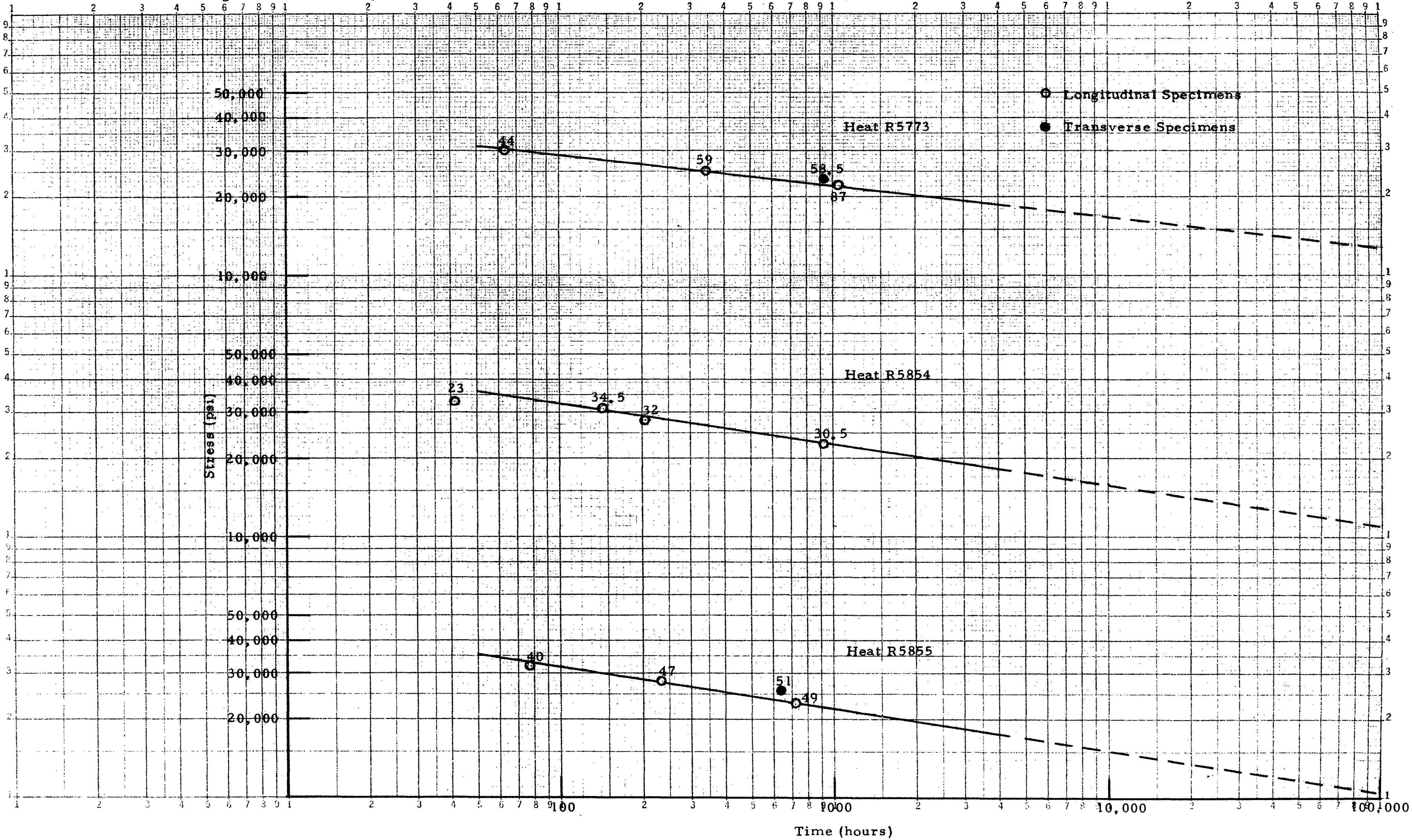



Figure 3 Comparative Stress-Rupture Time Curves for the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes from Heats 1072-73 and 6454.

Figure 4 Stress-Rupture Time Curves at 1200°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes from Heats R5773, R5854, and R5855.



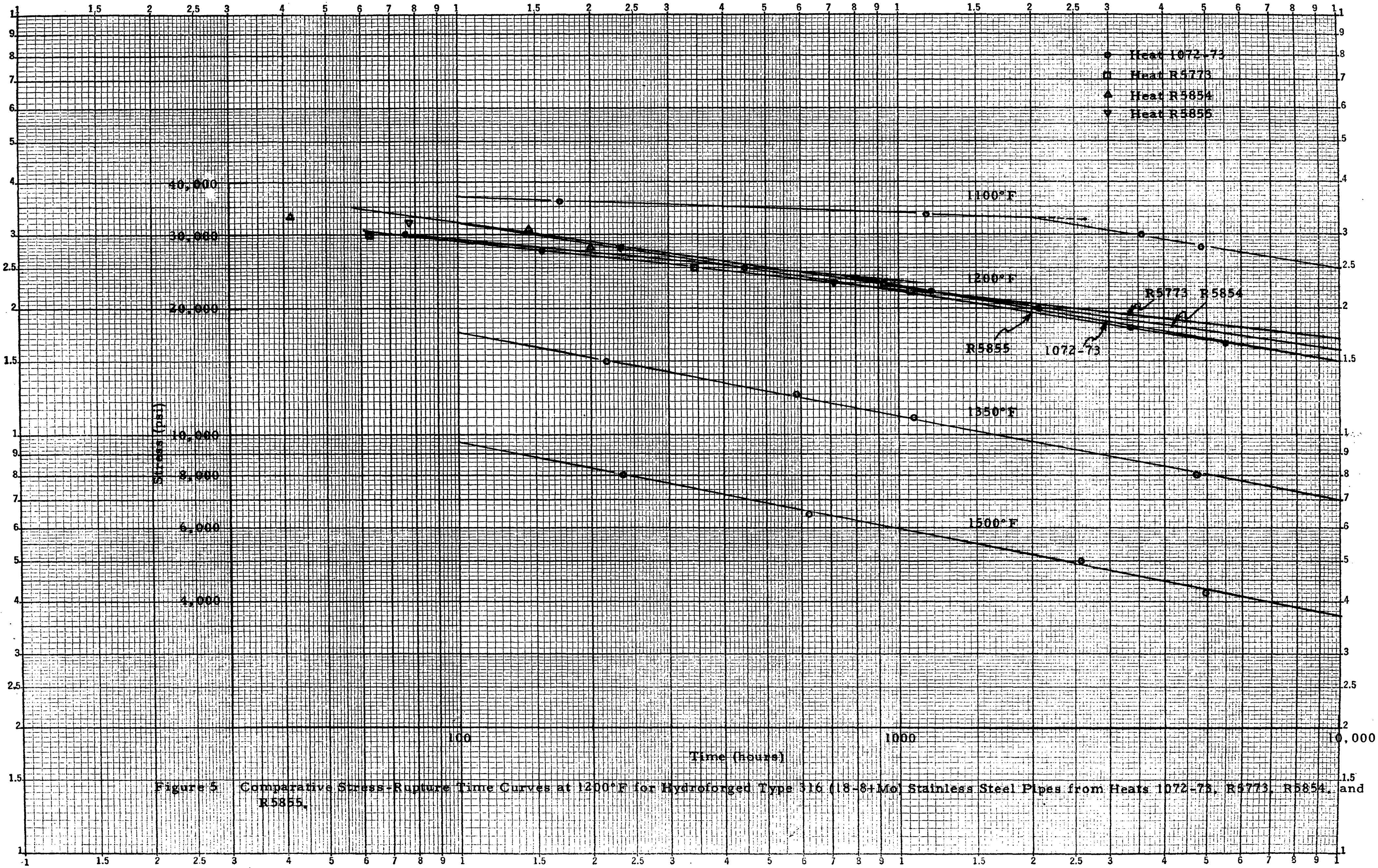



Figure 5 Comparative Stress-Rupture Time Curves at 1200°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes from Heats 1072-73, R5773, R5854, and R5855.

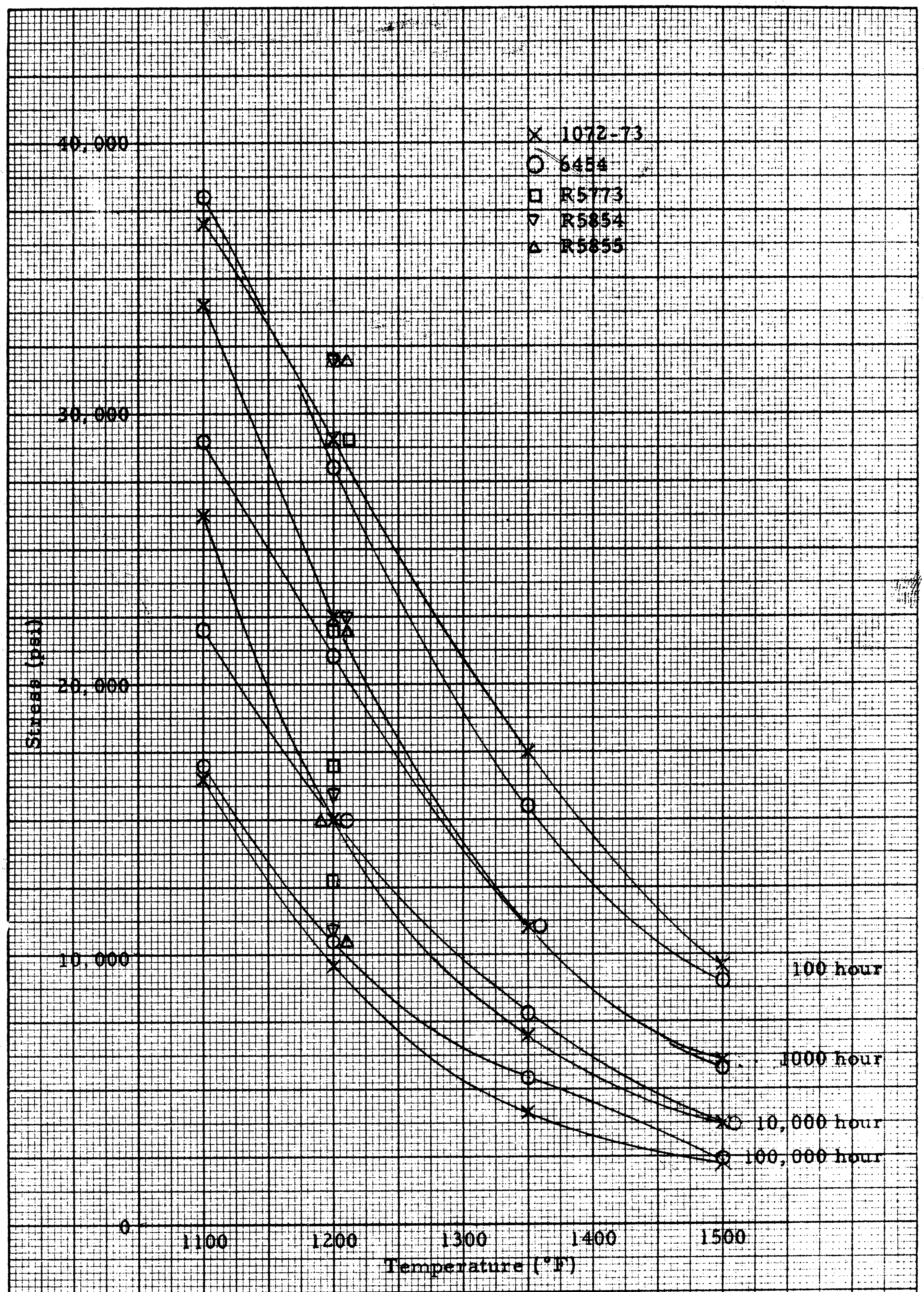



Figure 6 Comparative Rupture and Creep Strengths Versus Temperature for Five Heats of Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes.

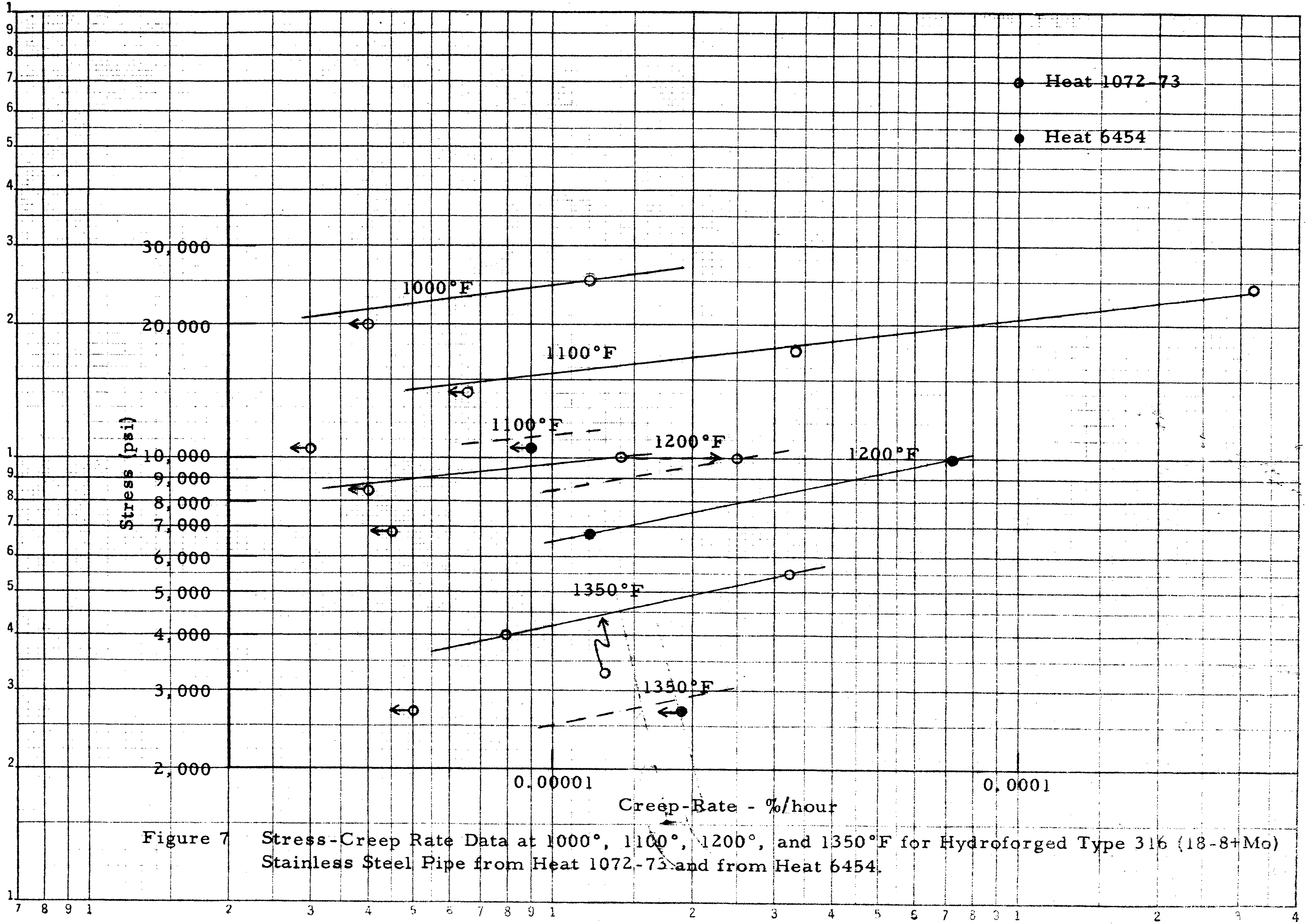



Figure 7 Stress-Creep Rate Data at 1000°, 1100°, 1200°, and 1350°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73 and from Heat 6454.

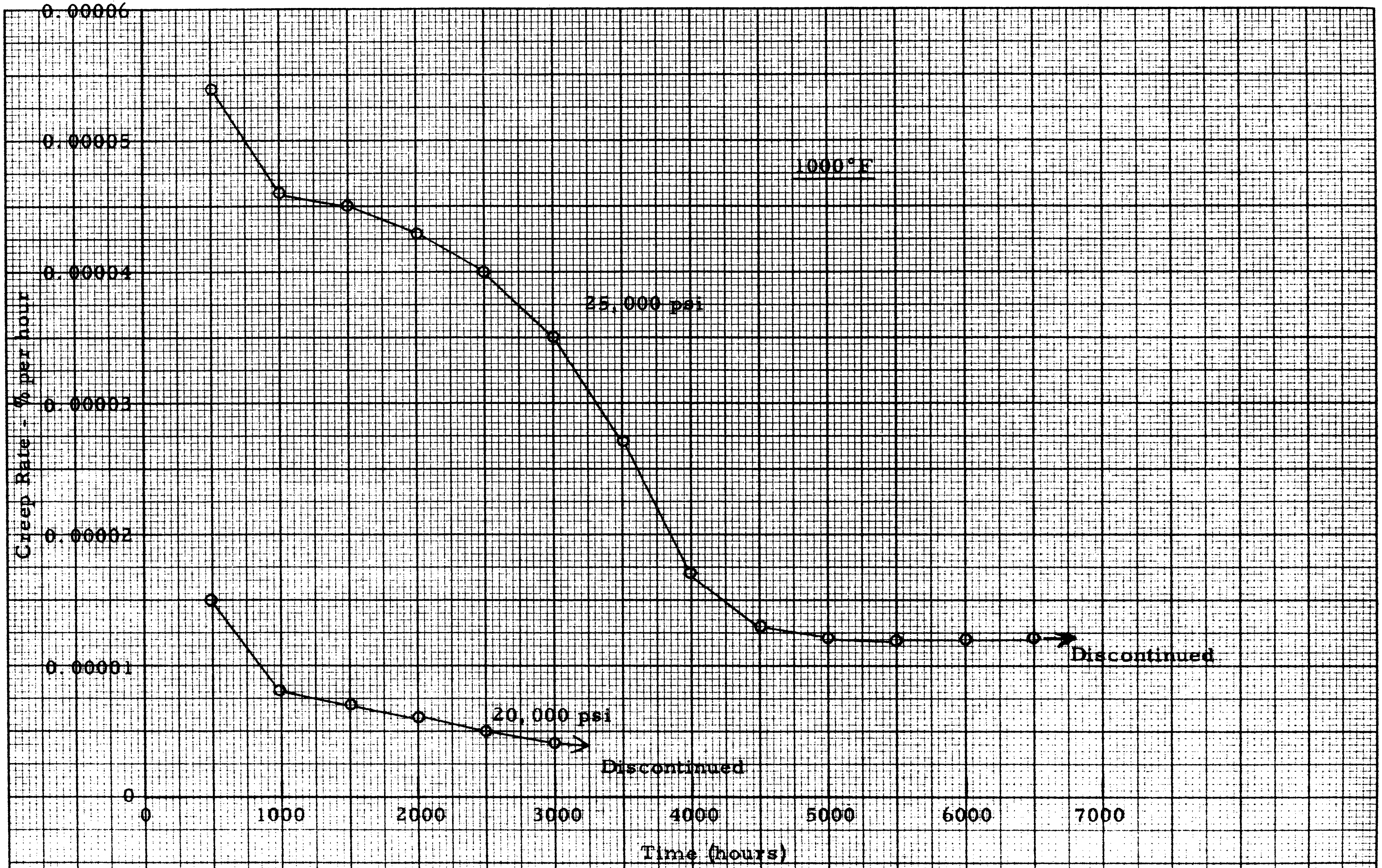



Figure 8 Creep Rate Versus Time Data from Creep Tests at 1000°F on Specimens from Hydroforged Type 316 Steel Pipe from Heat 1072-73.

