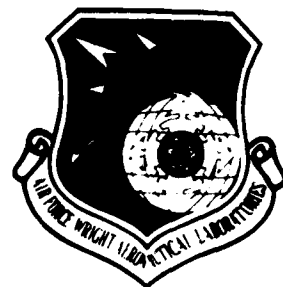




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A CONSTITUTIVE REPRESENTATION FOR IN100

University of Cincinnati  
Department of Aerospace Engineering  
and Applied Mechanics  
Cincinnati, OH

D. C. Stouffer

June 1981

Technical Report AFWAL-TR-81-4039

Final Report for the Period of September 1978 - January 1981

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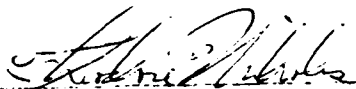
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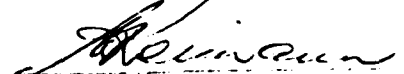
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FOR THE COMMANDER:



THEODORE NICHOLAS  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The mechanical response of IN100 at 732°C (1350°F) is calculated using the state variable constitutive equation of Bodner and Partom. The model is based on the concept that the inelastic component of the strain rate is non-zero for all non-zero values of stress and that separate loading and unloading conditions are not required. The plastic strain rate depends on a state variable that describes the resistance to plastic flow. In this report, it is demonstrated that the coefficients in evolution equation for the state variable can be determined from a systematic analysis of tensile and creep data. The model is used			

to predict the stress relaxation and cyclic response of the material.

## FOREWORD

This final technical report was prepared by the Department of Aerospace Engineering and Applied Mechanics of the University of Cincinnati. Dr. T. Nicholas, AFWAL was the project engineer. This report describes the application of the results of research on the development of a constitutive model for high temperature superalloys to IN100 at 732°C (1350°F). The report is the completion of task 4.2.10 of Contract F33615-78-C-5199, Constitutive Modeling on project, task and work unit 2307-P1-10. The research reported was conducted by D. C. Stouffer for the period from September 1978 to January 1981.

The author expresses appreciation to Dr. T. Nicholas for his suggestions and comments during the project. The author also acknowledges the help of Mar-Test Inc., Cincinnati, Ohio for their assistance in performing the required experiments.

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## SECTION I INTRODUCTION

The objective of this report is to present a working constitutive equation for IN100 at 732°C (1350°F). The specific constitutive equation should be capable of predicting a wide variety of mechanical responses including tensile, creep, stress relaxation and cyclic behavior. It should also be efficient for use in a computer code and the material parameters should be easily determined from an experimental program.

An earlier report, Reference [1], on the evaluation of three constitutive equations indicated that the state variable constitutive equation developed by Bodner and his co-workers, References [2-4], could generally satisfy the above requirements for high temperature response of superalloys. The representation is fully three dimensional and has been extended to include anisotropic response that is either initially present or induced by the deformation itself, Reference [5]. Work is currently in progress to include damage and life prediction in the formulation, see Reference [6]. The representation has been applied to many materials including another superalloy Rene 95, Reference [7].

The work on a representation for IN100 has been in progress for about two years as part of a general effort in constitutive modeling. Early in the program a preliminary method was developed to establish the material parameters in the constitutive theory directly from the experimental data. This method was used to estimate the material constants for IN100 from only three experiments for use on another project, Reference [8]. Since then, the method has been further developed and applied to Rene 95, References [9, 10]. For the case of Rene 95 a correlation between the hardness, an internal state variable describing the resistance to plastic flow, and the deformation mechanism is proposed. Generally it was shown that prior to the onset of nominal macroscopic

yield (0.20% offset strain for example), the rate of hardening recovery exponent is about a factor of ten higher than after the initiation of plastic flow. This result allowed for the identification of the yield stress from the hardening data and also permitted the observation of two distinct regions of creep behavior.

In this report, the methods developed for Rene 95 are applied to IN100 at 732°C (1350°F) for a data base of twenty experiments. When the estimated parameters from the first three experiments were used to predict the tensile response of a family of eight experiments over three decades of strain rate, it was found that the estimate was not adequate. As a consequence, the material parameters were updated using the full set of data. The tensile and creep response of the material can now be reproduced by the model relatively well. In addition, the response of a relaxation test and an unsymmetrical hysteresis loop is predicted. Many of the same trends reported in Reference [10] can be identified; however, some aspects of the data base are incomplete and a definitive conclusion about the relationship between the rate of hardening and deformation cannot be obtained.

