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SIXTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS

AT ELEVATED TEMPERATURES

by

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SUMMARY

Results previously reported for this joint investigation under Contract No. AF 18(600)-62 covered creep and relaxation properties at one temperature each for three high-temperature alloys. A qualitative relationship was indicated between notched-bar rupture properties and relaxation characteristics. Certain metallurgical variables have also been studied for their effects on notch behavior and the partial results available to date have been presented in past reports.

The present report summarizes results obtained during the first quarter of 1954 These include creep-rupture and relaxation behavior at 1350°F for Waspaloy with conventional heat treatment, together with relaxation characteristics at 1500°F for S-816 and Waspaloy in various conditions.

The new data support the previous finding of a close association between notched-bar rupture properties and relaxation ability of an alloy. Further rupture tests are in progress with smooth and notched bars of S-816 and Waspaloy with a cold rolling step introduced between conventional solution and aging treatments. Results from these tests are expected to offer either a strong support or else refute the role of relaxation as a major factor in notch behavior.

More work is planned in an effort to evaluate effects of notch preparation methods and of localized stains at the notch root on test results.

INTRODUCTION

This report covers experimental results for tests performed in the first quarter of 1954 under Contract No. AF 18(600)-62 which calls for study of factors affecting notch sensitivity of heat-resistant alloys. Special attention is being given to the significance of creep and relaxation, and to effects of certain metallurgical variables in rupture tests of notched bars.

Preliminary studies on these areas of special interest are summarized in a Technical Report prepared by the present authors. (See Ref. 1.). In that report, it is postulated that varied response to notches must be related to relaxation characteristics of alloys at service temperatures, so that a material may be strengthened or weakened by a notch according to the portion of total rupture life consumed while initial stress concentrations around a notch are reduced and redistributed by a creep-relaxation process.

For three alloys, each studied at a single test temperature, the two cases of notch strengthening (S-816 at 1350°F and Waspaloy at 1500°F) were accompanied by high rates of relaxation in smooth-bar tests. Inconel X-550 at 1350°F showed marked notch weakening at long rupture times; relaxation was relatively slow in tests on this alloy, especially at longer times when residual stresses were below about 50,000 psi. Further work is indicated before a quantitative correlation is attempted between notch properties and comparative relaxation and stress-rupture characteristics.

Other tests reported in Reference 1 showed Waspaloy at 1350°F to exhibit nearly equal rupture lives for smooth and notched bars at a given stress. Cold working of both S-816 and Waspaloy after the materials had

been solution-treated resulted in low elongations at failure in rupture tests at 1500°F. For Waspaloy, moderate deviations from the conventional solution temperature of 1975°F seemed to result in little or no change in notch properties for conditions studied.

If a correlation between relaxation and notch properties is to have general validity, it must be able to relate differences in notch behavior effected by changes in heat treatment with the accompanying changes in relaxation characteristics. Consequently, limited relaxation data have now been obtained for conditions outlined in the preceding paragraph. It has also been suggested that similar test data should be obtained for different heats of the same alloys which exhibit varying notch properties with identical heat treatments and test conditions.

CURRENT STATUS OF THE INVESTIGATION

Comparison of Notched-Bar Rupture Behavior with Relaxation Properties for Conventional Heat Treatments.

Data from previous reports and gathered together in Reference 1 cover the following alloys and temperatures:

S-816 at 1350°F
Waspaloy at 1500°F
Inconel X-550 at 1350°F

Test results obtained are believed complete enough to permit analytical treatment of any fiber loaded to stresses in the elastic range or up to plastic strains of the order of one percent. Tests have now been completed to obtain

necessary data for Waspaloy at 1350°F, including short-time tensile, creep-rupture and relaxation properties.

However, before a proposed quantitative correlation is attempted two further points require clarification:

(1) Fibers in a sharply-notched bar immediately at the base of the notch will strain plastically for some of the test conditions being investigated. The magnitude of plastic strain on loading must be ascertained to determine whether additional relaxation and creep data are needed, since effects on these properties of more than about one percent strain have not been obtained.

(2) Properties of the critical fibers near the base of a notch could be altered by very localized high temperatures and/or cold working during notch preparation. Notched bars with the same geometry may show different behavior according as the notches were ground or turned with a lathe tool.

Some studies into these problems have been started by the present authors and by another contractor participating in this program. However, several different approaches may be found necessary before satisfactory answers are found. For this reason the exact status of these particular studies is difficult to state.

Investigation of Some Metallurgical Variables And Their Effects on Notch Behavior

Preliminary tests reported previously indicated that for the range of metallurgical variables investigated, cold working after solution treatment of S-816 or Waspaloy resulted in marked decrease of elongation at rupture compared with specimens having conventional treatment. Further tests are still in progress to learn whether these low elongations are accompanied by notch brittleness at a test temperature of 1500°F. Results should be ready for reporting by the end of the next quarter. Some relaxation properties for S-816 and Waspaloy with non-conventional treatments are included in the present report.

Correspondence has been initiated seeking to obtain two different heats of Waspaloy with greater and lesser susceptibility to notch embrittlement than the one already tested here, but to date no promise of delivery has been obtained. If suitable stock is received by July, it should be possible to include some results on it in the present program.