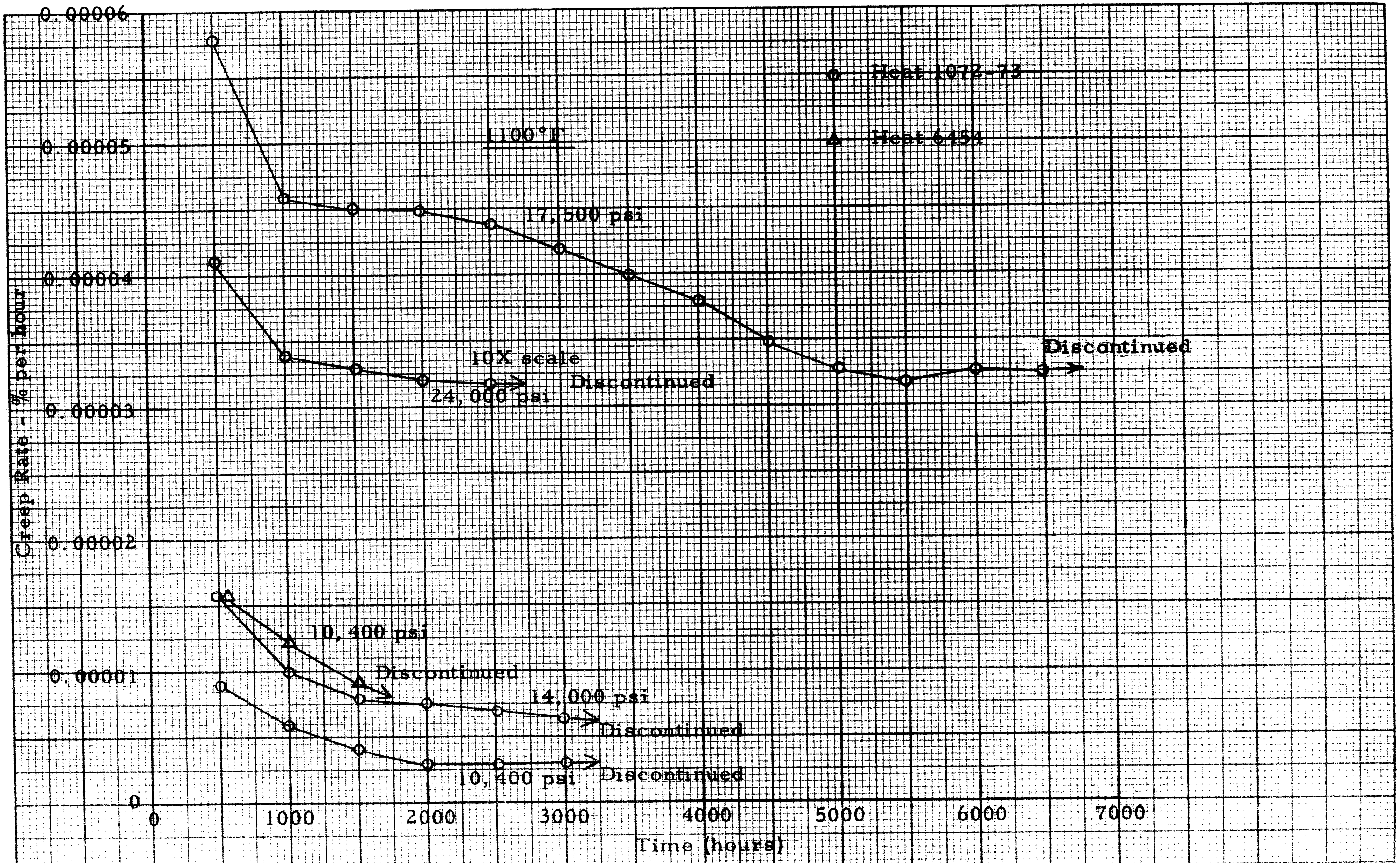



Figure 9 Creep Rate Versus Time Data from Creep Tests at 1100°F on Specimens from Hydroforged Type 316 Steel Pipe from Heats 1072-73 and 6454.

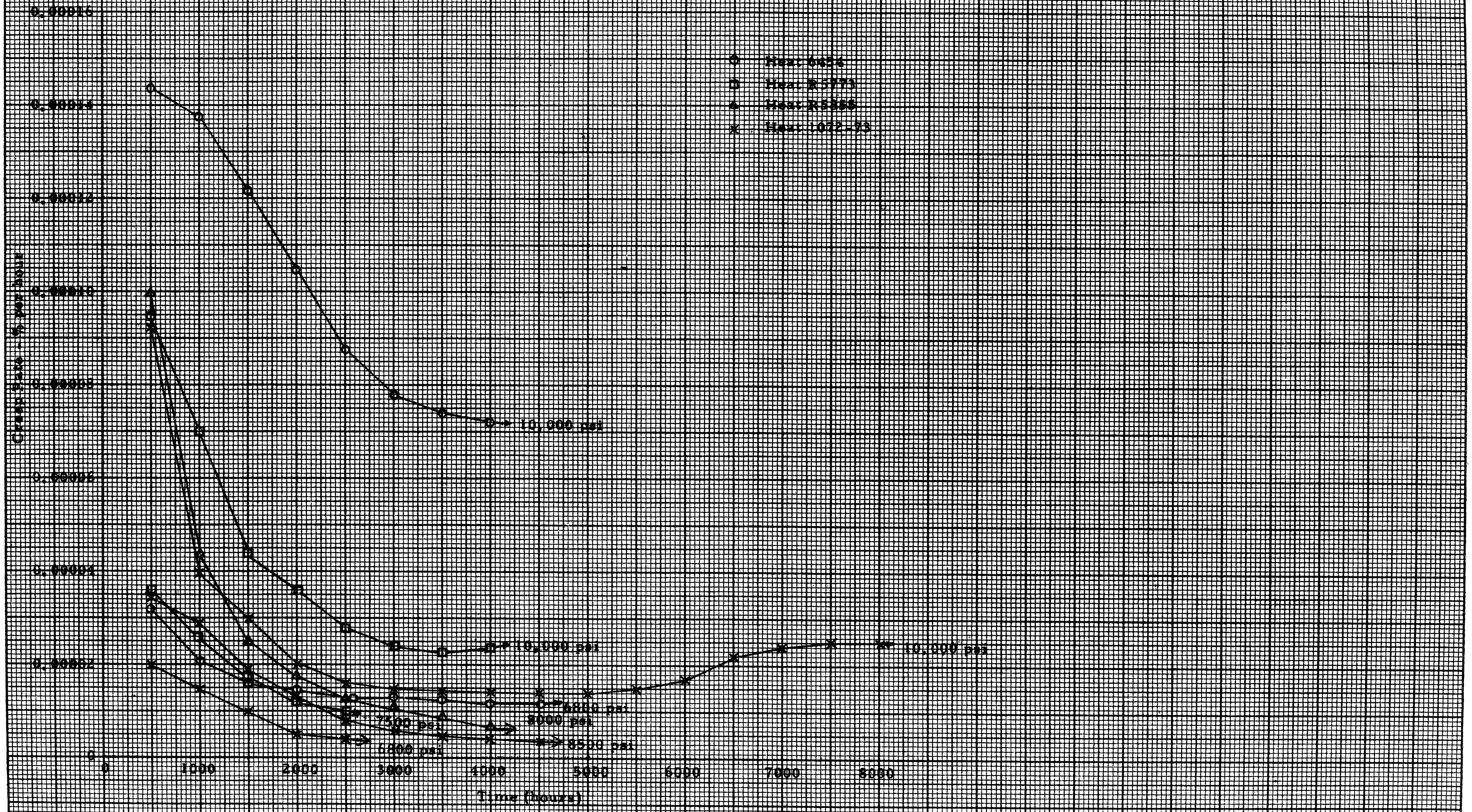



Figure 10 Creep Rate Versus Time Data at 1200°F for Four Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes.

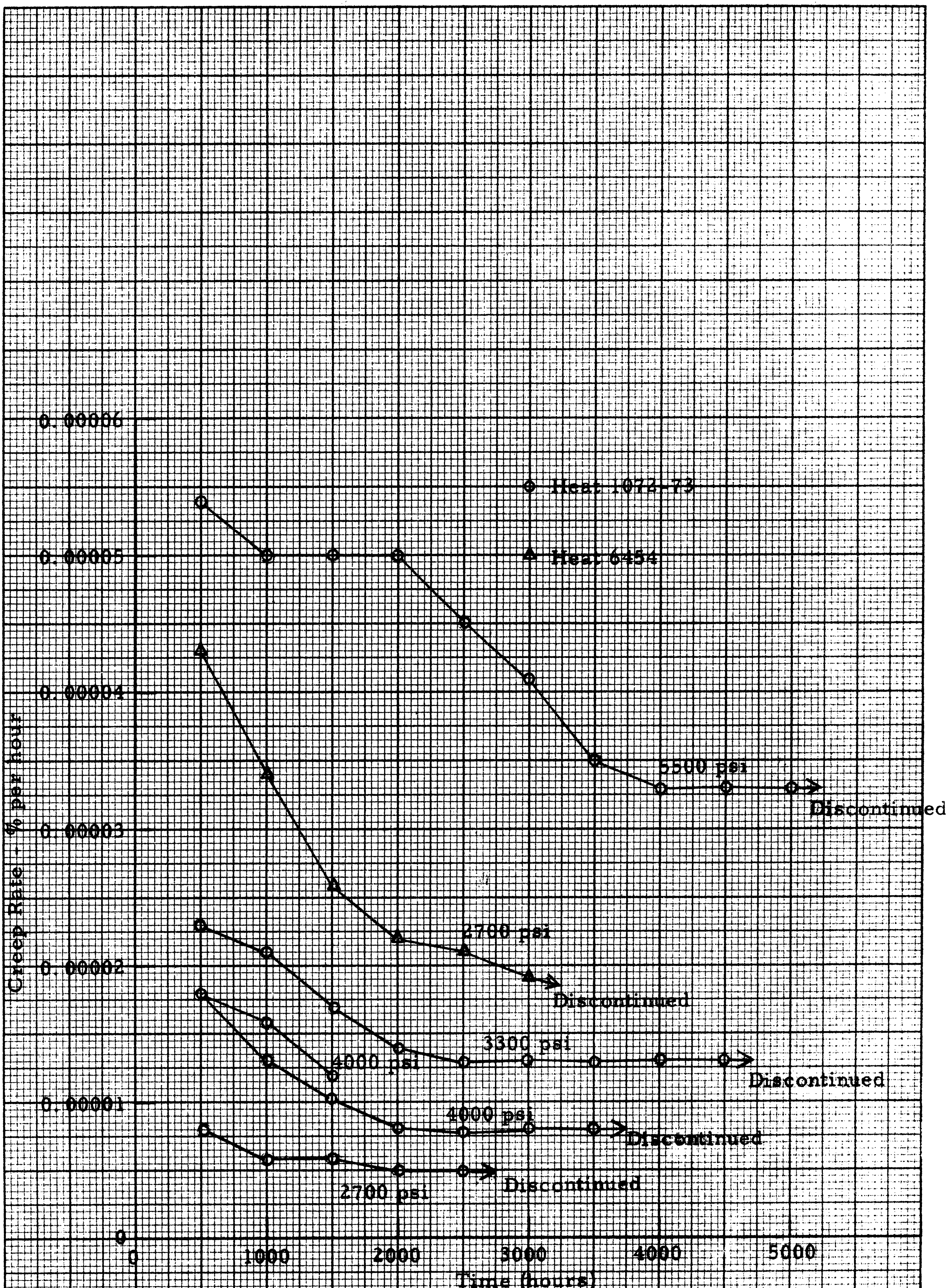



Figure 11 Creep Rate Versus Time Data from Creep Tests at 1350°F on Specimens from Hydroforged Type 316 Steel Pipe from Heats 1072-73 and 6454.

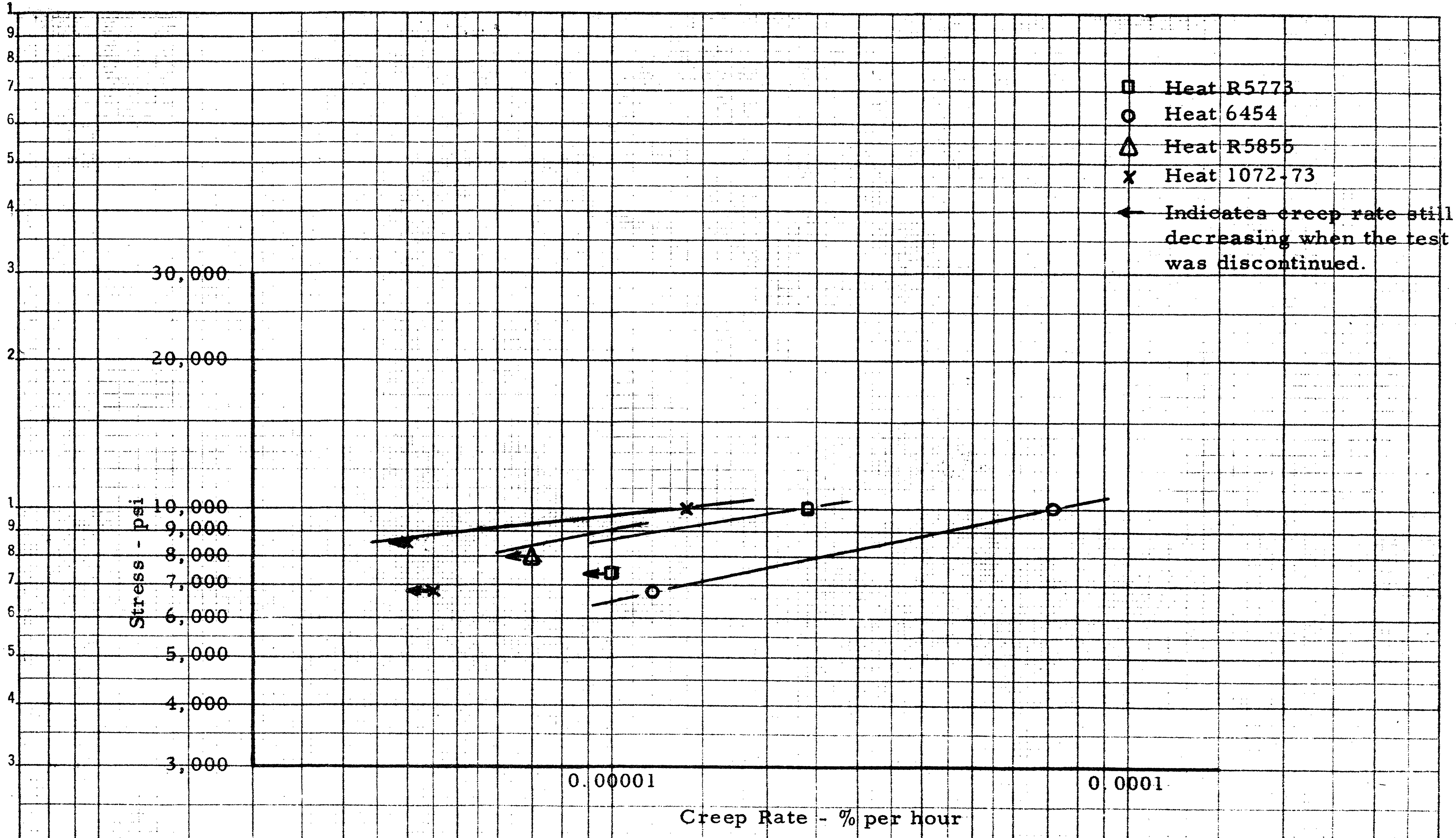



Figure 12. Stress-Creep Rate Data at 1200°F for Four Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes.

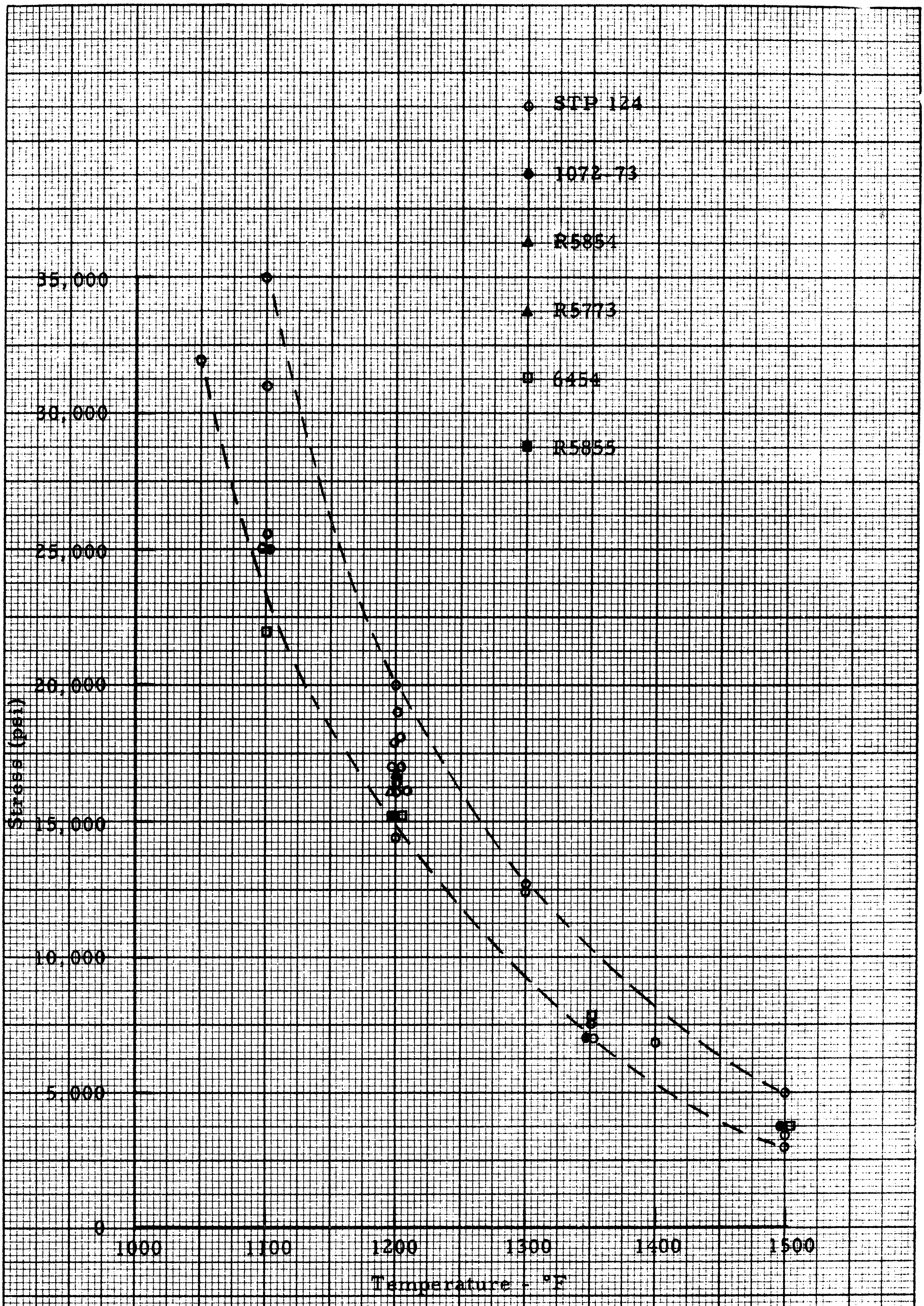



Figure 13 Comparison of 10,000-Hour Rupture Strengths of Hydroforged Type 316 Austenitic Steel Pipes with 10,000-Hour Rupture Strengths for 18-8+Mo Steel in ASTM Special Technical Publication Number 124.