SECTION II  
A STATE VARIABLE CONSTITUTIVE EQUATION

The constitutive theory of Bodner and Partom is based on the assumption that the total strain rate,  $\dot{\epsilon}(t)$ , can be separated into elastic,  $\dot{\epsilon}^e(t)$ , and inelastic,  $\dot{\epsilon}^I(t)$ , components. Let E represent the elastic modulus, then the Bodner-Partom equation can be written in one dimensional form.

$$\dot{\epsilon}(t) = \frac{\dot{\sigma}(t)}{E} + \dot{\epsilon}^I(t) \quad (1)$$

where  $\sigma(t)$  is the current value of the stress. Inherent to Equation 1 is that the inelastic strain rate is non-zero for all non-zero values of stress. The specific representation used by Bodner and his co-workers for the inelastic strain rate is given by

$$\dot{\epsilon}^I(t) = \frac{2}{\sqrt{3}} D_0 \frac{\sigma(t)}{|\sigma(t)|} \exp \left[ -\frac{(n+1)}{2n} \left\{ \frac{Z(t)}{\sigma(t)} \right\}^{2n} \right] \quad (2)$$

The constant  $D_0$  represents a limiting value of the inelastic strain rate and is generally taken at  $10^4 \text{ sec}^{-1}$  unless the strain rates are very high. The constant  $n$  controls the strain rate sensitivity and  $Z(t)$  is a state variable. The general mathematical structure of Equation (2) is based on dislocation dynamics expressed in the context of continuum mechanics and has proven consistent with the observed response for many metals. This formulation is similar to the classical yield surface theory. The structure of the Prandtl-Reuss formulation is preserved, but a yield surface itself is not part of Equations (1) and (2).

A representation for the state variable  $Z(t)$  is necessary for the use of the above equation. Physically,  $Z$  can be interpreted as a macroscopic hardening parameter that controls the resistance to inelastic flow. The evolution equation for the state variable is generally sought in the form of a differential equation for the hardening rate,  $\dot{Z}$ , that depends on stress, temperature and hardness,  $Z$ . A more specific representation is based on the concept that only the inelastic rate of working,  $\dot{W}^P$ , and current hardness,  $Z$ , control the rate of hardening. Using the standard form of the representation, Reference [9], let

$$\dot{Z} = m(Z_1 - Z)\dot{W}^P - AZ_1 \left(\frac{Z - Z_2}{Z_1}\right)^r \quad (3)$$

with  $Z_0$  designated as the initial value of  $Z$ . The two terms in Equation (3) are defined so that  $AZ_1 [(Z-Z_2)/Z_1]^r$  is negligible during rapid load histories. Thus, during a tensile test that is fast compared to creep test, Equation (3) reduces to the first term alone. The constant  $Z_1$  corresponds to the maximum value for  $Z$  and  $m$  is an exponential coefficient controlling the rate of hardening. For long time response, such as creep, the second term corresponding to hardening recovery is necessary. During the minimum creep rate response both  $\dot{W}^P$  and  $\sigma$  are constant, thus  $\dot{Z}$  is constant ( $Z=0$ ) and the rate of hardening must equal the rate of recovery. The coefficient  $Z_2$  corresponds to the minimum recoverable value of hardness, and  $A$  and  $r$  are the coefficient and exponent, respectively, controlling the rate of hardening recovery.

The main purpose of this report is to establish the coefficients in the Bodner-Partom equation for IN100 at 732°C (1350°F). This is accomplished by inverting Equation (2),

$$Z = \sigma \left[ \frac{2n}{n+1} \ln \left( \frac{2 D_0}{\sqrt{3} \dot{\epsilon} \Upsilon} \right) \right]^{1/2n} \quad (4)$$

to obtain a history of Z of each history of stress and inelastic strain rate measured during an experiment. This provides a powerful technique to directly determine the material parameters from the observed laboratory response.

### SECTION III THE MECHANICAL RESPONSE

Twenty mechanical tests have been conducted on IN100 at 732°C (1385°F) at the Air Force Wright Aeronautical Laboratory, Ohio and Mar-Test Inc., Cincinnati, Ohio. The material was obtained at different times from different heats resulting in five groups of specimens designated as series C, G, T, GT and ENTEN. The experimental program, summarized in Table 1, includes eight tensile tests, eleven creep tests and one combined test. The controlled experimental variable is shown in Table 1 and the observed stable values for stress or secondary creep rate is also given for the tensile and creep tests, respectively.