SOME PROPERTIES AT 1350°F OF WASPALOY WITH CONVENTIONAL HEAT TREATMENT

Two relaxation tests and four tests of creep to rupture were run at 1350°F on specimens of Waspaloy given conventional heat treatment. This treatment consisted of a four-hour solution at 1975°F, air cool + four hours aging at 1550°F, air cool + sixteen hours of aging at 1400°F, air cool. (The final aging

period of 16 hours is erroneously stated as 4 hours on page 8 of Reference 1.)

Creep and Rupture Time Data

Four specimens allowed to creep to rupture at constant load supplied the following stress-rupture time data:

Stress (psi)	Rupture Life (hr)	Elongation (%)[a]	Reduction of Area (%)
90,000	0.29	2.5	8.5
80,000	1.4	3.	7.
70,000	7.4	4.	8.
40,000	512.1	3.	6.5

(a) Based on gauge length of 2.1 inches.

These results have been combined in Figure 1 with the following data obtained for this same heat by Simmons, et al. (Ref. 2).

Stress (psi)	Rupture Life (hr)	Elongation (%)	Reduction of Area (%)
60,000	10.6	2.6	5.3
55,000	56.6	3.0	5.8
50,000	161.4	5.2	6.7
45,000	265.1	5.3	6.9
35,000	1201.6[a]	--	--

(a) Discontinued.

Creep curves for the four specimens run at the University of Michigan are presented Figure 2.

Short-time Tensile Characteristics

Figure 3 gives the short-time tensile characteristics of Waspaloy at 1350°F determined from the loading curve for the specimen allowed to creep to rupture at 90,000 psi. The 0.2% offset yield strength and proportional limit are 91,000 and 58,000 psi, respectively. The elastic modulus appears to be 24 x 10^6psi/in. /in.

Stress Relaxation Properties

Results from the two step-down relaxation tests at 1350°F are shown in Figure 4. The specimen loaded initially to 85,000 psi had such a high initial rate of relaxation at the start of the test that by the end of five hours its residual stress level was below that for the specimen started at 60,000 psi. This is in agreement with past observations for other conditions where initial stresses above the proportional limit seemed to augment relaxation rate during early stages of the test.

RELAXATION CHARACTERISTICS AT 1500°F FOR S-816 AND FOR WASPALOY WITH VARIOUS UNCONVENTIONAL HEAT TREATMENTS.

The curves of Figure 5 are for S-816 with a heat treatment which resulted in very low elongation in rupture tests at 1500°F. (2325°F, 1 hr, W.Q. + 13.5% reduction at 1200°F + 1400°F, 12 hr, A.C.). A third test started at a lower stress would seem a valuable addition to this plot.

Relaxation characteristics at 1500°F for one specimen each of Waspaloy with three different heat treatments are assembled on Figure 6. Neither moderate variation in solution temperature alone, nor cold rolling between conventional solution and aging steps seems to result in any significant change in relaxation characteristics from those for specimens with conventional heat treatment. (Compare with Figure 7, reproduced from Figure 24 of Reference 1.)

A LOW-STRESS RELAXATION TEST FOR INCONEL X-550 AT 1350°F.

To round out the results previously reported for this alloy (Figure 25, Ref. 1), relaxation data for a 40,000 psi initial stress are now available:

Residual Stress (psi)	Time (hr)
40,000	0
38,000	7.6
36,000	51.1
34,000	197.4

DISCUSSION

Comparison of Relaxation and Stress-Rupture Properties.

Carlson and Simmons (Ref. 3) have shown that Waspaloy is notch ductile at 1500°F but slightly notch embrittled at 1350°F. S-816 with conventional heat treatment was found by them to be definitely strengthened by a notch in tests at 1500°F. Tests in progress by the present authors indicate no strengthening and perhaps notch weakening for S-816 at 1500°F when treated the same as the specimen used to obtain the relaxation data of Figure 5.

In Reference 1, rough estimates were given of the portion of life expended by a fiber of a smooth bar relaxing from the 0.2% offset yield stress to the stress at which rupture would occur in 1000 hours under steady load. For S-816 at 1350°F and Waspaloy at 1500°F the fractions calculated were 0.0009 and 0.20 respectively. Estimations of corresponding fractions at 1350°F for Waspaloy with conventional heat treatment, and at 1500°F for S-816 reduced 13.5% at 1200°F between conventional solution and aging steps are presented in Table 1, (See page 10.)

Values obtained for fractions of life expended in smooth bars are not directly comparable to those for fibers in notched bars, but their general trends appear to support qualitative observations that relaxation characteristics and notch behavior under creep rupture conditions are related. The change from 0.20 to 0.27 of a total life used up agrees with the slight but definite decrease in notch strength for Waspaloy as the test temperature drops from 1500° to 1350°F.

TABLE I

PORTION OF LIFE ESTIMATED TO BE EXPENDED BY A FIBER OF A SMOOTH BAR WHILE IT RELAXES FROM THE 0.2-PERCENT OFFSET YIELD STRESS TO THE 1000-HOUR RUPTURE STRESS.