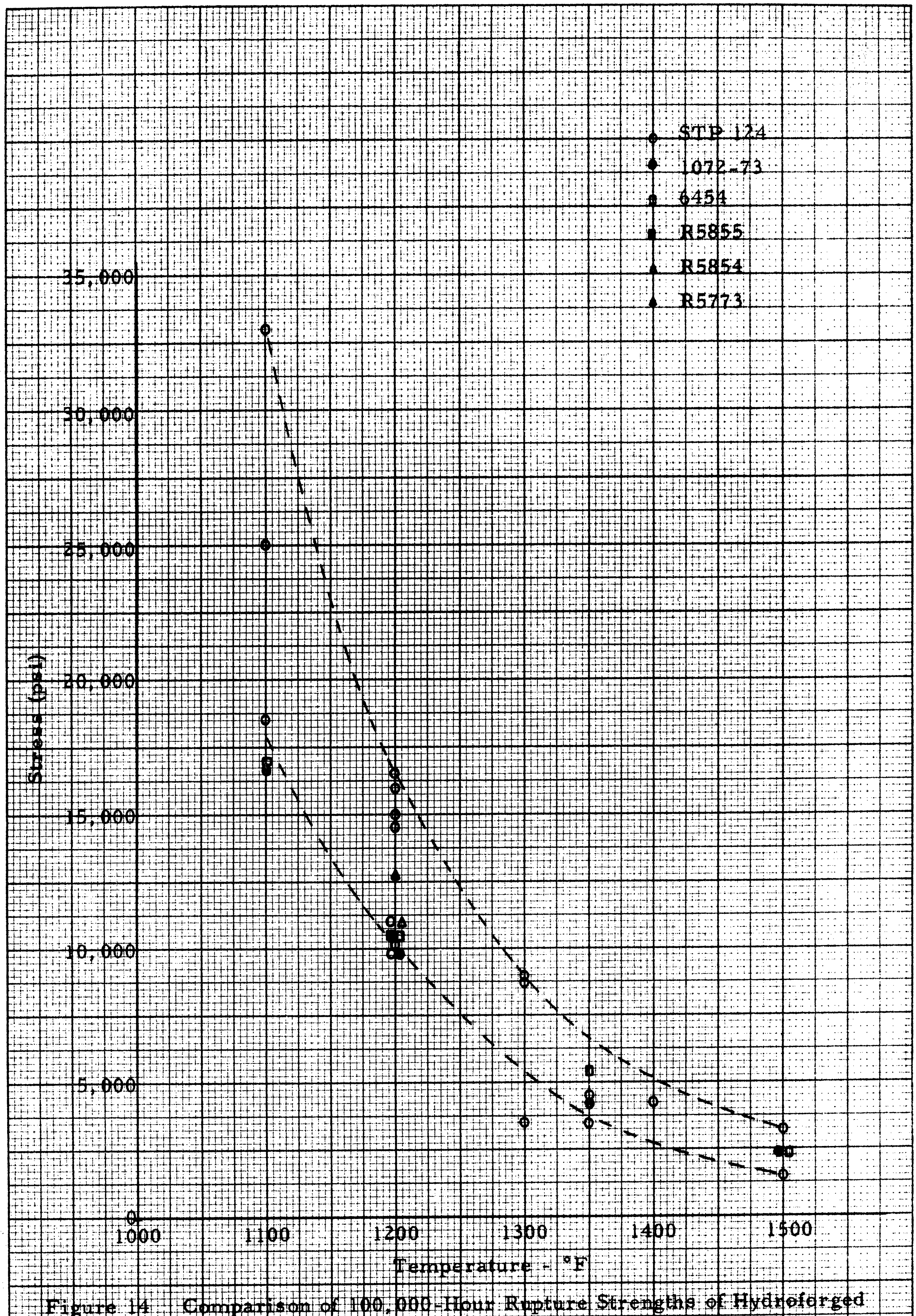



Figure 14 Comparison of 100,000-Hour Rupture Strengths of Hydroforged Type 316 Austenitic Steel Pipes With 100,000-Hour Rupture Strengths for 18-8+Mo Steel in ASTM Special Technical Publication No. 124.

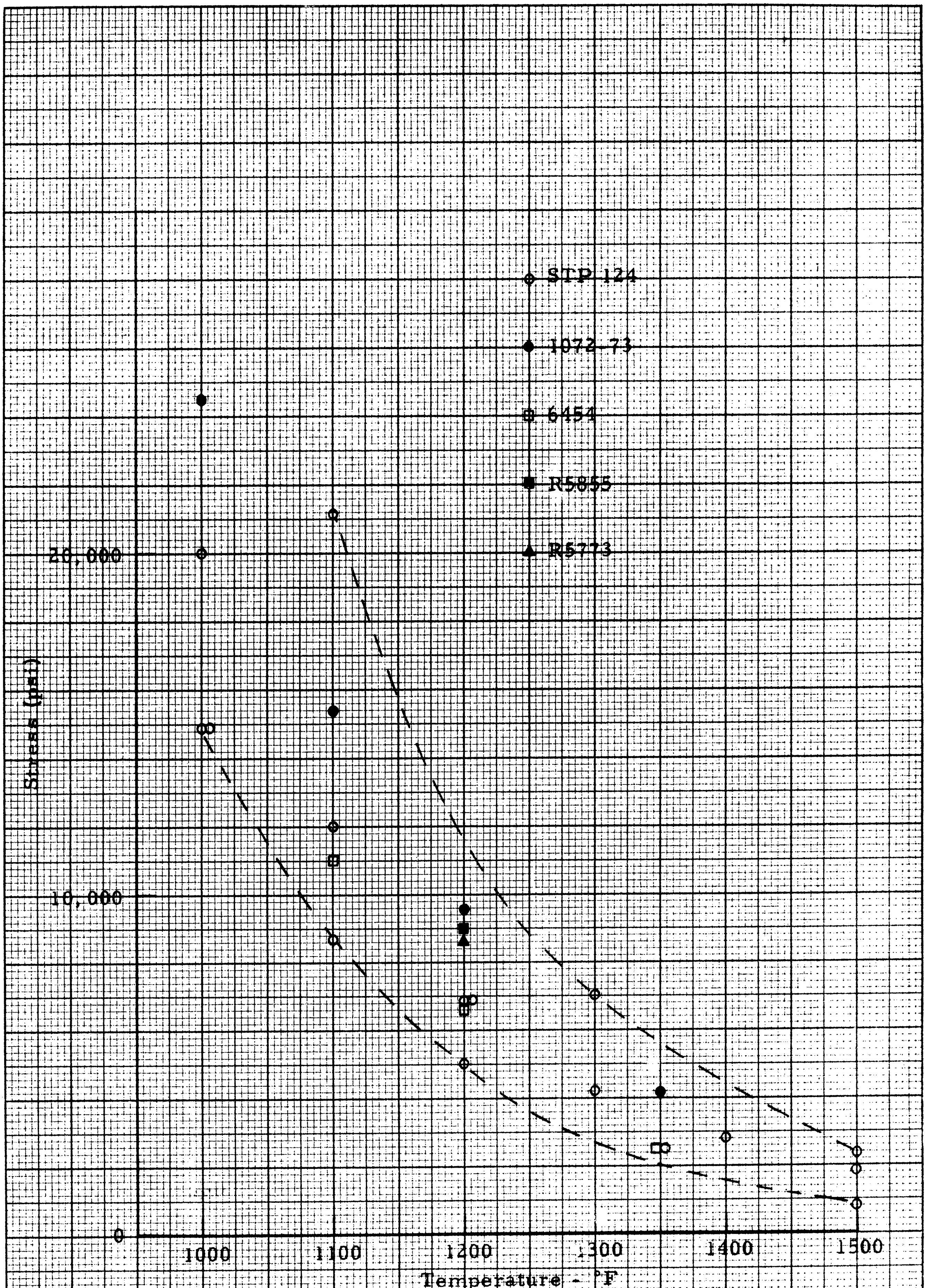



Figure 15 Comparison of 0.00001-Percent Per Hour Creep Strengths of Hydroforged Type 316 Austenitic Steel Pipes With 0.00001-Percent Per Hour Creep Strengths for 18-8+Mo Steel in ASTM Special Technical Publication No. 124.

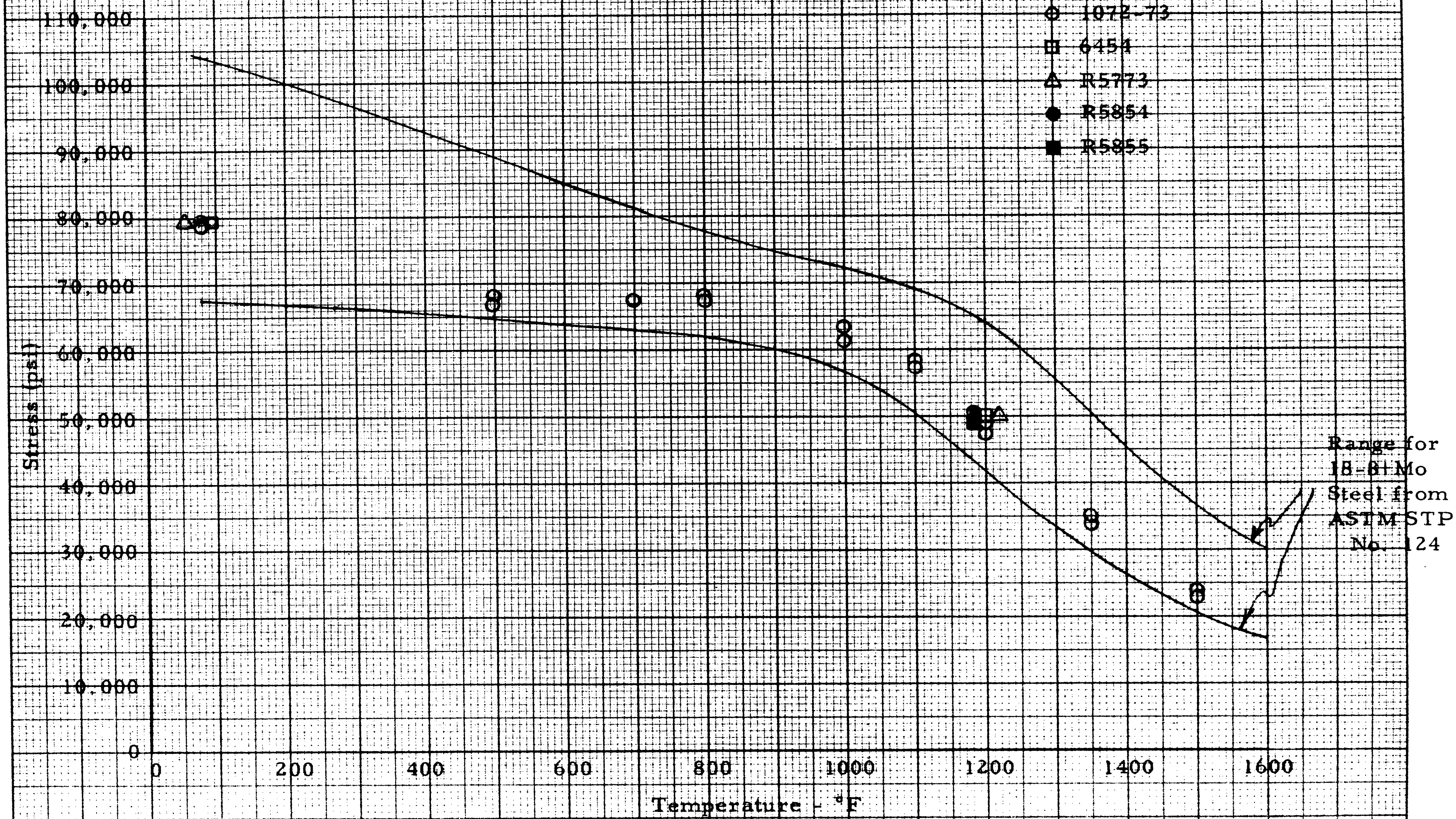



Figure 16 Comparison of the Tensile Strengths of Hydroforged Type 316 Austenitic Steel Pipes With the Range of Tensile Strengths for 18-8+Mo Steel in ASTM Special Technical Publication Number 124.

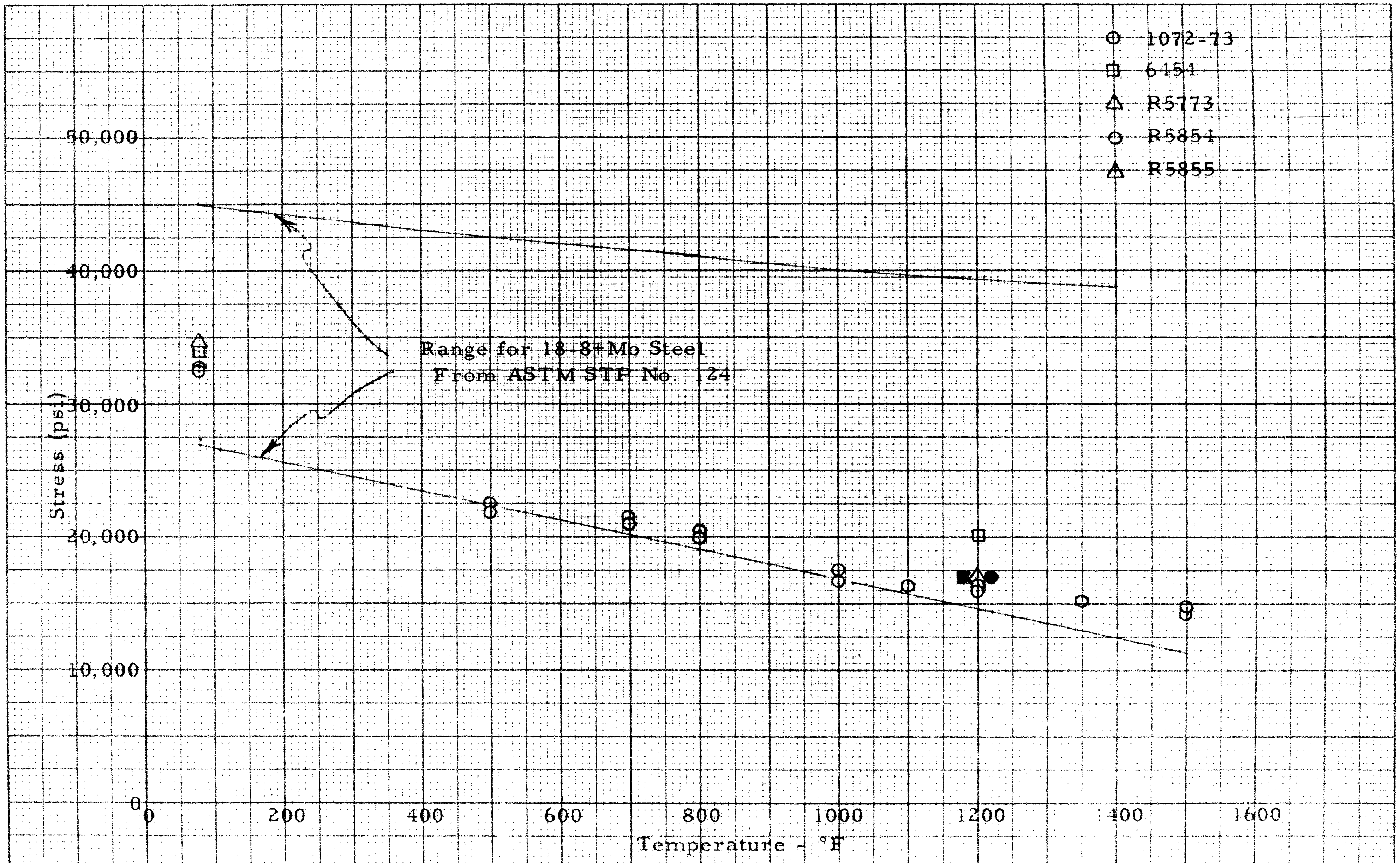



Figure 17 Comparison of the Yield Strengths of Hydroforged Type 316 Austenitic Steel Pipes With the Range of Yield Strengths for 18-8+Mo Steel in ASTM Special Technical Publication Number 124.

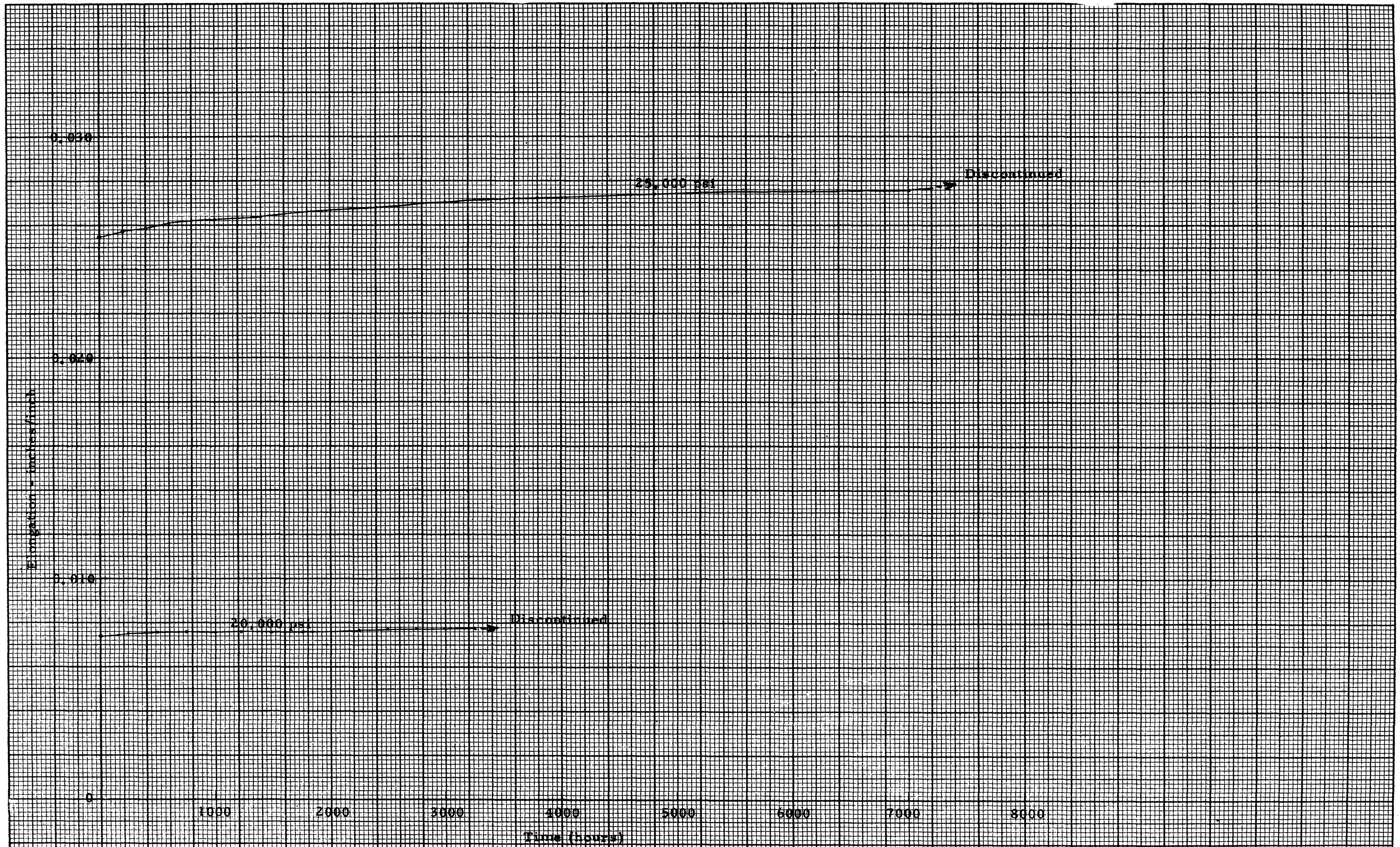



Figure 18 Creep Curves at 1000°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.