The results of seven tests conducted under constant strain rate control ranging from  $1.4 \times 10^{-3} \text{ sec}^{-1}$  to  $1.6 \times 10^{-6} \text{ sec}^{-1}$  and one test under constant head rate control at  $8.3 \times 10^{-4} \text{ sec}^{-1}$  are shown in Figure 1. There is significant variation in the level of the stress response due to the imposed variation in strain and head rate. Note however, the total accumulated strain in these tests is not important since several of the specimens were not failed. For four different values of strain rate (Tests 2, 4, 6 and 8) the response obtained a maximum stress and maintained that value of stress for all subsequent values of strain. However, for Tests 5, 7 and 9 a different response was obtained. In these experiments the value of the stress decayed from the maximum value obtained at about one percent strain. In Test 5 the amount of reduction in stress to a lower stable value was small. In Test 7, at a lower strain rate, the reduction in stress to a stable value was larger; and in Test 9 the stress did not stabilize at a lower level. This wide variation in response might arise since the eight specimens are from four different heats. Since both types of response were observed at both AFWAL and Mar-Test Inc., it cannot be

accepted as an experimental problem. In this study no attempt is made to model the reduction in stress observed in Tests 5, 7 and 9.

The results of six creep tests are shown collectively in Figure 2 for time up to 100 minutes. The variation in the creep stress was almost twofold, 496 to 896 MPa (72 to 130 KSI), and the corresponding minimum creep rates are given in Table 1. The creep curves from Tests, 10, 14 and 15 are shown in Figure 3 for time up to 1000 minutes. Although not shown, Test 10 (stress at 496 MPa) obtained tertiary creep at about 1200 minutes. The response curves do not exhibit a significant primary creep phase and most of the response is dominated by tertiary creep. This is typical of other superalloys. Test 20, creep at 896 MPa (130 KSI) shown in Figure 2, does not appear to be ordered with respect to the other tests; however, this could result from specimens being manufactured from different material heats.

If the deformation mechanism controlling the tensile tests and creep tests are the same, the controlled and observed variables from the two types of tests shown in Table 1 correspond to the same physical process. That is, the stable value of stress obtained in a strain rate controlled tensile tests should correspond to the creep stress with the same constant (secondary) creep rate as the tensile test. A plot of the observed and controlled variables for both the creep at tensile tests is given in Figure 4. Considering the data is over five decades of strain rate, there appears to be reasonable consistency between both types of tests. Tensile Tests 7 and 8 correspond very closely to creep Tests 19 and 18, respectively, as shown in Figure 4 and Table 1. Thus, it does appear that the same basic deformation mechanism controls both creep and tensile behavior between 482 and 1100 MPa (70 and 164 KSI) at 732°C (1350°F).

SECTION IV  
A MODEL BASED ON LIMITED DATA

Very early in the research program an estimate of the material constants for IN100 at 732°C (1350°F) was supplied for use on another project, Reference [8]. At that time, data from only three tests was available for use in determining the parameters in the constitutive equation. These included two creep tests, Tests 10 and 19, and the tensile component of Test 21. In order to obtain the maximum amount of information from the limited amount of data, a systematic method was developed to establish the material parameters. This method has subsequently been applied to Rene 95, Reference [9, 10], and is applied to IN100 in the next section using the full set of data available in Table 1.

The work described above yielded the conclusion that at least two tensile tests at different strain rates are required to determine the exponent  $n$  controlling strain rate sensitivity. Unfortunately, this information was not available, so the value  $n = 3.5$  was assumed based on previous experience. The rest of the parameters were then determined and the three curves were reproduced very well. The values of the coefficients are recorded in Table 2 for reference.

The prediction of the tensile response based on the above coefficients is shown in Figure 5 and is compared to the full set of experimental tensile data. It is clear that the assumption of  $n = 3.5$  was not adequate to predict the variation of stress level resulting from the threefold variation in strain rate. The value of  $n = 3.5$  corresponds to relatively small amount of strain rate sensitivity, whereas the IN100 response curves show a considerable amount of strain rate sensitivity. This result prompted a re-evaluation of the material parameters based on the full set of experimental data given in Table 1.