Alloy and Test Temperature:		Waspaloy at 1350°F		S-816 at 1500°F	
Heat Treatments:		1975°F, 4 hr, A.C. + 1550°F, 4 hr, A.C. + 1400°F, 16 hr, A.C.		2325°F, 1 hr, W.Q. + 13.5% Red. at 1200°F + 1400°F, 12 hr. A.C.	
0.2% Offset Yield Stress, psi		90,000		70,000 (Estimated)	
1000-hr Rupture Stress, psi		36,000		25,000	
Total Stress Decrement, psi		54,000		45,000	
Est. Time Required to Relax Each Third of Total Decrement, hours:	1st:	0.15		0.02	
	2nd:	1.0		0.5	
	3rd:	19		10	
Average Stress for Each Period, psi / Rupture Life at this Stress, hours:		Stress	Life	Stress	Life
	1st:	81,000	1.1	62,500	0.6
	2nd:	63,000	15	47,500	5.3
	3rd:	45,000	280	32,500	125
Fraction of Life Expended for Each Period:	1st:	0.15/1.1 = 0.137		0.02/0.6 = 0.033	
	2nd:	1.0/15 = 0.067		0.5/5.3 = 0.094	
	3rd:	19/280 = 0.068		10/125 = 0.080	
Total Fraction of Life Expended in Reaching 1000-hr Rupture Stress:		0.272		0.207	

S-816 at 1500°F with the unconventional heat treatment appears to use up nearly 21% of its life in relaxing from its yield point stress to its 1000-hour rupture stress. This fraction of life expenditure is some 200 times greater than for conventional heat treatment and a 1350°F test temperature. In view of this apparent extreme change in ability of this material to relax high initial stresses early in a test, experiments now in progress on smooth and notched bars of S-816 in the rolled condition are expected to offer an important support or refutation to the role of relaxation as a major factor in notch behavior.

The finding that variation in solution temperature made little or no change in relaxation properties of Waspaloy at 1500°F agrees with observations in Reference 1 that moderate changes in solution temperature did not change the relative notch strengthening of this alloy. No valid conclusion yet appears possible from the meager data on Waspaloy reduced 15% at room temperature between the solution and aging steps.

Extrapolating the relaxation data for Inconel X-550 at 1350°F with 40,000 psi initial stress, about 1,000 hours are required to lower the residual stress to 30,000 psi. Applying methods established in Reference 1, the fraction of life consumed in this 1000-hour relaxation period would be about 0.45 or 0.5. This is double the life expenditure had the final stress of 30,000 psi been acting during the whole 1000 hours.

FUTURE EXPERIMENTAL WORK

Work for the next quarter is to concentrate on completion of tests required to establish notch behavior of both S-816 and Waspaloy at 1500°F with extraneous cold working introduced into the heat treatments.

At the same time a variety of procedures is to be considered in an effort to evaluate effects of notch preparation methods on test results and to determine changes in notch geometry on loading and during testing.

One or two further relaxation tests at 1500°F for initial stress below 40,000 psi are planned to round out the picture for S-816 rolled after solution treatment.

If heats of the present alloys can be procured with notch properties different from heats already studied, tests will be made, insofar as time and equipment permits, to determine whether corresponding differences in relaxation characteristics exist.

BIBLIOGRAPHY

1. Voorhees, H.R. and Freeman, J. W. Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures: Part 1. Preliminary Studies of the Influence of Relaxation and Metallurgical Variables. Wright Air Development Center, Technical Report 54-175 (Part 1). May 1954.

2. Simmons, W.F., Carlson, R.L. and MacDonald, R.J. Sixth Quarterly Progress Report on Investigation on Notch Sensitivity of Heat-Resistant Alloys at High Temperatures. (Rupture Strength of Notched Bars at High Temperatures.) Battelle Memorial Institute, 15 March 1954.

3. Carlson, R.L. and Simmons, W.F. Fifth Quarterly Progress Report on an Investigation on Notch Sensitivity of Heat Resistant Alloys at Elevated Temperatures. Battelle Memorial Institute, 15 October, 1953.