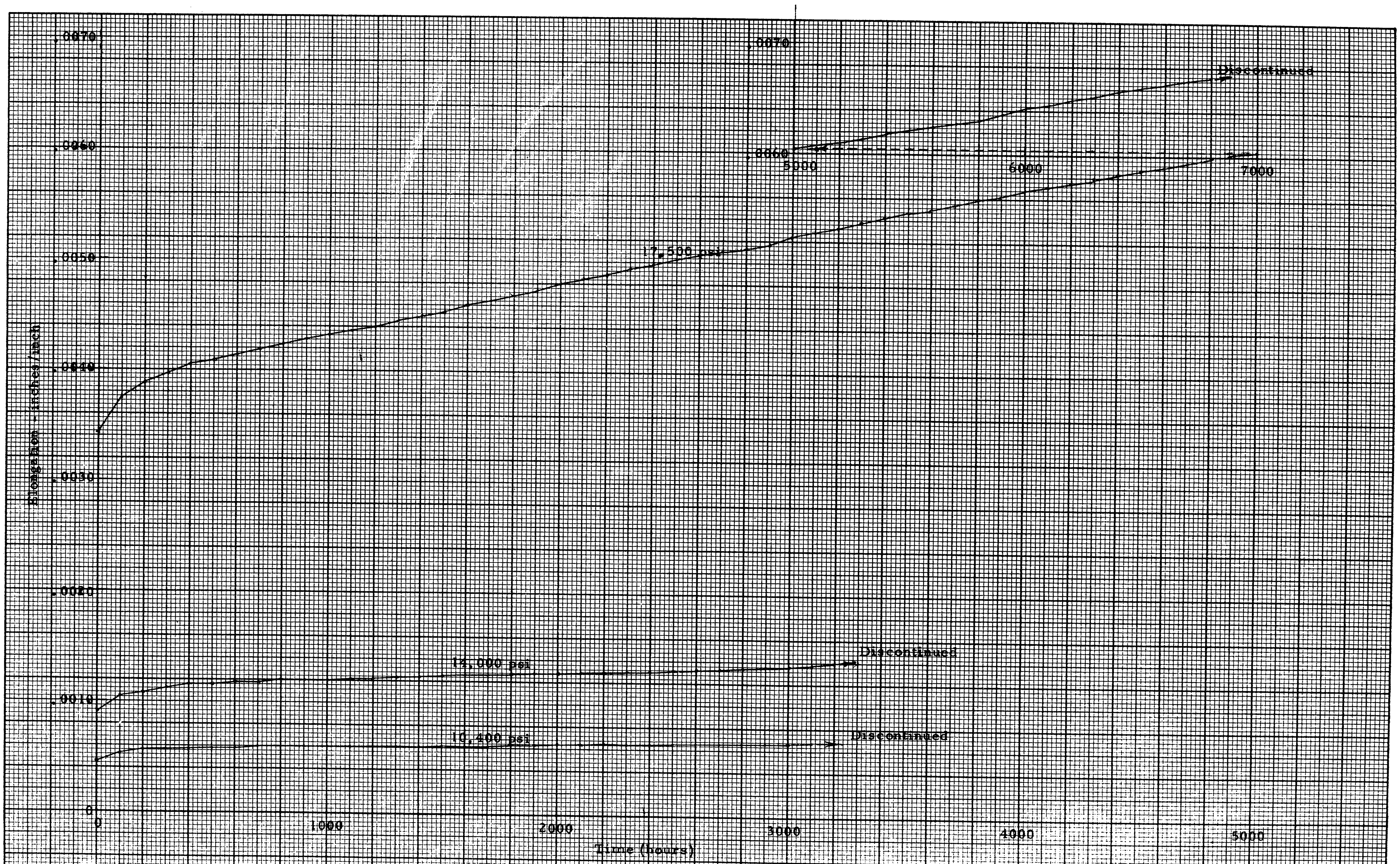



Figure 19. Creep Curves at 1100°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.

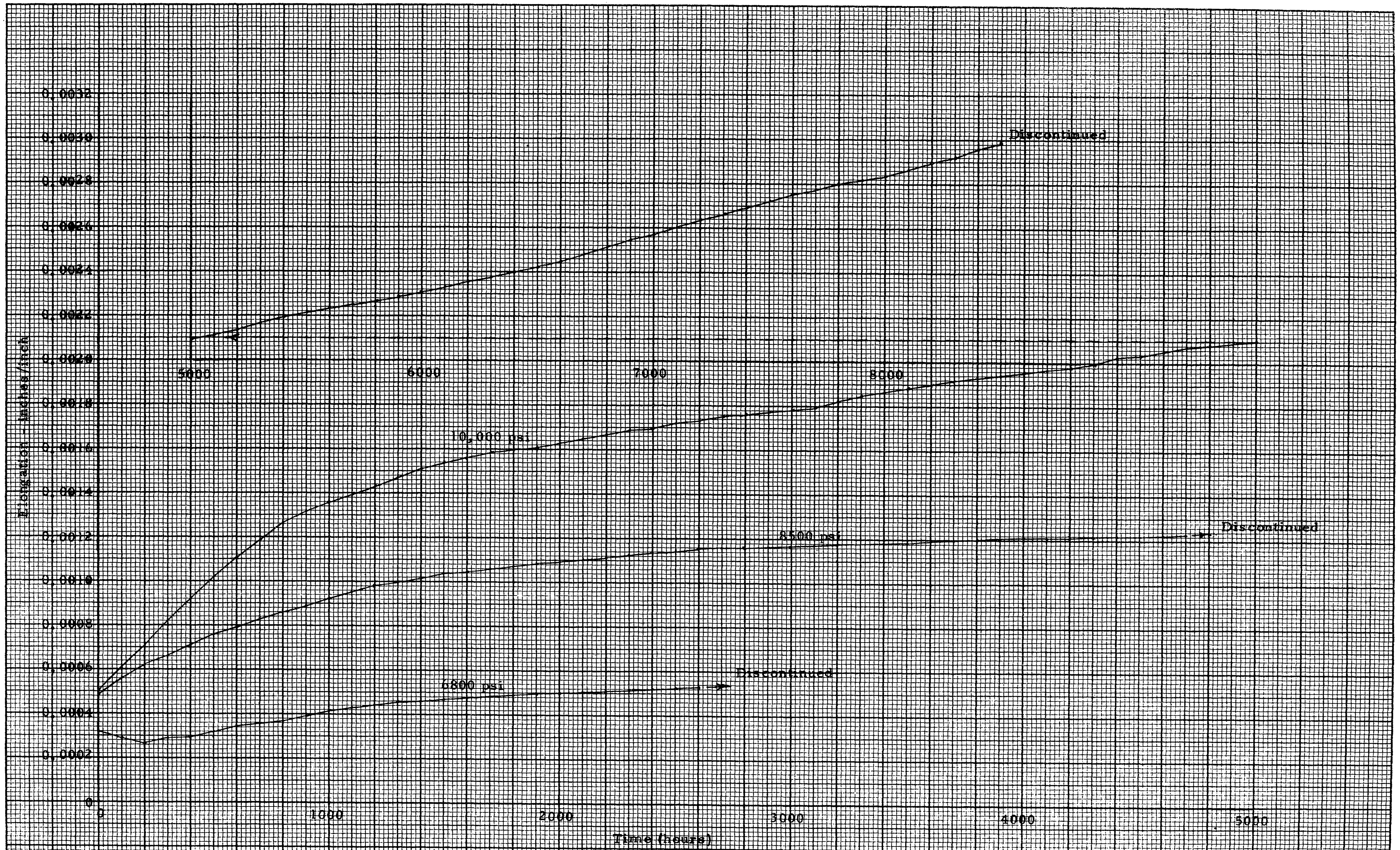



Figure 20. Creep Curves at 1200°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.

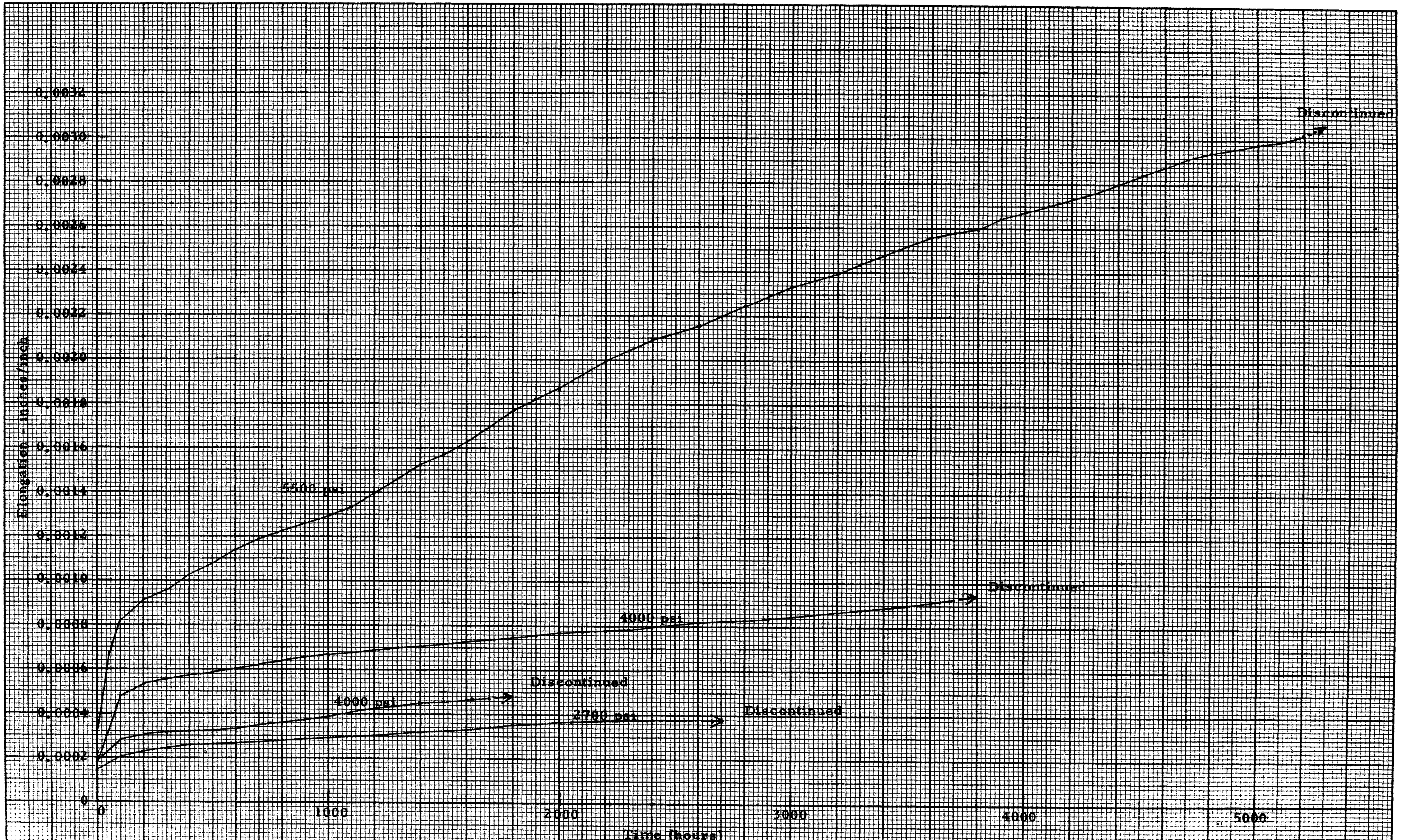



Figure 21 Creep Curves at 1350°F for Hydroforged Type 316 (18-8-Mo) Stainless Steel Pipe from Heat 1072-73.

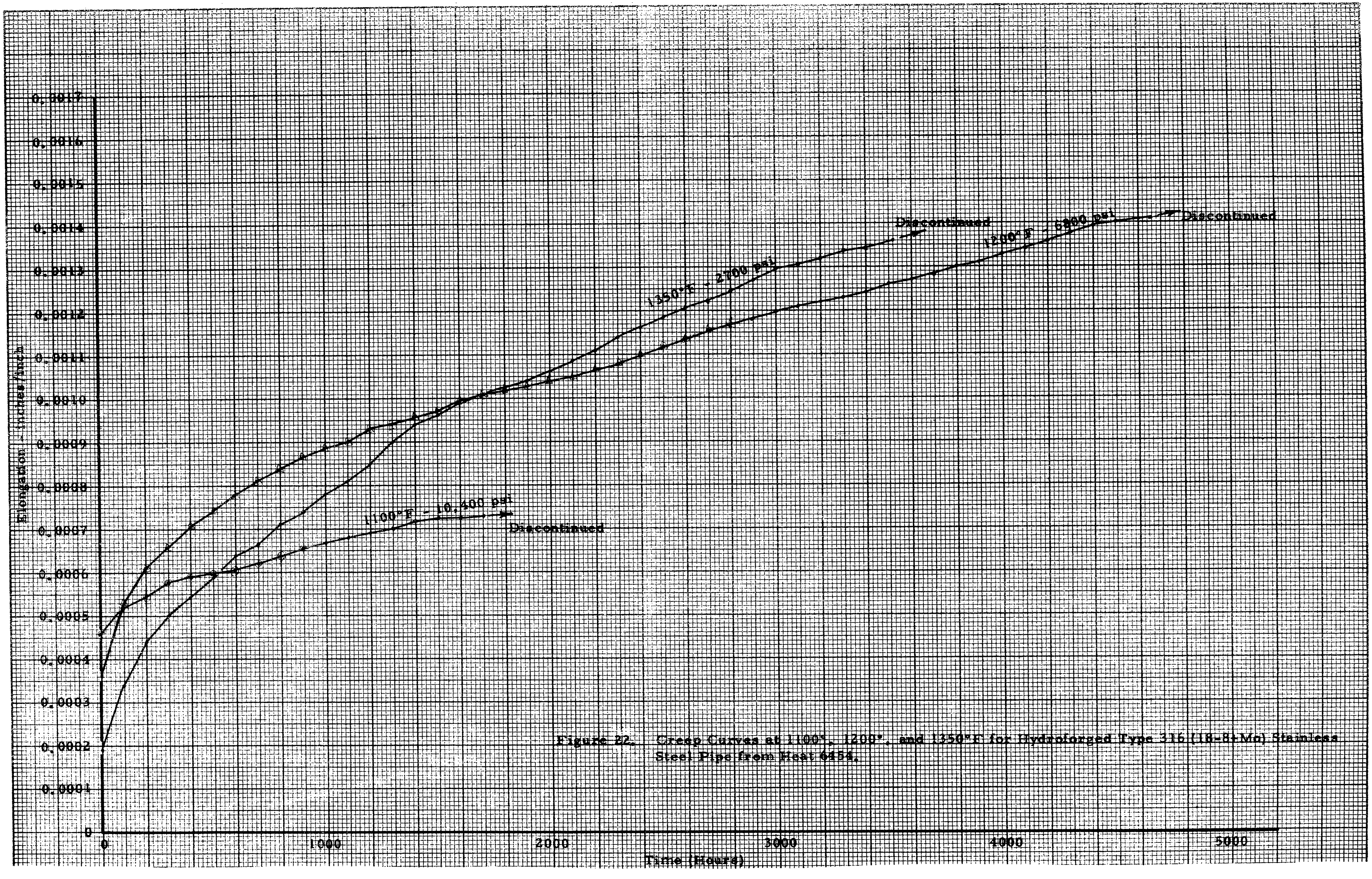



Figure 22. Creep Curves at 1100°, 1200°, and 1350°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 6454.

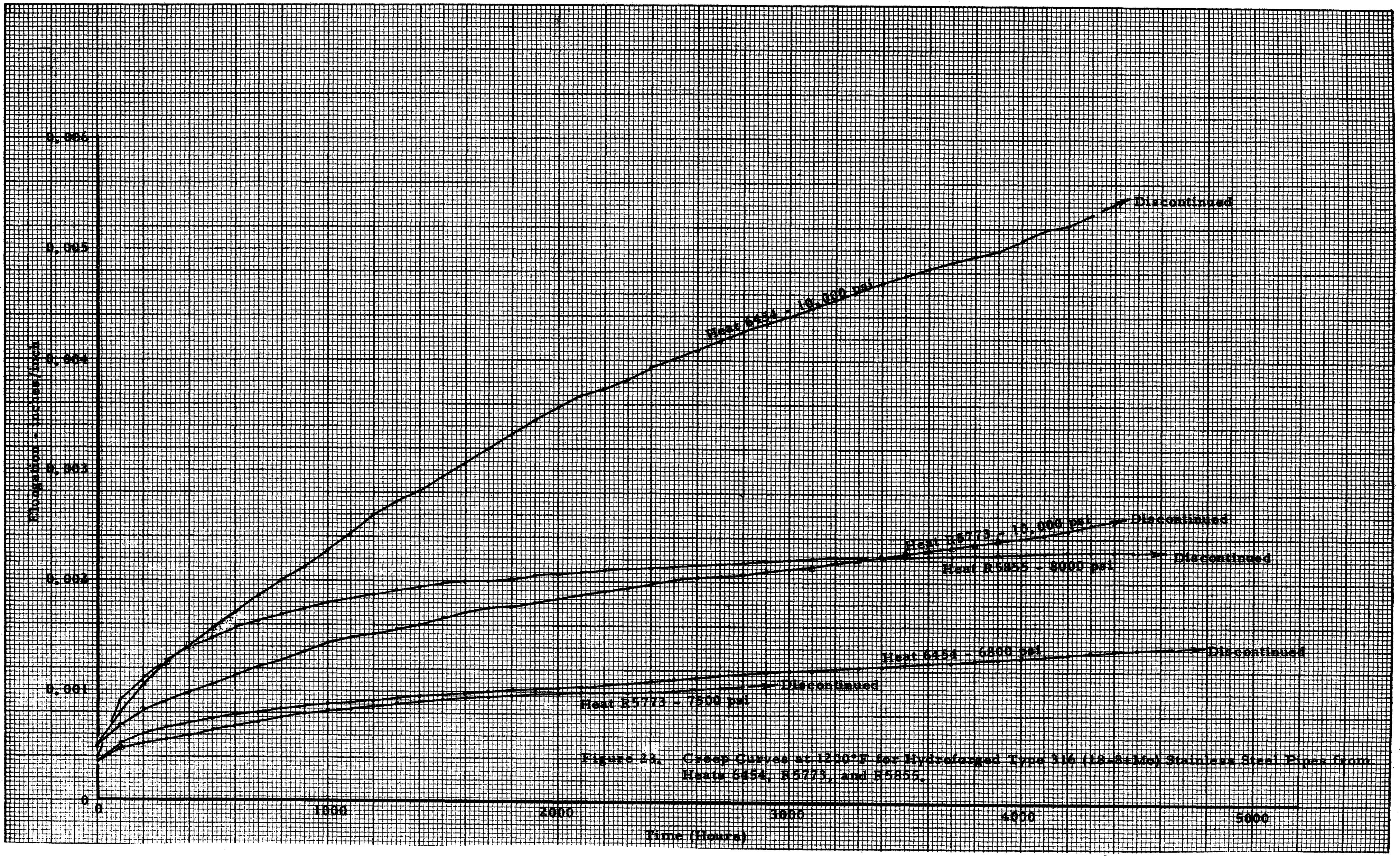



Figure 23. Creep Curves at 1200°F for Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes from Heats 6454, R5773, and R5855.

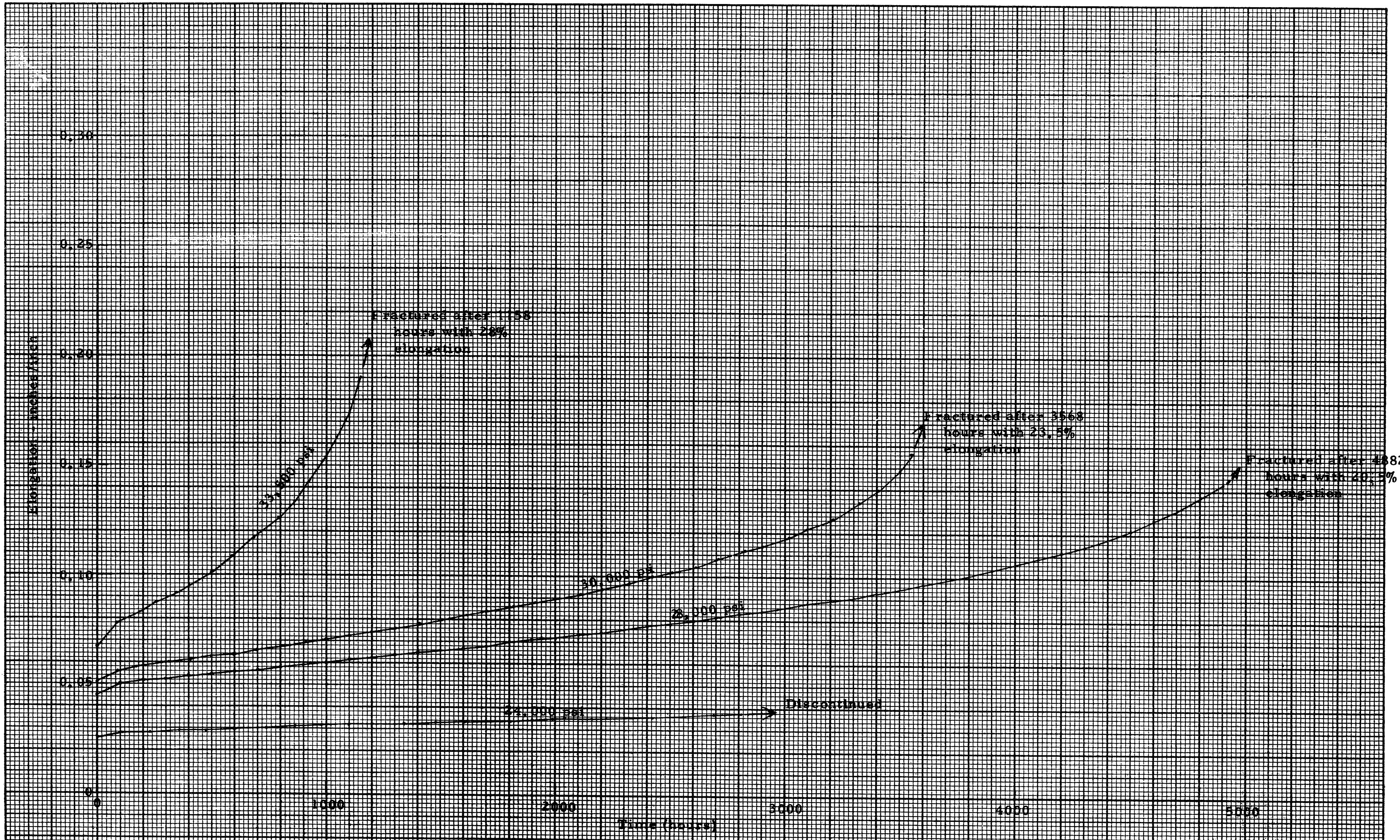



Figure 24. Creep Curves for Rupture Tests at 1100°F on Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.

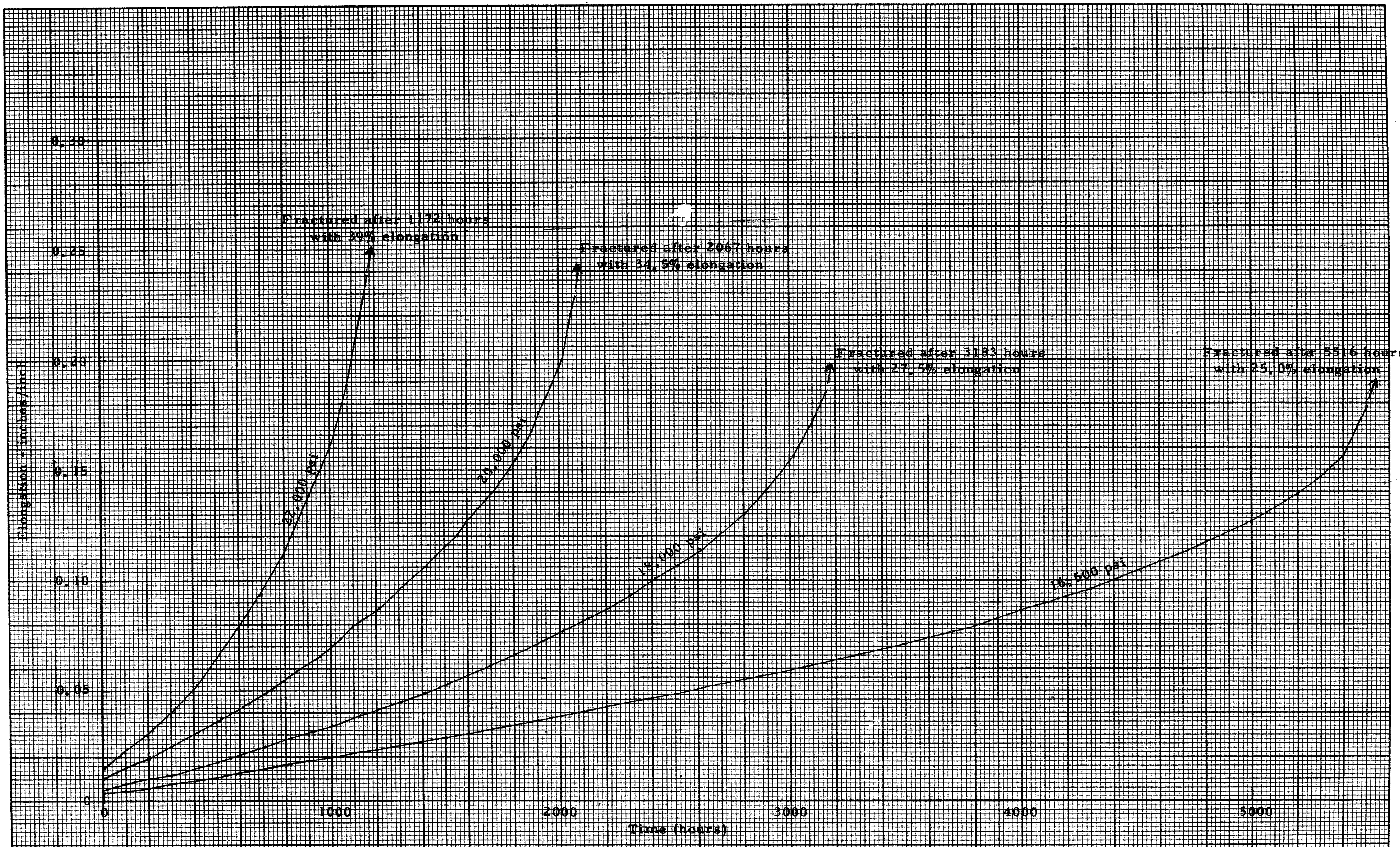



Figure 25 Creep Curves for Rupture Tests at 1200°F on Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73.

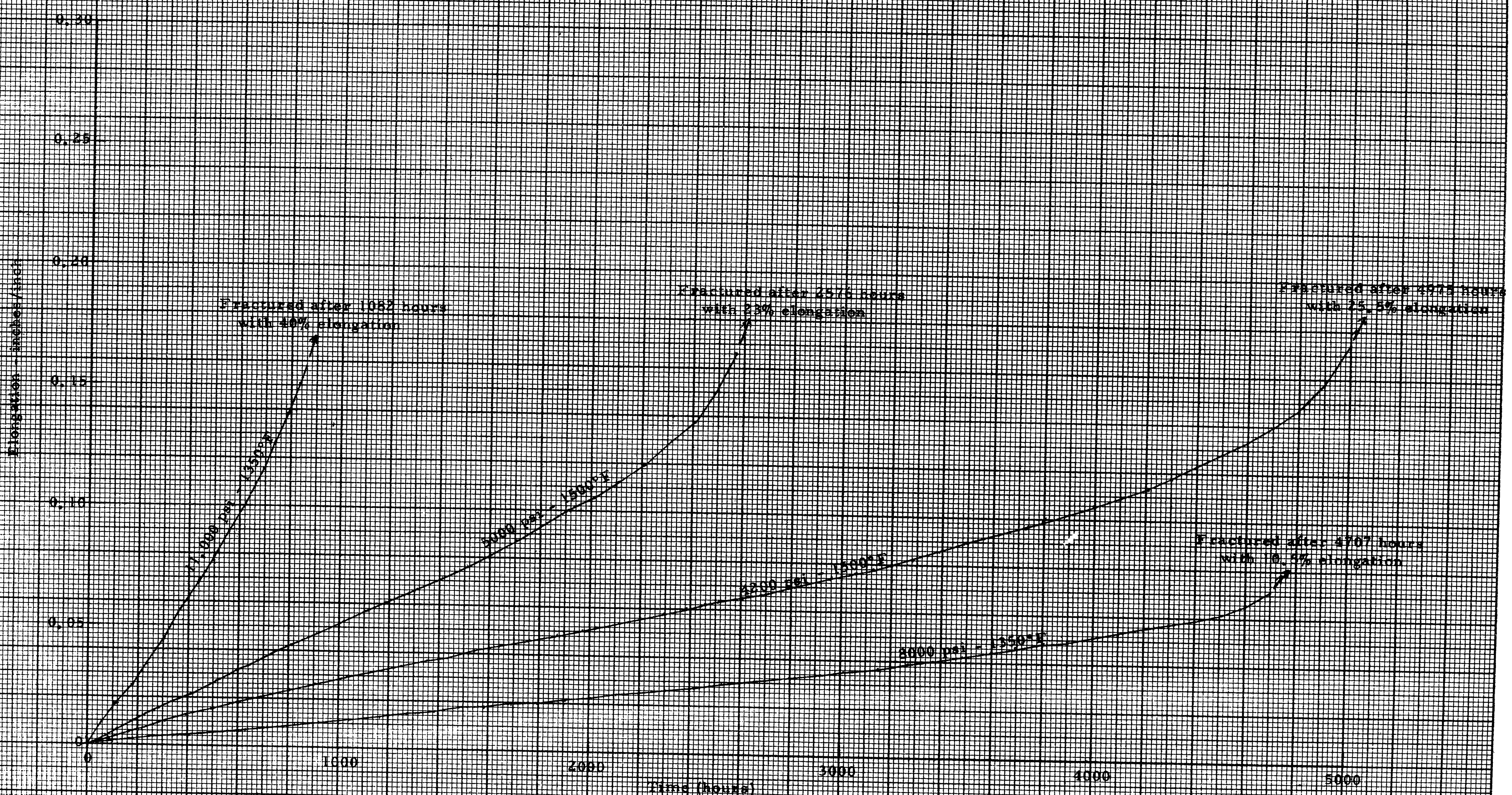



Figure 26 Creep Curves for Rupture Tests at 1350° and 1500°F on Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe From Heat 1072-73.

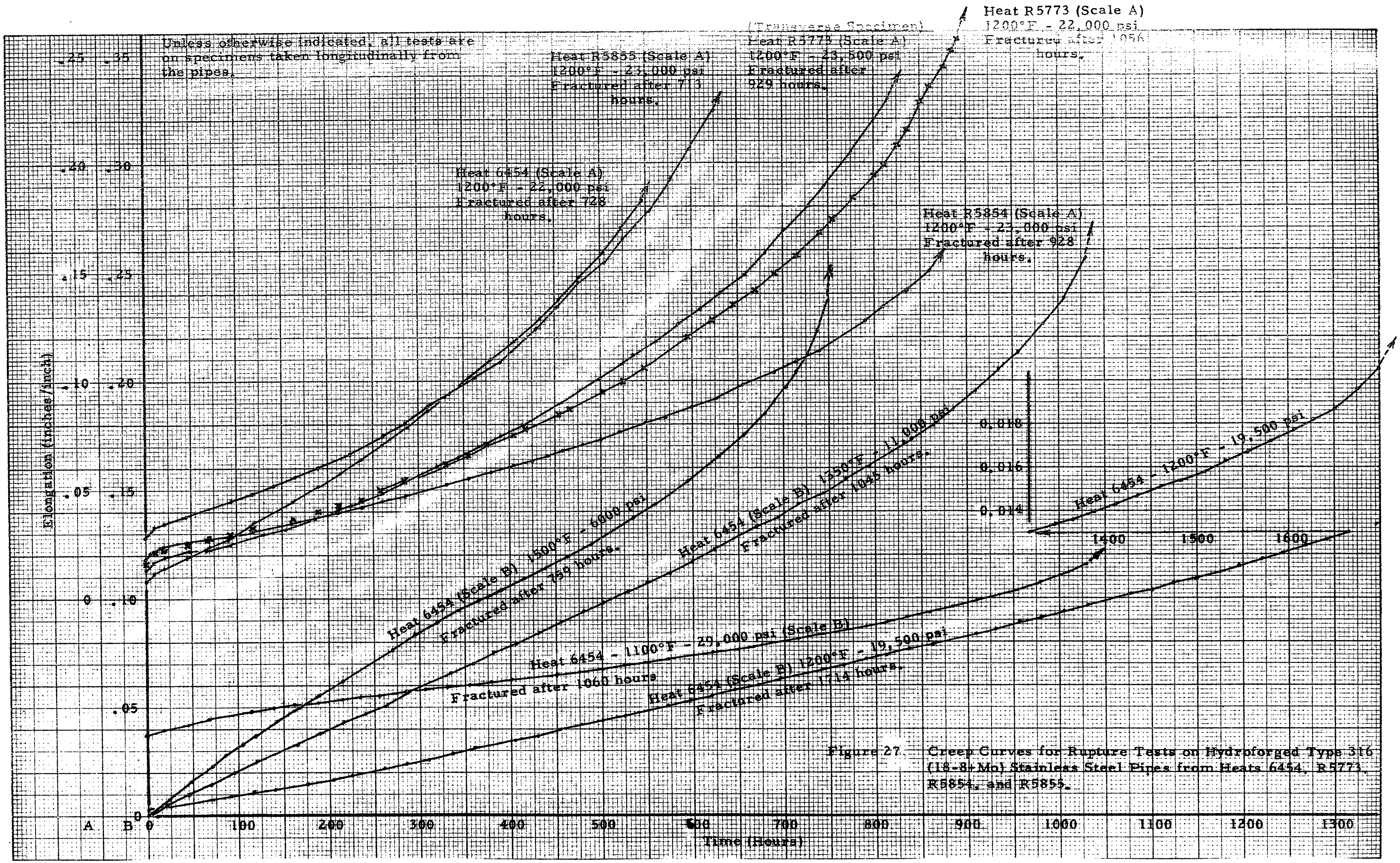
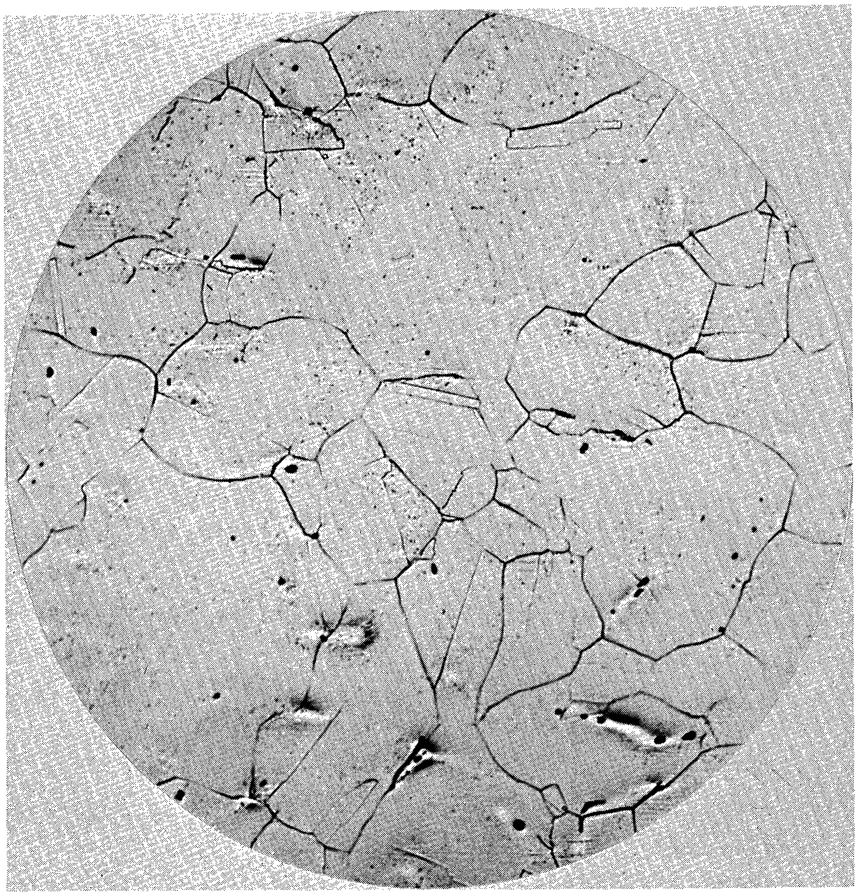
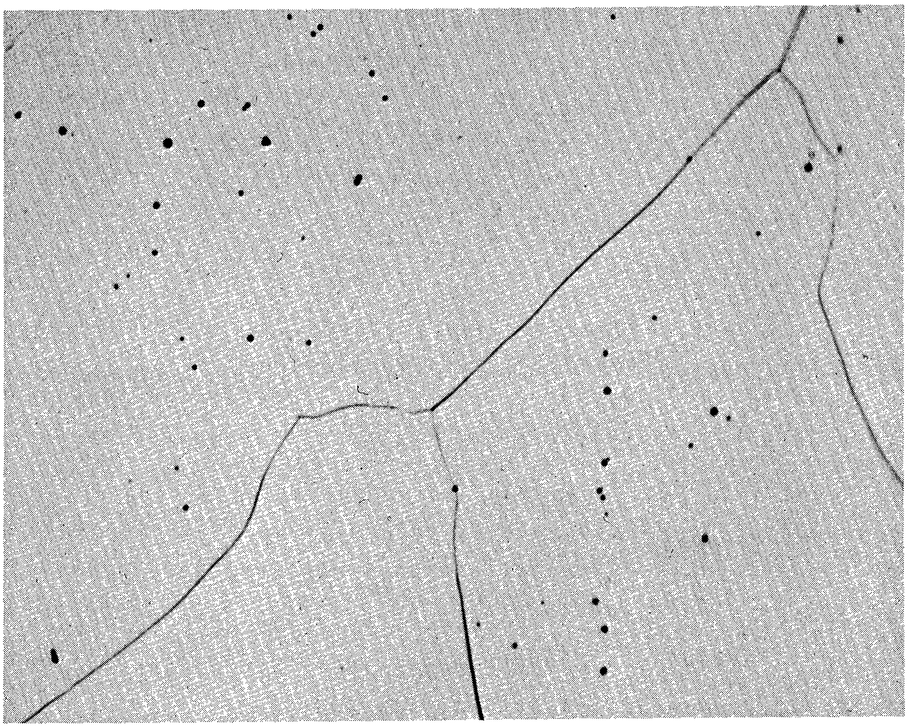



Figure 27. Creep Curves for Rupture Tests on Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipes from Heats 6454, R5773, R5854, and R5855.