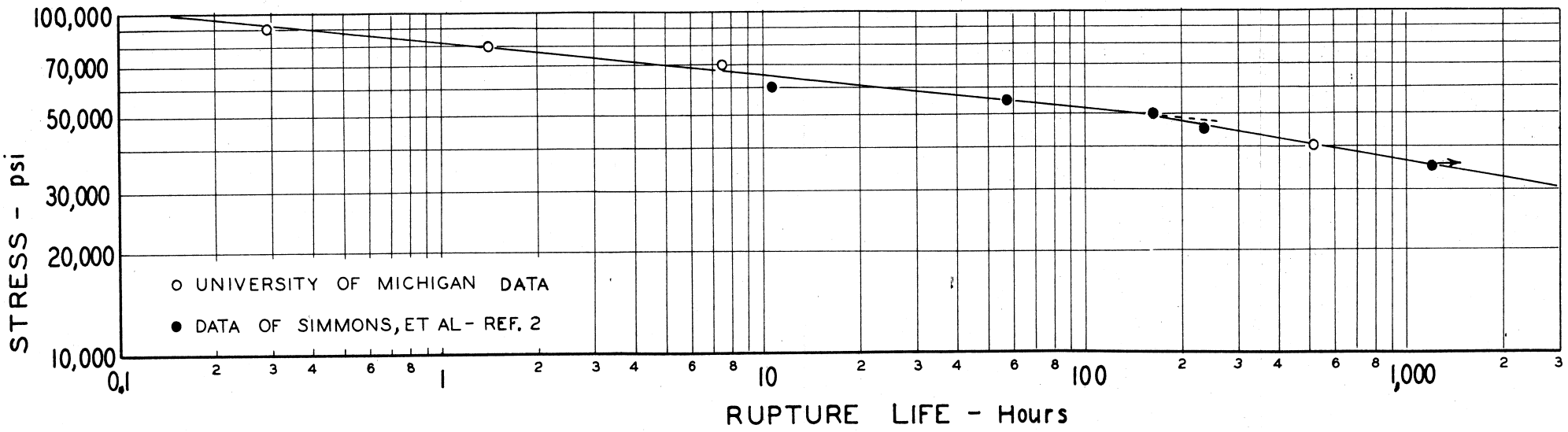

FIG. 1 - STRESS VERSUS RUPTURE LIFE AT 1350°F FOR WASPALOY WITH CONVENTIONAL HEAT TREATMENT. (1975°F, 4 HR, A.C. + 1550°F, 4 HR, A.C. + 1400°F, 16 HR, A.C.)

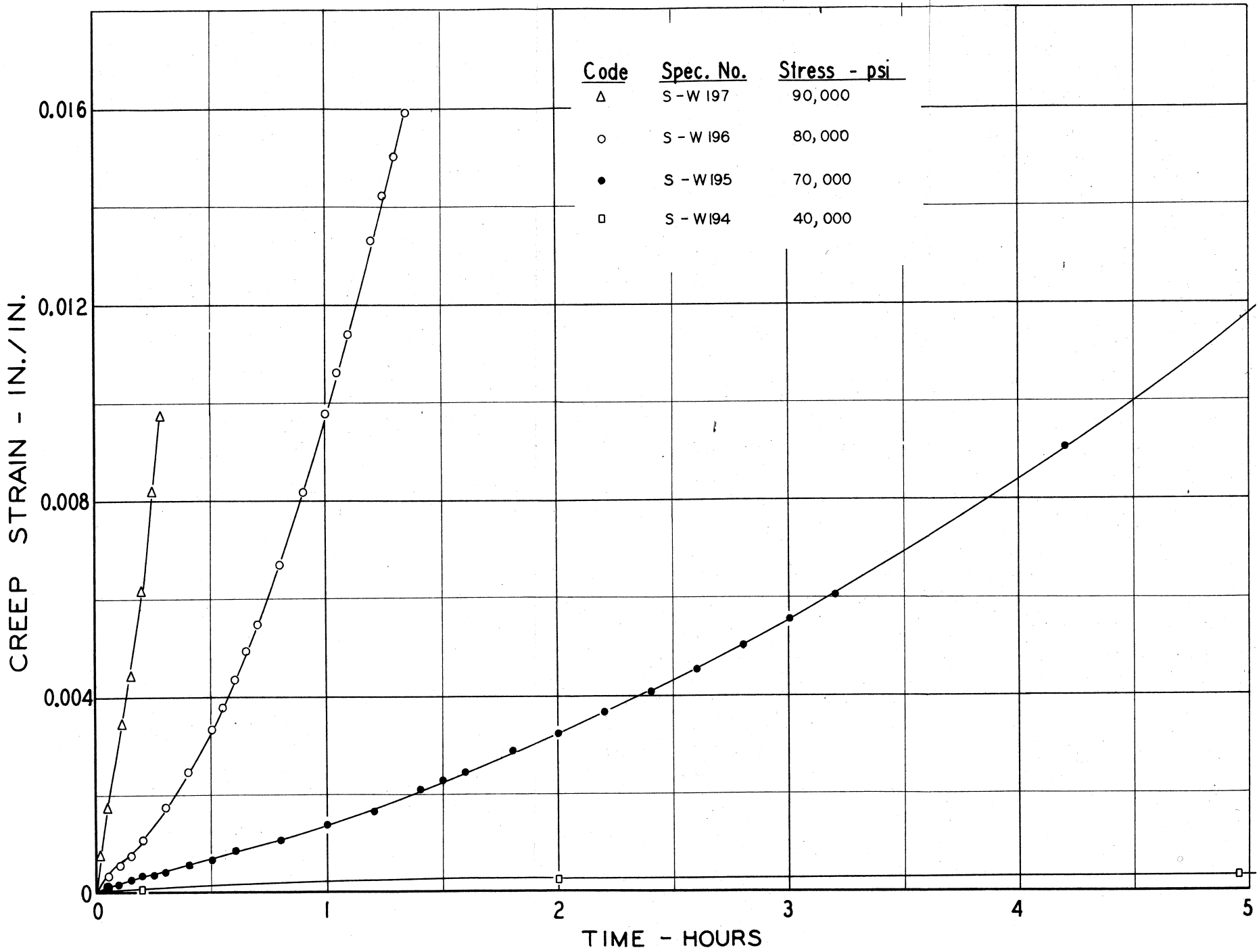

FIG. 2 - CREEP CHARACTERISTICS AT 1350°F FOR WASPALOY WITH CONVENTIONAL HEAT TREATMENT. (1975°F, 4HR, A.C. + 1550°F, 4 HR, A.C. + 1400°F, 16 HR, A.C.)

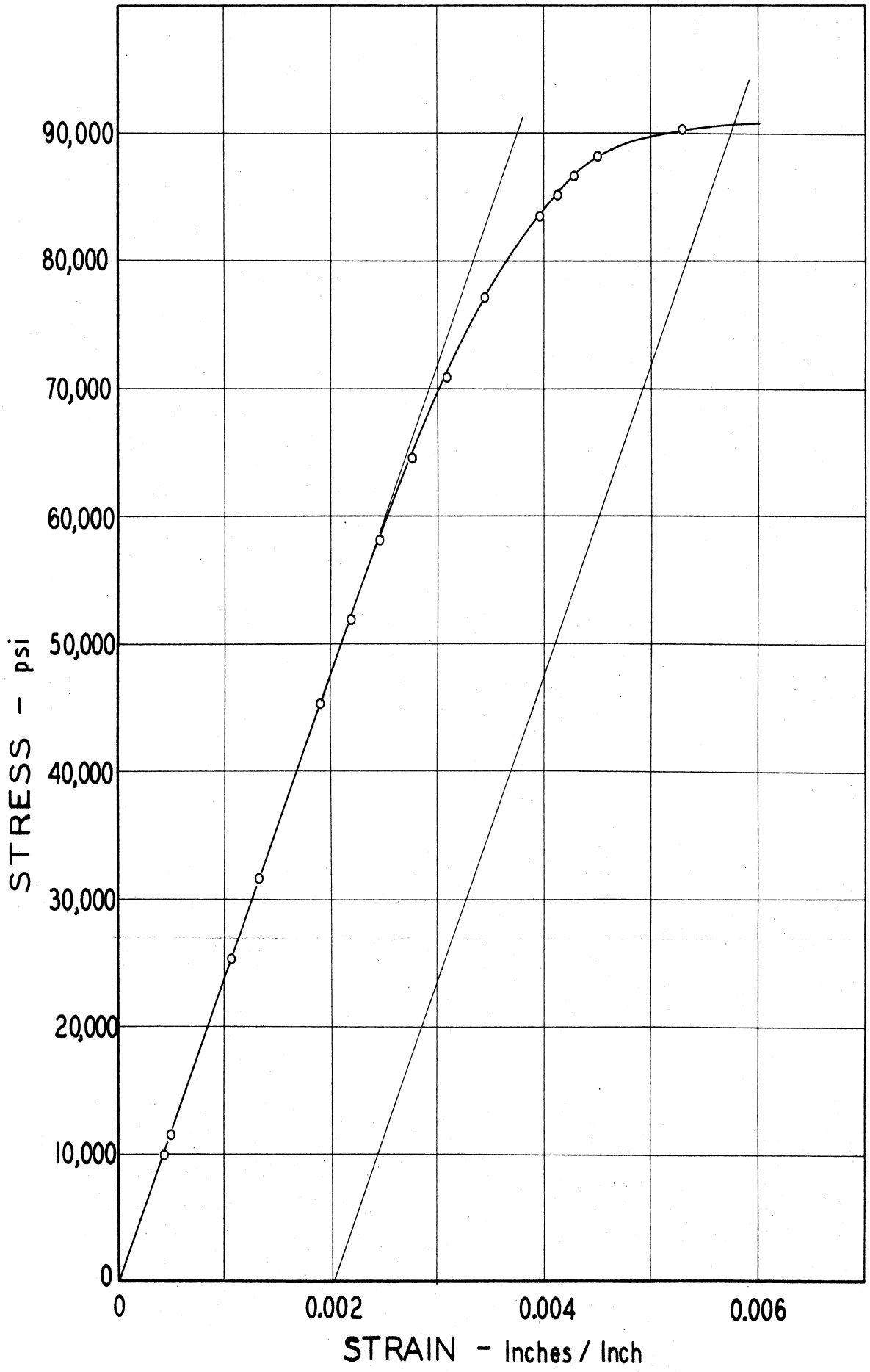

FIG. 3 - SHORT-TIME TENSILE CHARACTERISTICS AT 1350°F OF WASPALOY WITH CONVENTIONAL HEAT TREATMENT. (1975°F, 4 HR, A.C. + 1550°F, 4 HR, A.C. + 1400°F, 16 HR, A.C.)