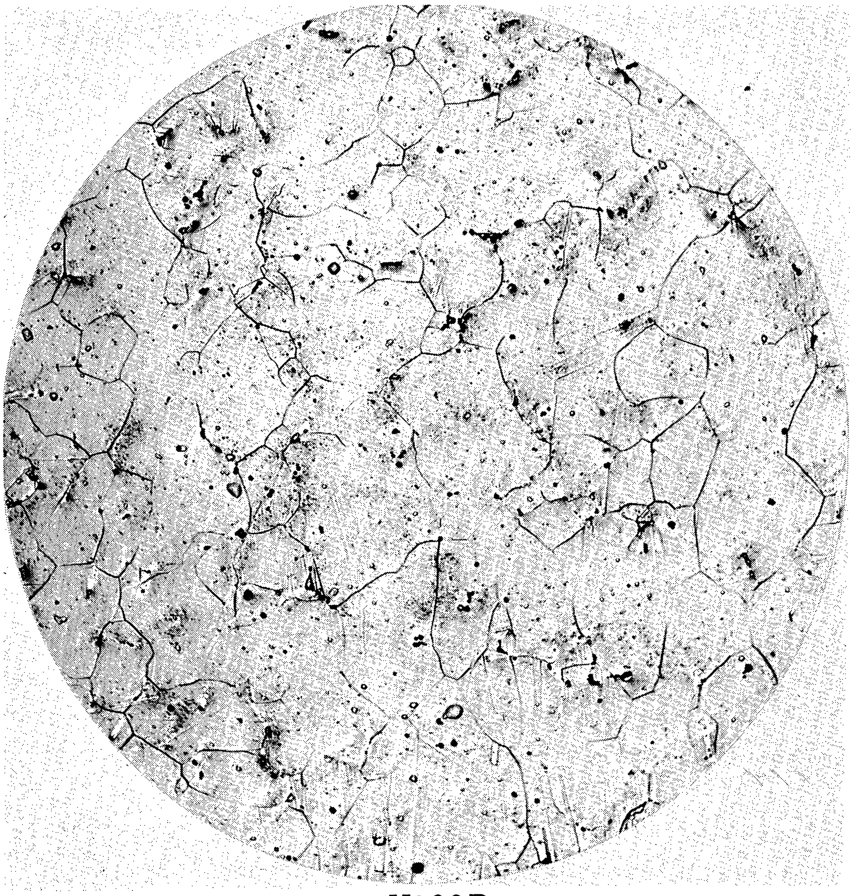


X100D

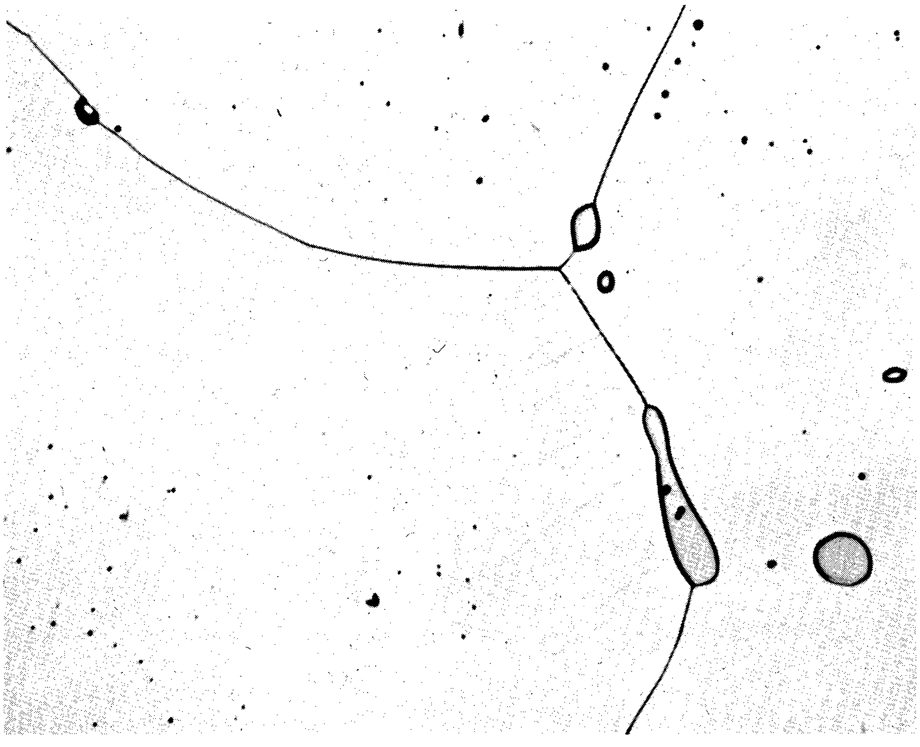


X1000D

Figure 28 Original Microstructure of the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Water quenched from 1950°F.

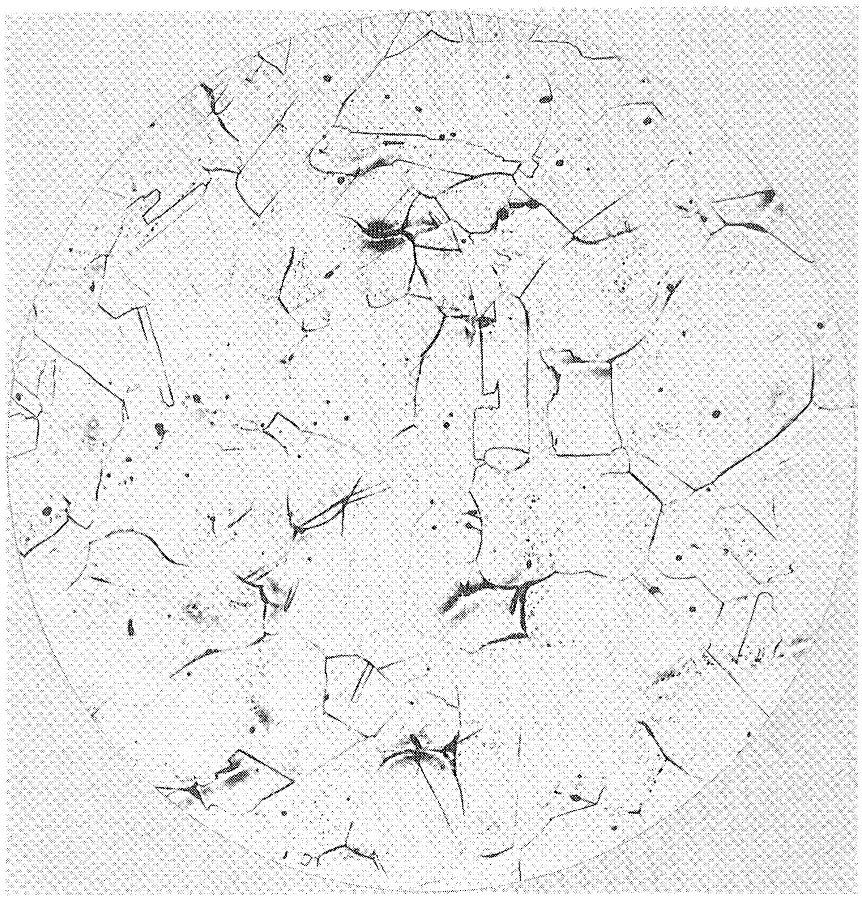


X100D

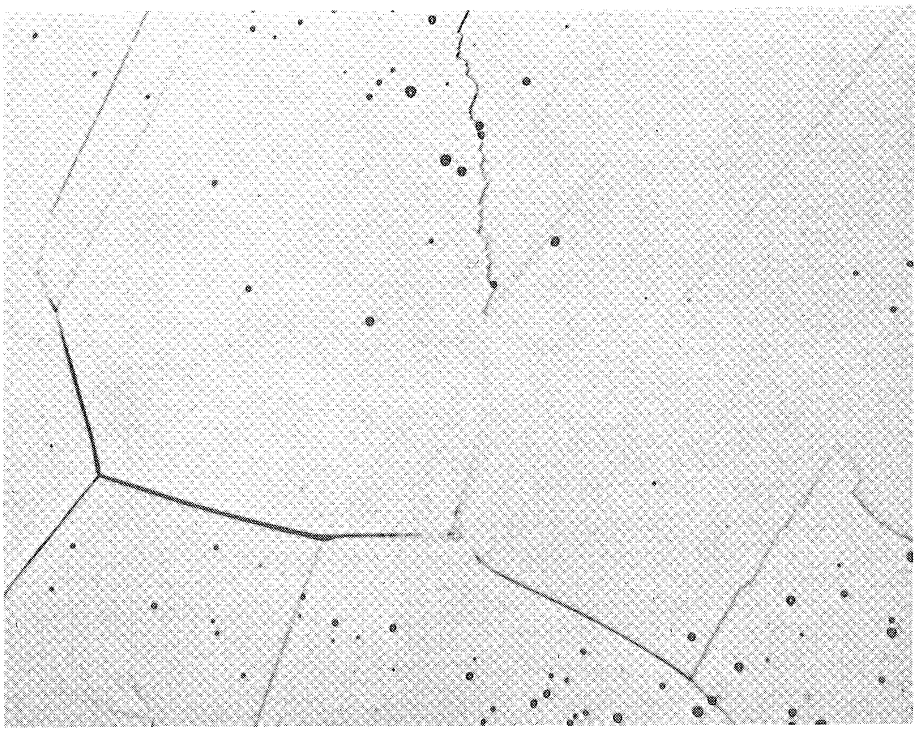


X1000D

Figure 29 Original Microstructure of the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 6454, Water Quenched from 1950°F.

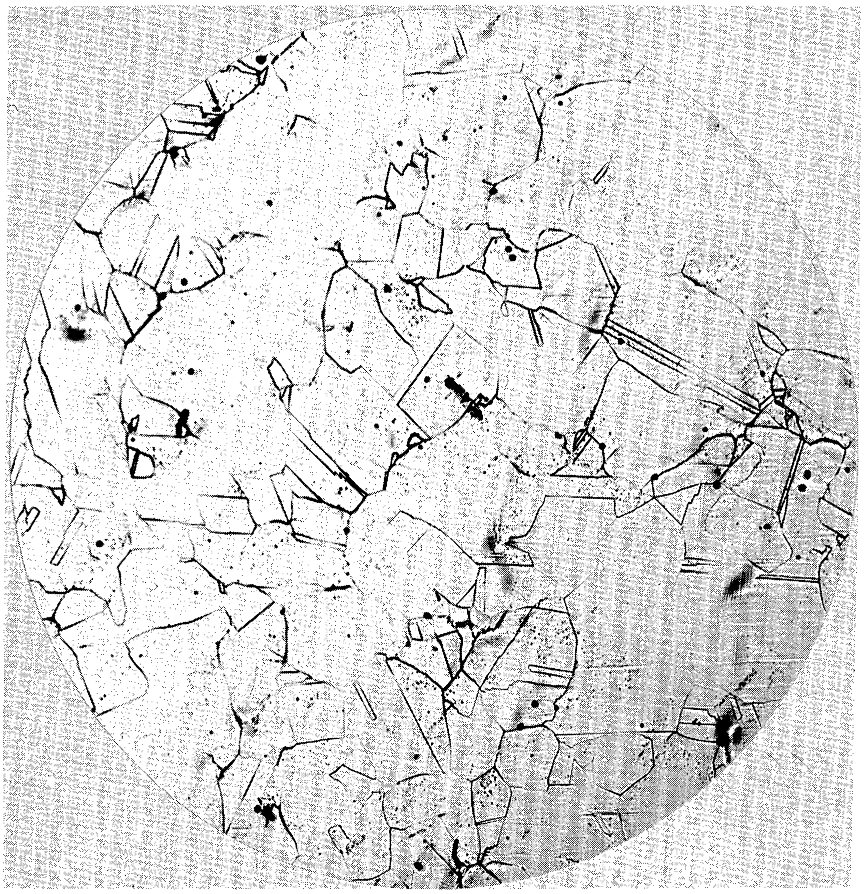


X100D

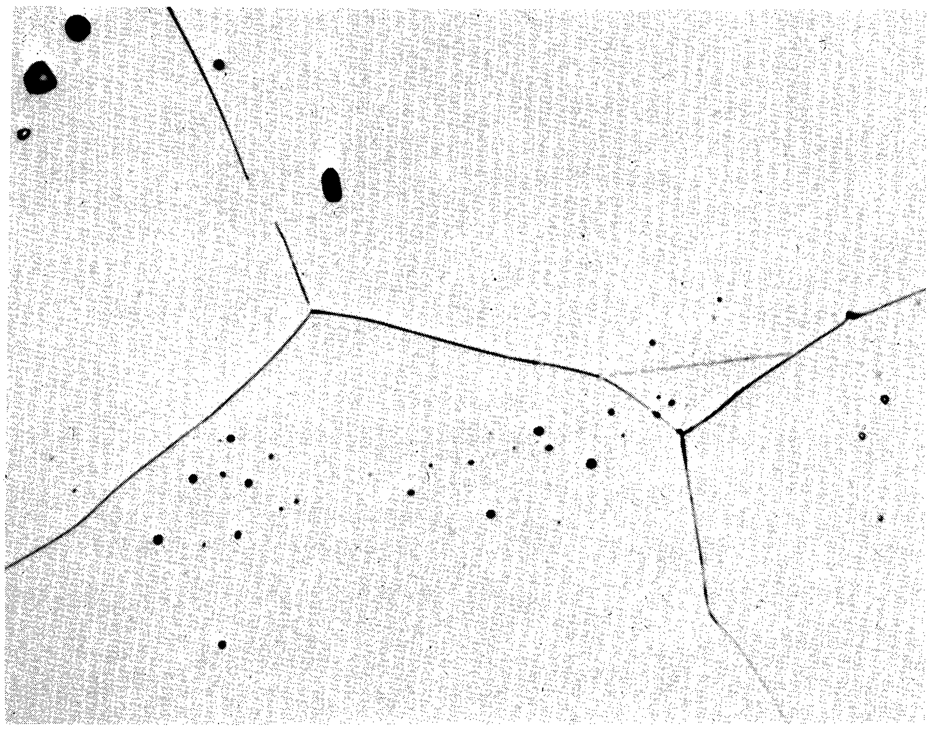


X1000D

Figure 30 Original Microstructure of the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat R5773, Water Quenched from 1950°F.

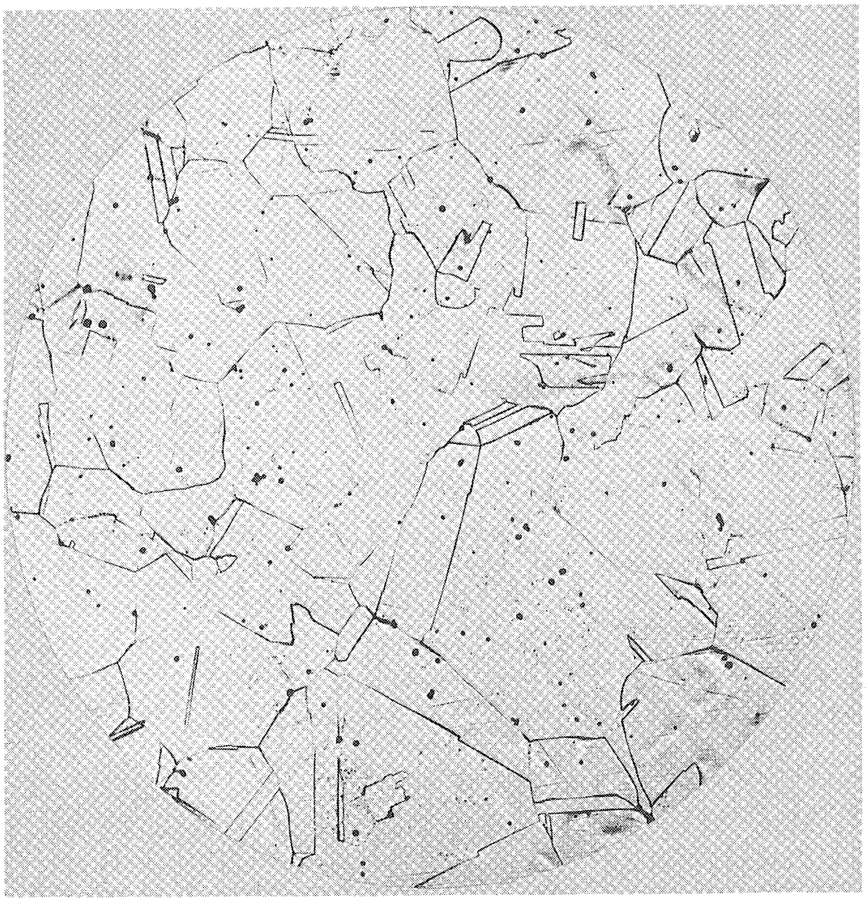


X100D

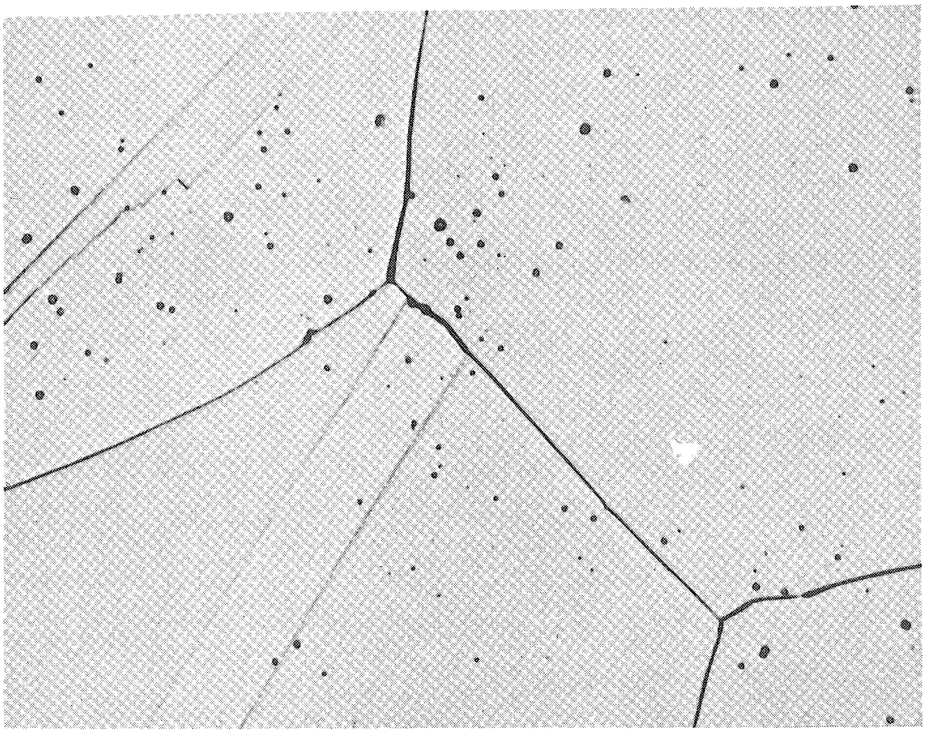


X1000D

Figure 31 Original Microstructure of the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat R5854, Water Quenched from 1950°F.