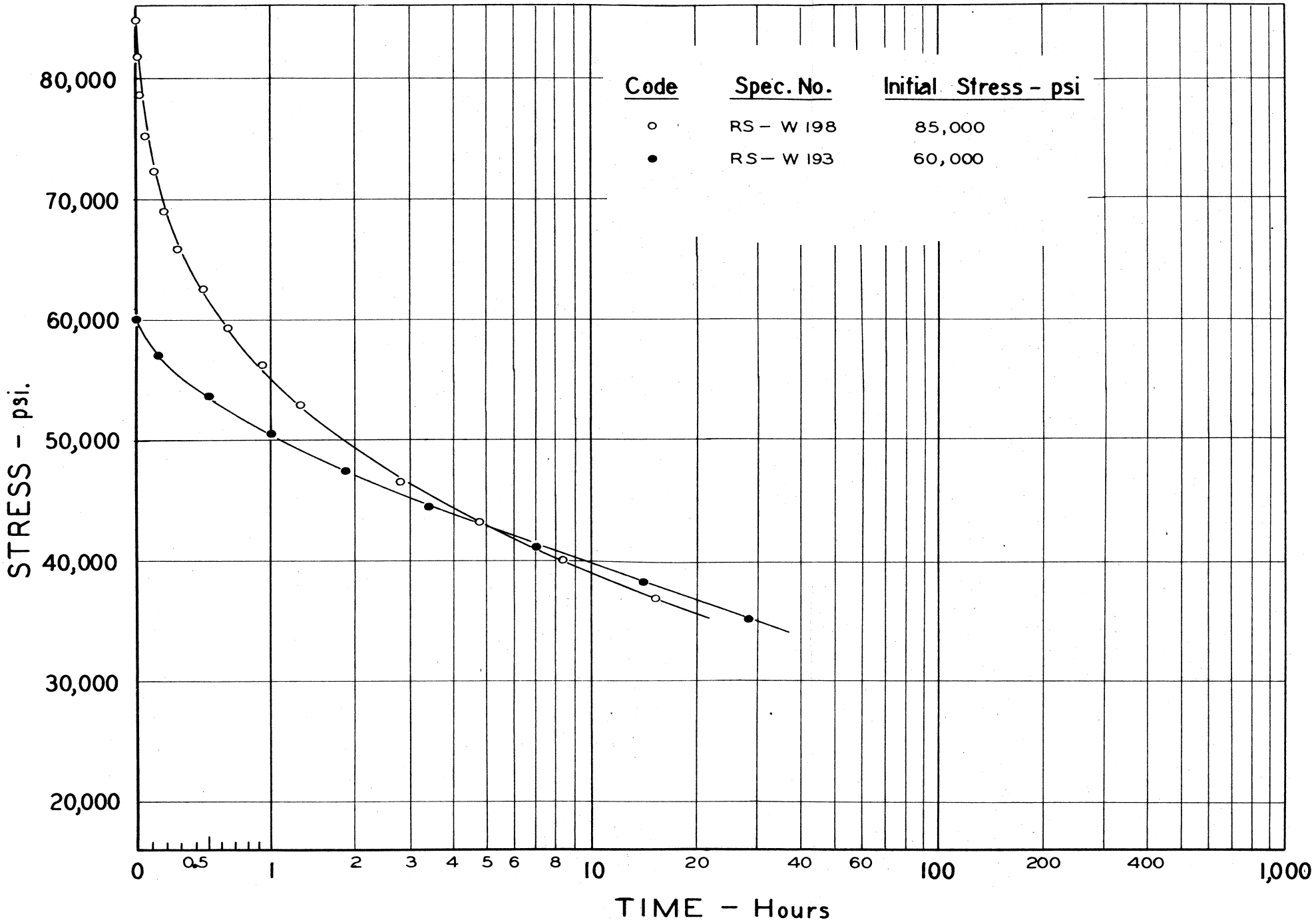

FIG. 4 - RELAXATION CHARACTERISTICS AT 1350°F OF WASPALOY WITH CONVENTIONAL HEAT TREATMENT. (1975°F, 4 HRS, A.C. + 1550°F, 4 HRS, A.C. + 1400°F, 16 HRS, A.C.)