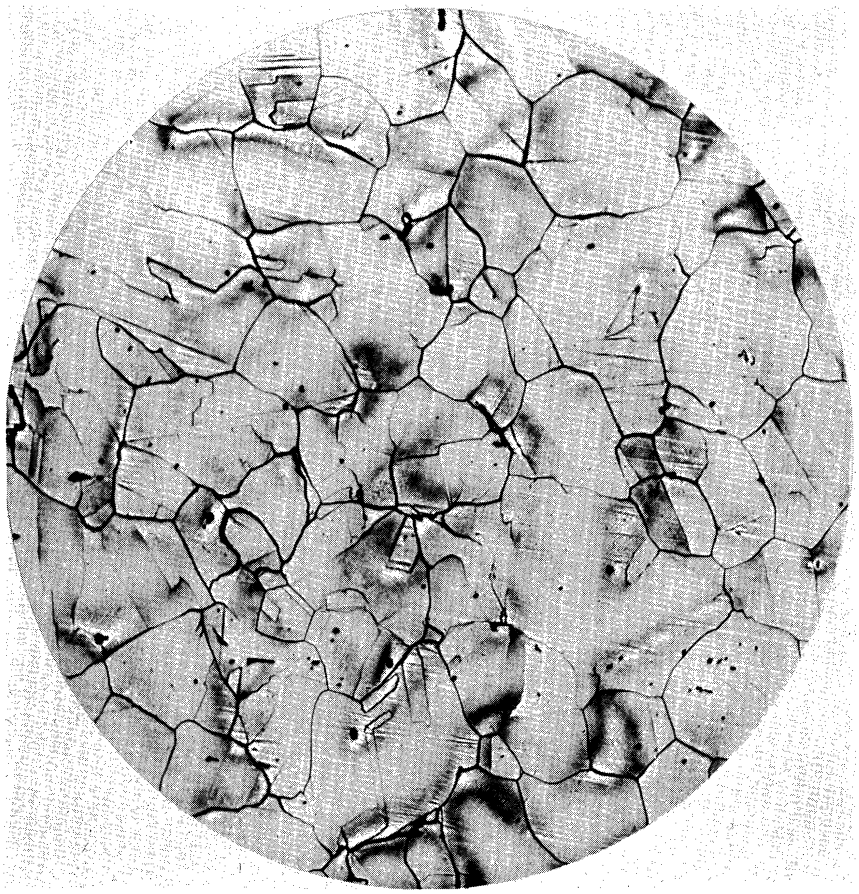


X100D

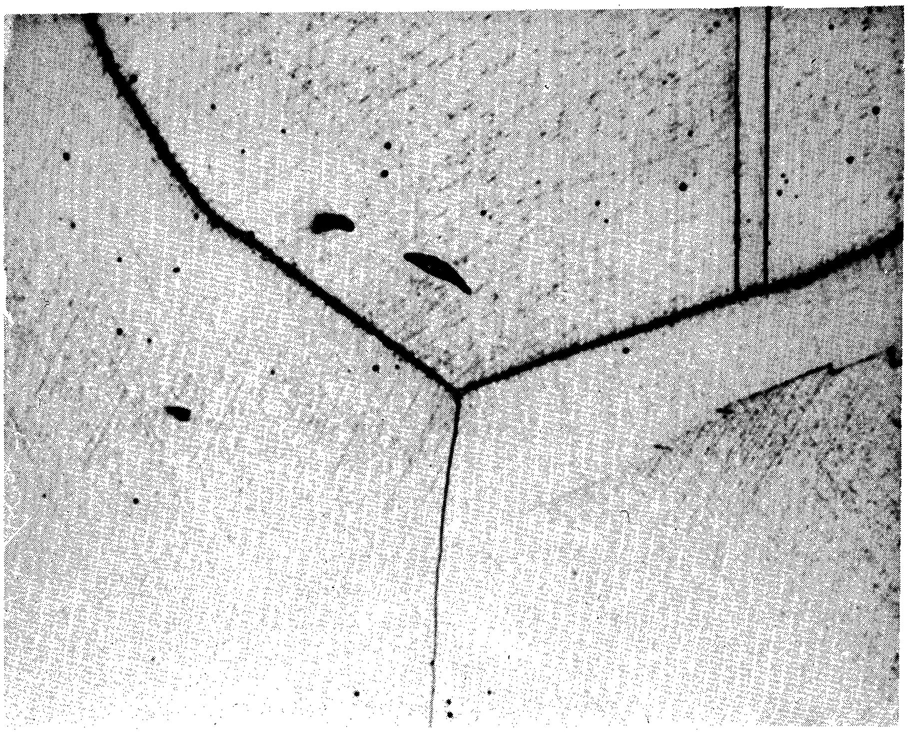


X1000D

Figure 32 Original Microstructure of the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat R5855, Water Quenched from 1950°F.

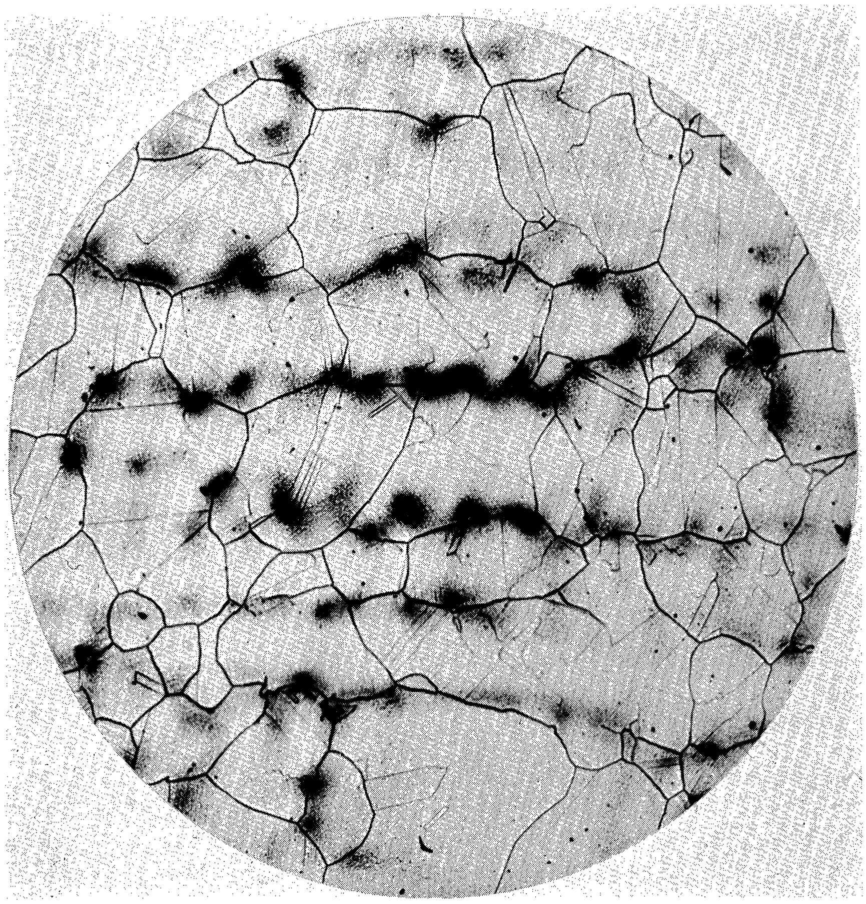


X100D

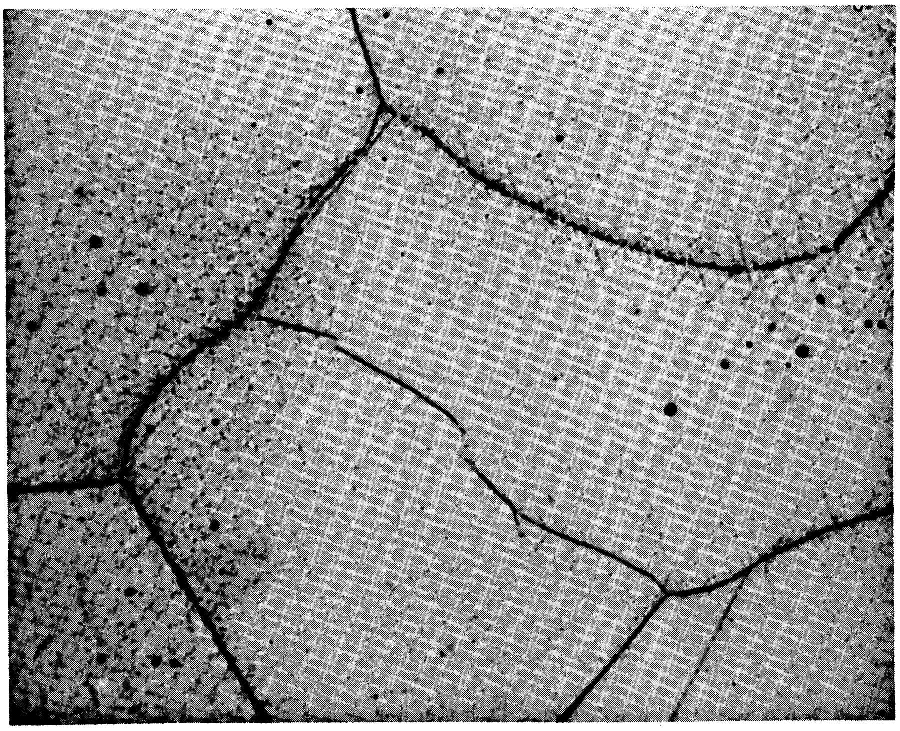


X1000D

Figure 33 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 6887 hours at 1000°F under a stress of 25,000 psi.

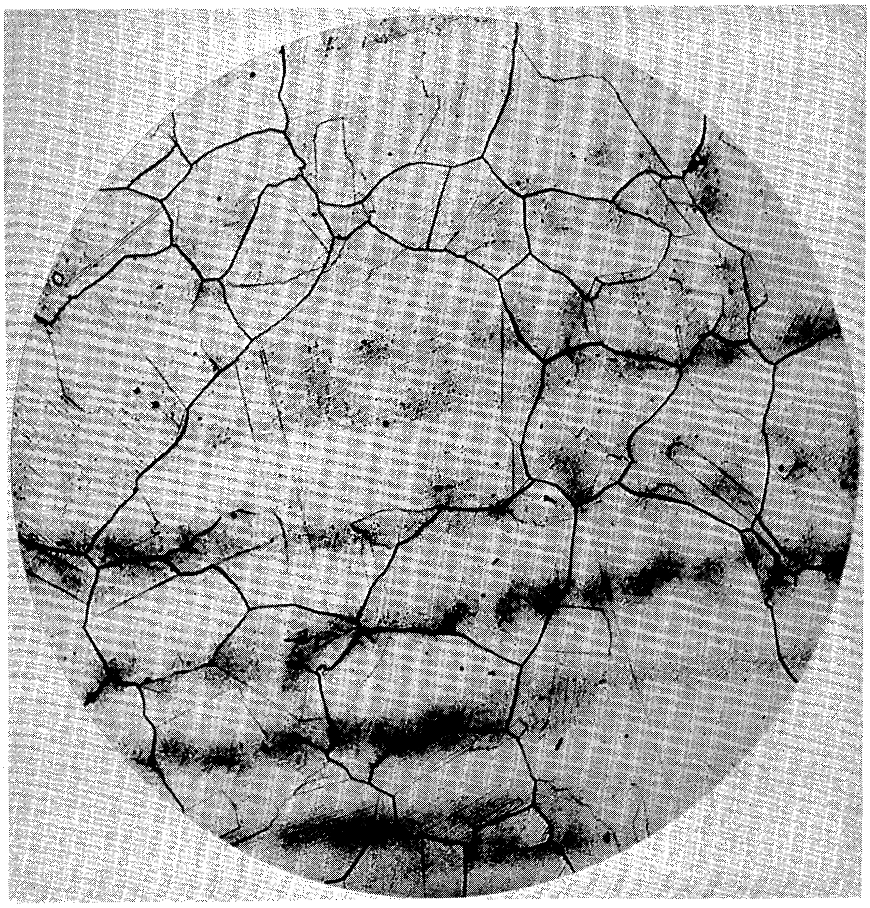


X100D

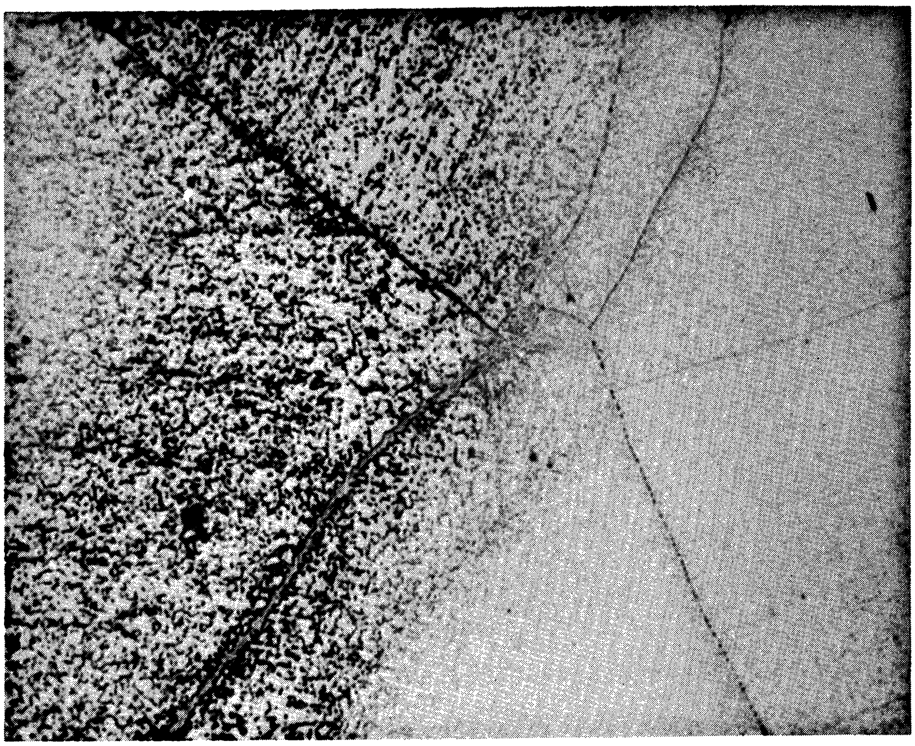


X1000D

Figure 34 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 6790 hours at 1100°F under a stress of 17,500 psi.



X100D

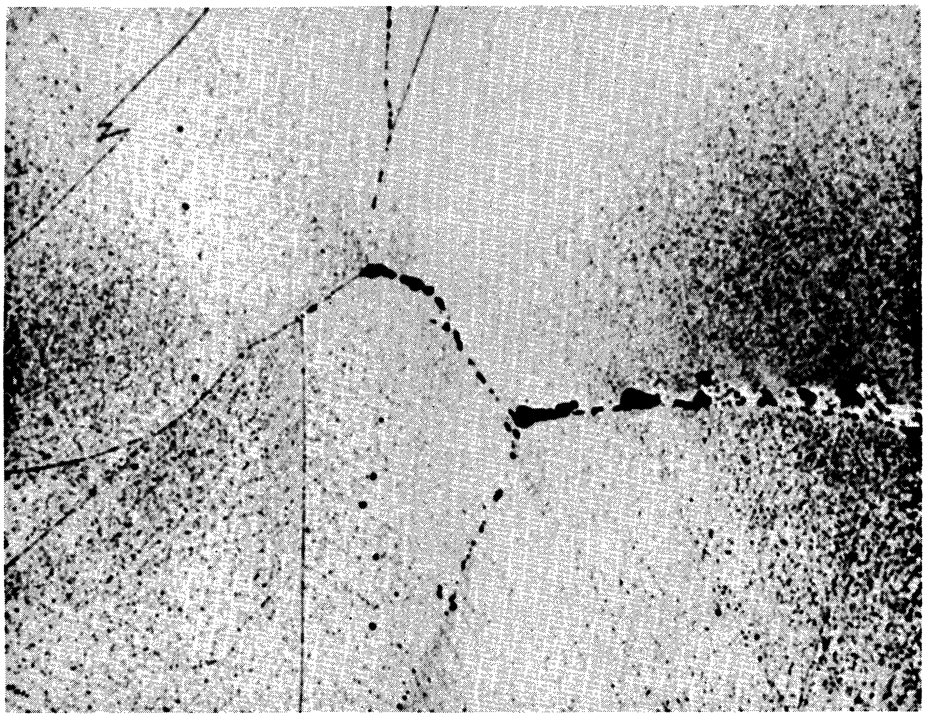


X1000D

Figure 35 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 4067 hours at 1100°F under a stress of 14,000 psi.

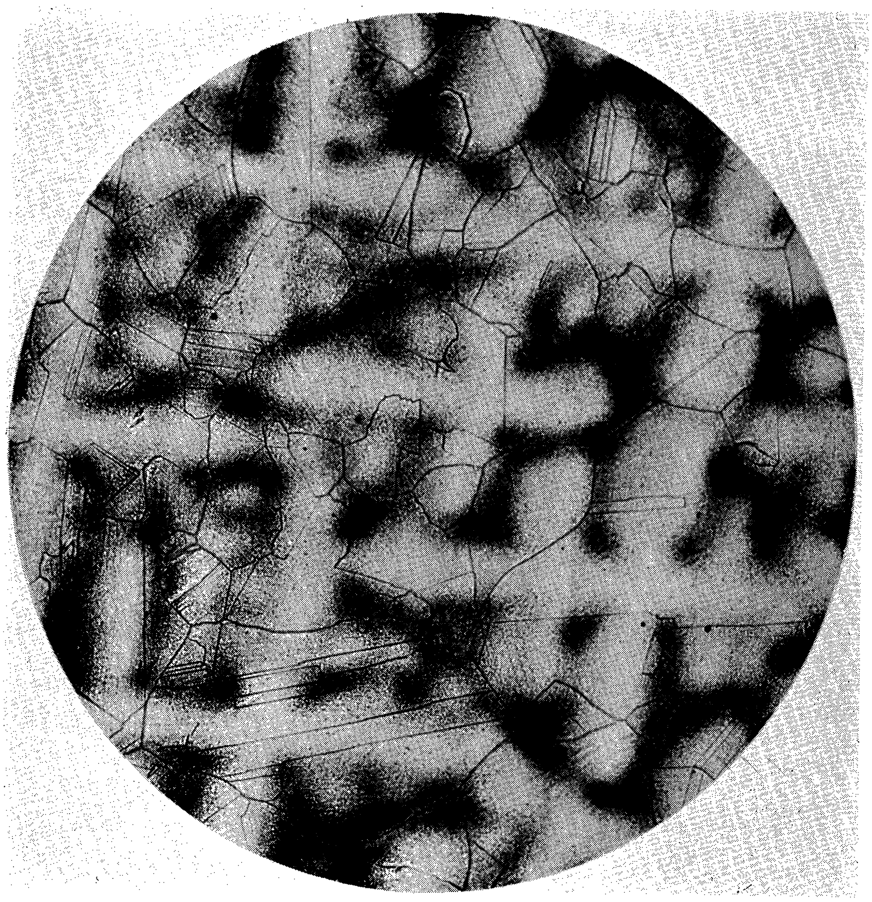
Fracture X100D

Surface Adjacent the Fracture X100D

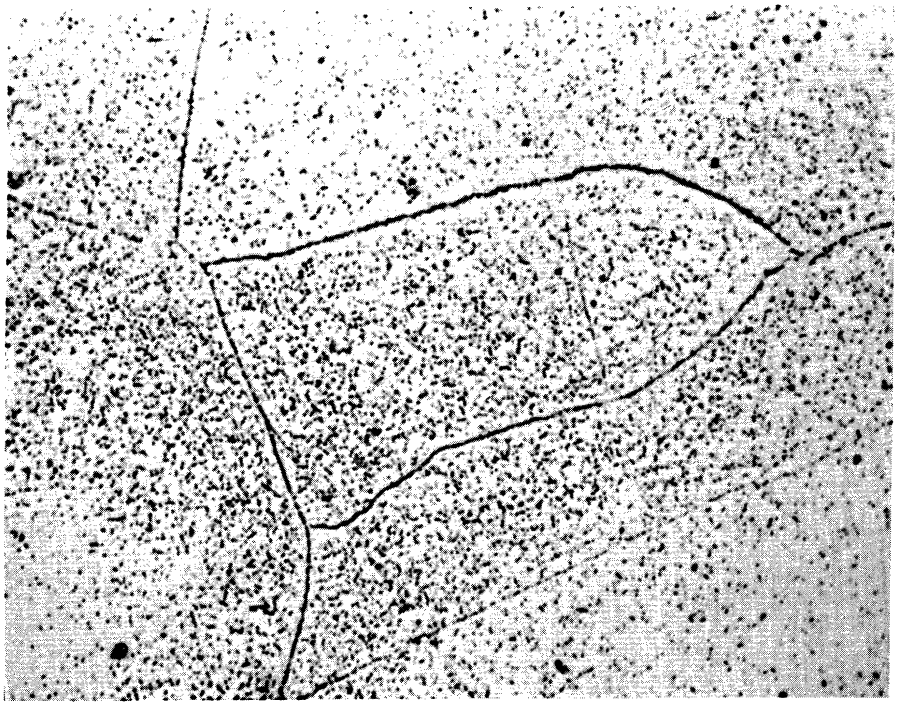


Interior X1000D

Figure 36 Microstructure of a Rupture Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Fractured after 4882 hours at 1100°F under a stress of 28,000 psi.