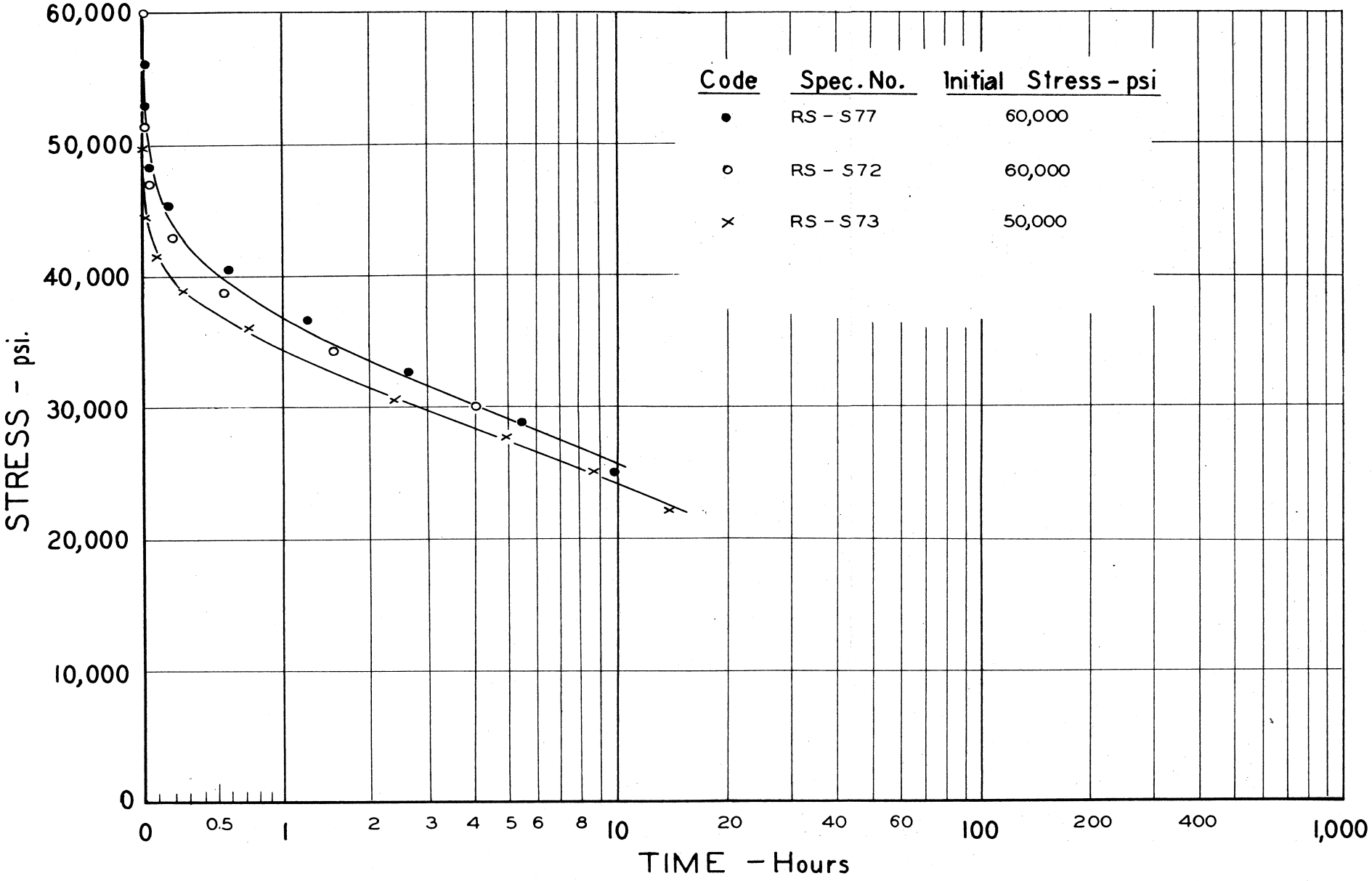

FIG. 5 - RELAXATION CHARACTERISTICS AT 1500°F OF S-816 ROLLED AFTER SOLUTION TREATMENT. (2325°F, 1 HR, W.Q. + 13.5% RED. AT 1200°F + 1400°F, 12 HR, A.C.)