X100D

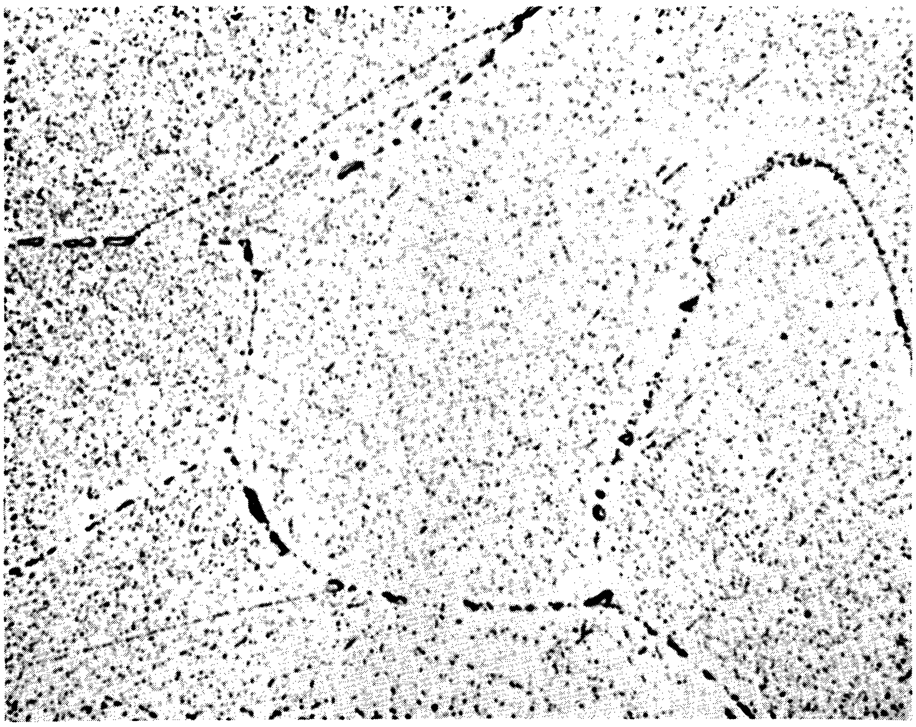


X1000D

Figure 37 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 8499 hours at 1200°F under a stress of 10,000 psi.

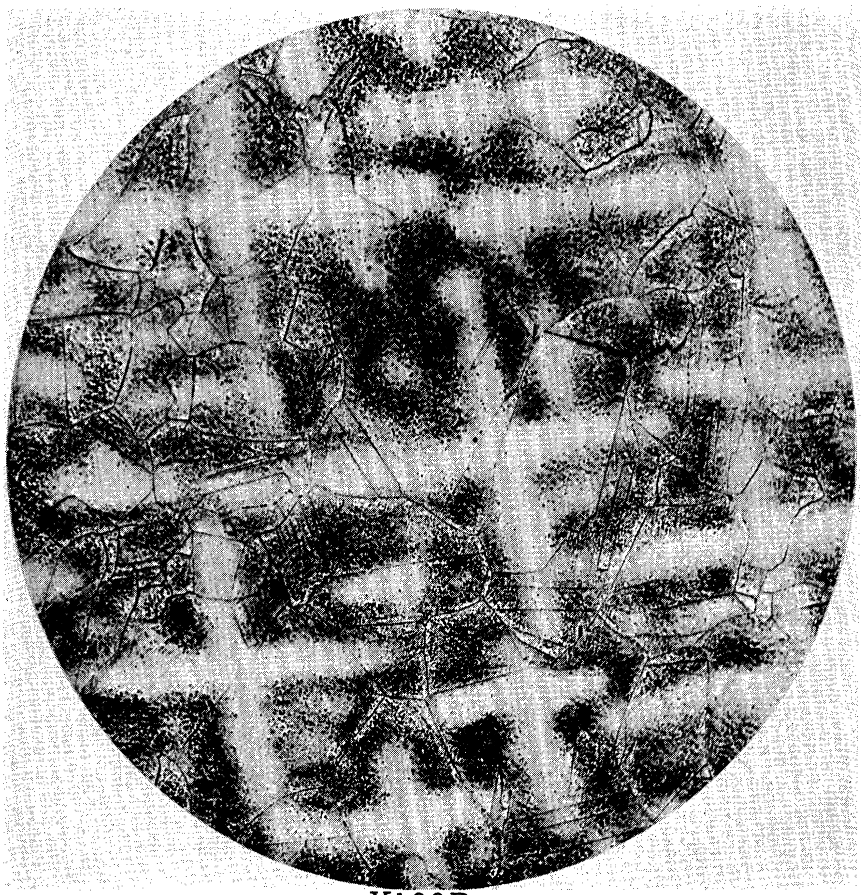
Fracture X100D

Surface Adjacent the Fracture X100D



Interior X1000D

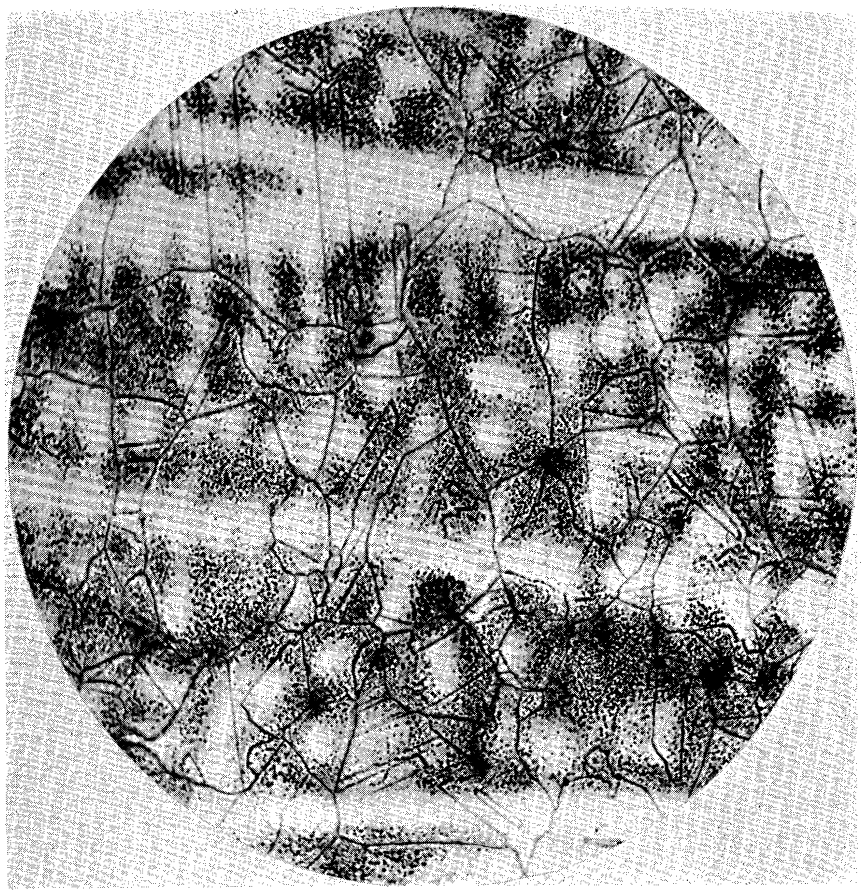
Figure 38 Microstructure of a Rupture Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Fractured after 5516 hours at 1200°F under a stress of 16,500 psi.



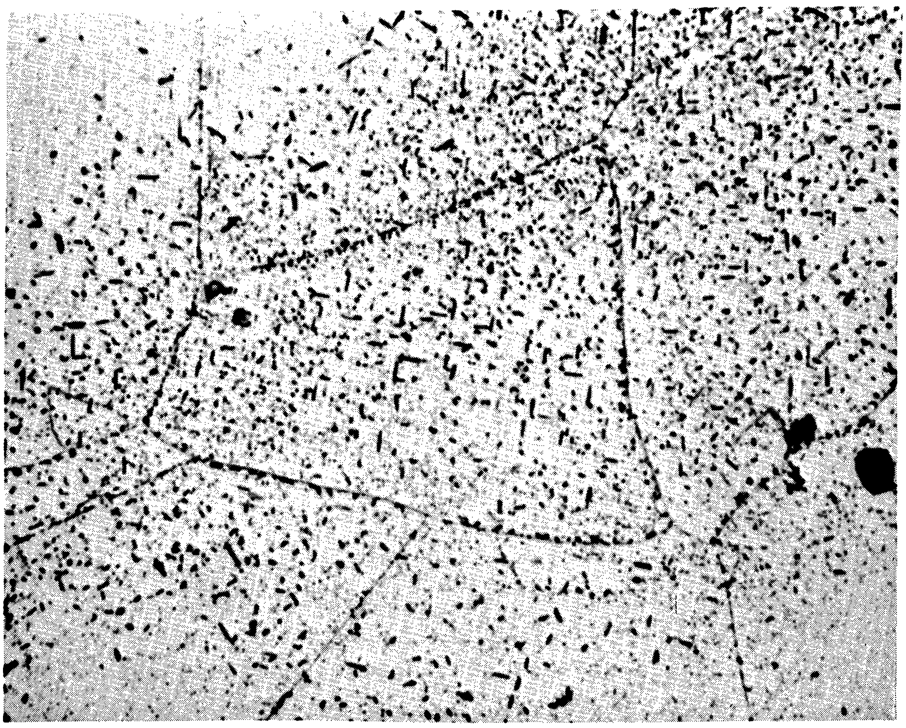
X100D

X1000D

Figure 39 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 5272 hours at 1350°F under a stress of 5500 psi.

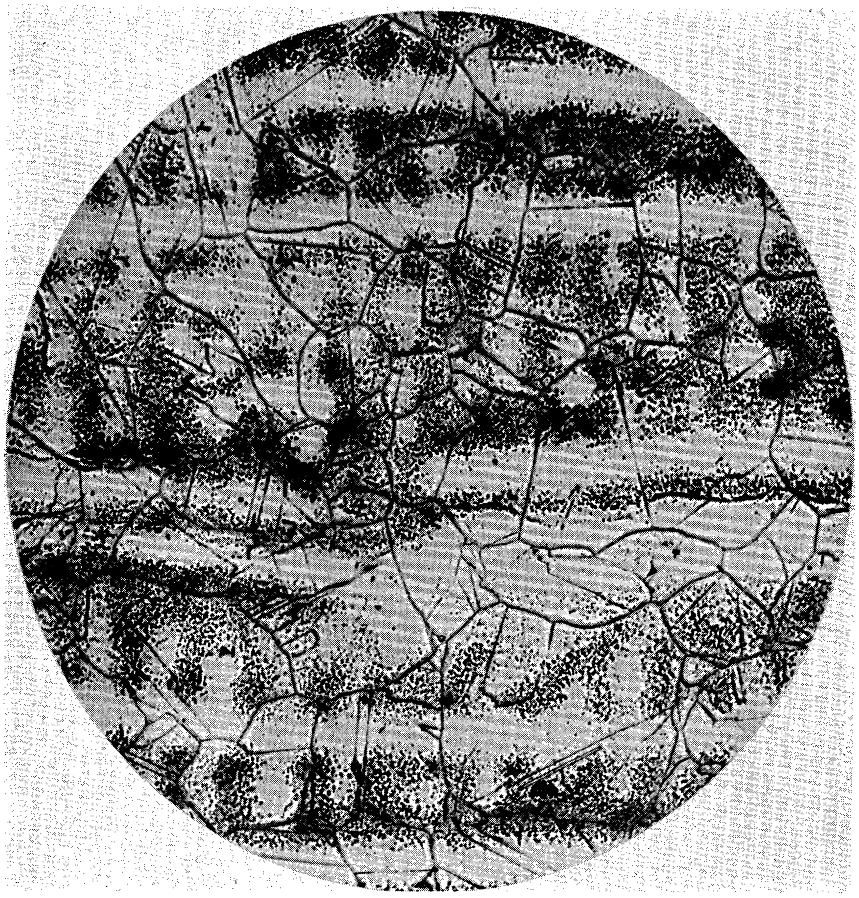


X100D

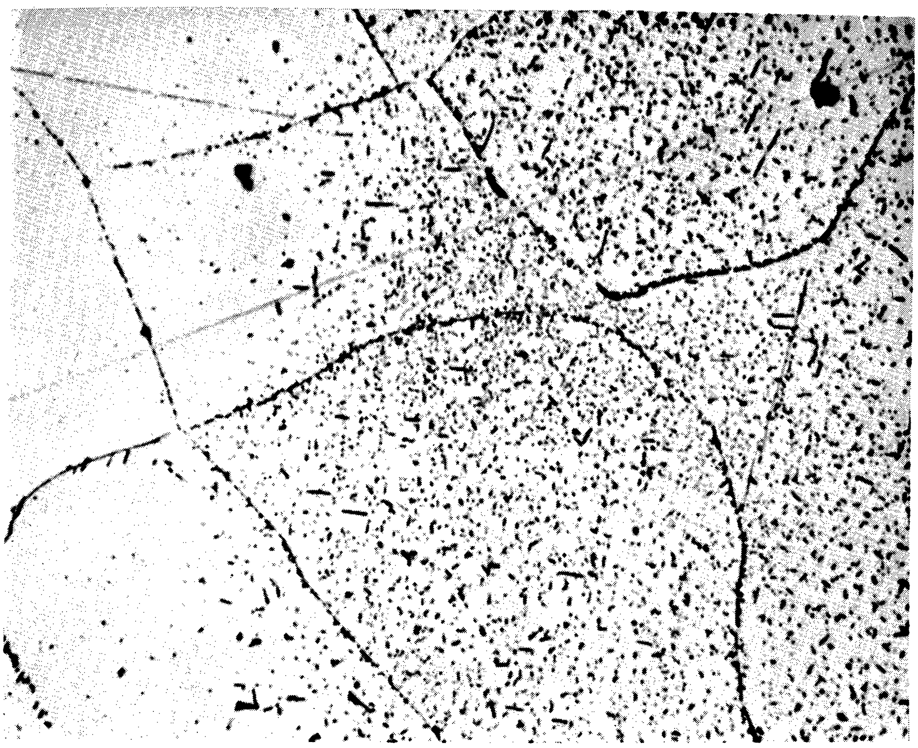


X1000D

Figure 40 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 3745 hours at 1350°F under a stress of 4000 psi.



X100D

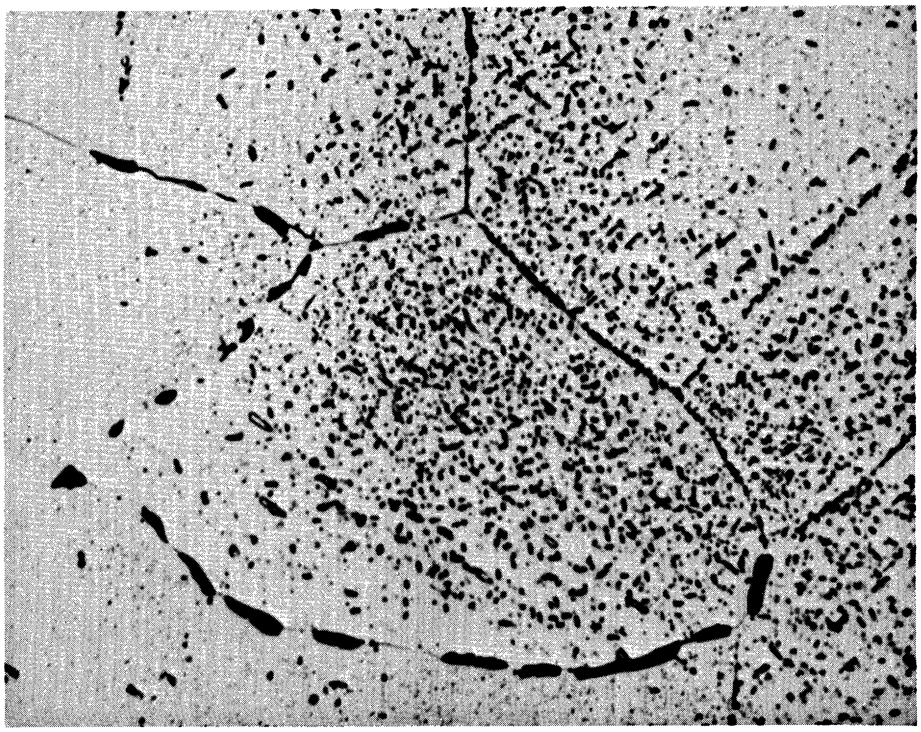


X1000D

Figure 41 Microstructure of a Creep Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Creep tested for 4646 hours at 1350°F under a stress of 3300 psi.

Fracture X100D

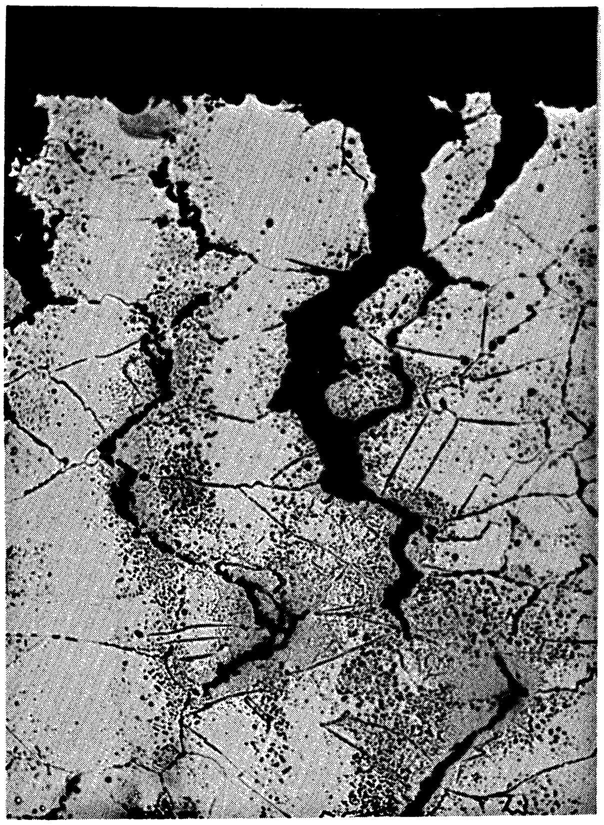
Surface Adjacent the Fracture X100D



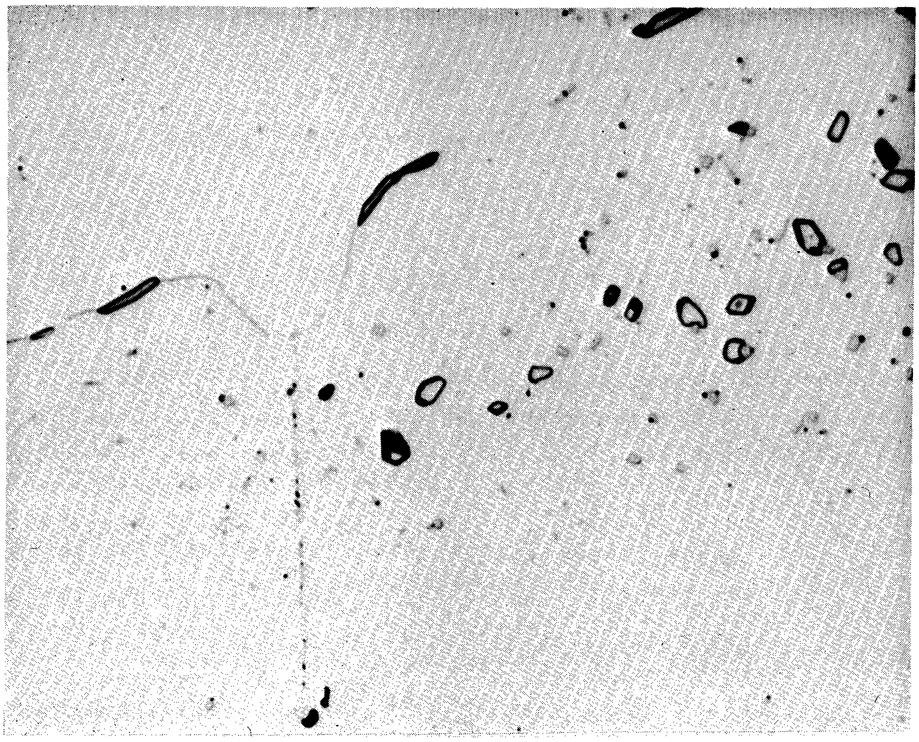
Interior X1000D

Figure 42 Microstructure of a Rupture Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Fractured after 4707 hours at 1350°F under a stress of 8000 psi.

Fracture X100D



Surface Adjacent the Fracture X100D



Interior X1000D

Figure 43 Microstructure of a Rupture Specimen from the Hydroforged Type 316 (18-8+Mo) Stainless Steel Pipe from Heat 1072-73. Fractured after 4975 hours at 1500°F under a stress of 4200 psi.