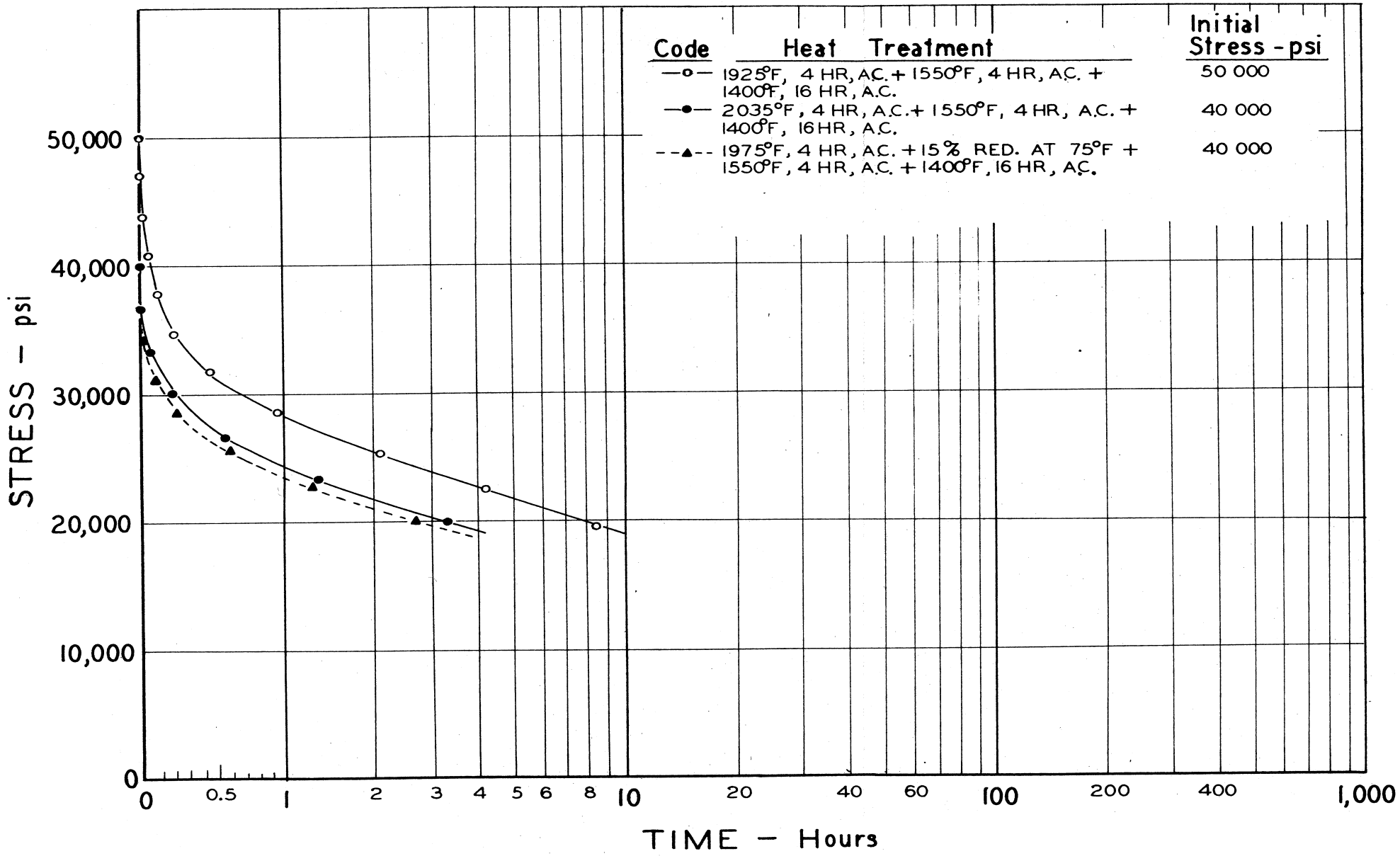

FIG. 6 - RELAXATION CHARACTERISTICS AT 1500°F OF WASPALOY WITH VARIOUS HEAT TREATMENTS.

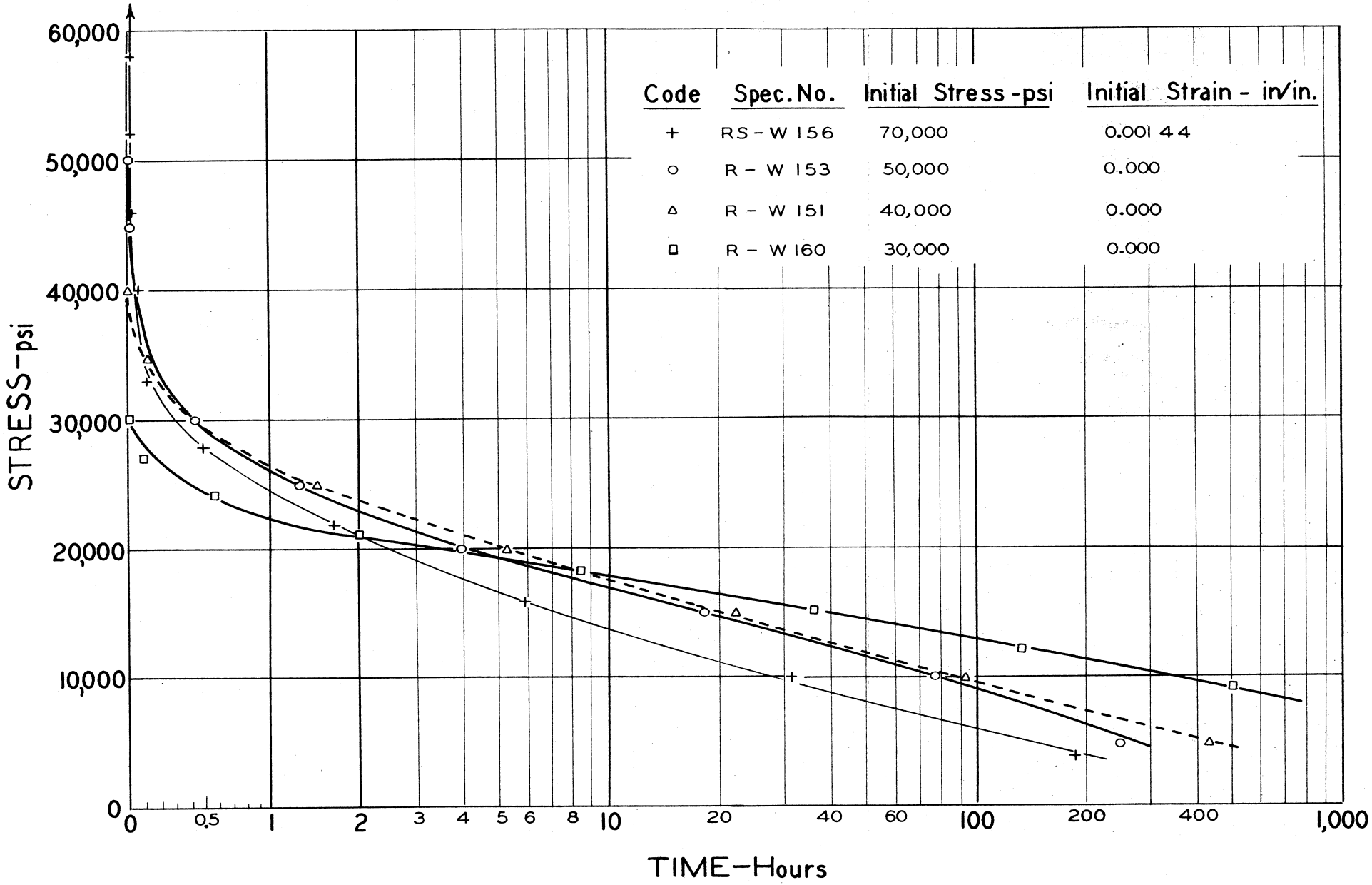

FIG. 7 - RELAXATION CHARACTERISTICS OF WASPALOY AT 1500°F