SECTION V  
RE-EVALUATION OF THE MATERIAL PARAMETERS

The first step in the re-evaluation of the material parameters is to determine  $n$  from the tensile data. Observe for Tests 2, 4, 6 and 8, when both the stress and strain rate are constant,  $Z$  must also be constant to satisfy Equation 2. Further, for short duration tests with no recovery, the material must be in a fully work hardened state to obtain the maximum value of stress. Thus, the hardness  $Z$  must have its maximum value  $Z_1$ . Rewriting Equation 2 for this steady flow condition gives

$$\ln \left[ - \ln \left( \frac{\sqrt{3} \dot{\epsilon}^p}{2 D_0} \right) \right] = - 2n [\ln Z_1 - \ln \sigma] + \ln \left( \frac{n+1}{2n} \right) \quad (5)$$

The left hand term of Equation (5) must be linear in  $\ln \sigma$  if it is an adequate representation of the experimental data. A plot of the data in the form of Equation (5) is shown in Figure 5. Points from Tests 2, 4 and 6 are almost linear, whereas, the data point from Test 8 is considerably below the line. Referring to Figure 4, it can be seen that Tests 2, 4 and 6 are well above the creep domain; however, Test 8 overlaps with the creep response region and recovery is most likely present. Thus, data point from Test 8 was excluded and a slope of  $n = 0.70$  was determined and  $Z_1$  was calculated to be 6693 MPa (1015.0 KSI).

In the absence of hardening recovery, Equation (3) is the first order linear differential equation

$$dZ = m (Z_1 - Z) dW^p \quad (6)$$

that can be integrated to give

$$\ln(Z_1 - Z) = \ln(Z_1 - Z_0) - mW^p \quad (7)$$

upon defining  $Z_0$  as the initial value of hardness  $Z$ . Using Equation (') with the measured values of  $\dot{\epsilon}^P$  and  $\sigma$ , the history of  $Z$  can be calculated for any experiment. Plotting  $\ln(Z_1 - Z)$  against  $W^P$ , as shown in Figure 7, for only Tests 2 and 4 to guarantee the absence of hardening recovery, the constants  $m = 2.57$  and  $Z_0 = 6304$  MPa (915.0 KSI) were determined. Thus, the parameters  $n$ ,  $Z_1$ ,  $Z_0$  and  $m$  can be easily evaluated from tensile response data.

During secondary creep (when the strain rate is approximately constant) the value of  $Z$  must be constant. Thus the hardening rate equation for secondary creep becomes

$$\dot{Z} = 0 = m(Z_1 - Z)\dot{W}^P - AZ_1 \left(\frac{Z - Z_2}{Z_1}\right)^r \quad (8)$$

The stationary values of  $Z$  correspond to stable microstructure during secondary creep in each test.

Using the corresponding values of stress and secondary creep rate, the stationary value of  $Z$  can be determined from Equation (4) as shown in Table 3. Since the lowest calculated stationary value of  $Z$  is 4568 MPa (663 KSI), the minimum value of  $Z$  was assumed to be  $Z_2 = 4134$  MPa (600 KSI). A plot of the data in Table 3 using the variables in  $\ln[m(Z_1 - Z)W^P]$  and  $\ln[(Z - Z_2)/Z_1]$  is shown in Figure 8. The large amount of scatter in Tests 14 and 15, creep at 620 MPa (90 KSI) make it very difficult to accurately determine the parameters  $A$  and  $r$  from Equation 8. A linear representation (solid line) was assumed as shown in Figure 8; and, the values  $r = 2.66$  and  $A = 1.9 \times 10^{-3} \text{ sec}^{-1}$  were calculated. However, it is possible that a bilinear representation (dashed lines in Figure 8) is the correct model. This type result was obtained for Rene 95 at 649°C (1200°F), Reference [10]. The upper curve corresponding to lower values of creep stress, represents a large variation in the stable value of  $Z$  for relatively small change in the creep stress. Further, this

result implies that the initial value of  $Z$  may be much lower than 6304 MPa (915 KSI) as determined in Figure 7 by extrapolation to zero plastic work. Unfortunately, the data is inconclusive on this aspect of the response.

A list of the parameters determined from the full set experimental data is also given in Table 2. The wide variation in the values arise from the difference of the value for  $n$ . It can be seen from Equation (2) that the value of  $n$  affects the value of the  $Z$  history calculated from the data, and therefore affects all the parameters in the hardening rate equation; i.e.,  $Z_0$ ,  $Z_1$ ,  $Z_2$ ,  $m$ ,  $A$  and  $r$ .

The revised set of parameters was used to calculate the tensile and creep response of the material. The calculated and experimental tensile response is shown in Figure 9. It can be seen that the calculated rate sensitivity of the tensile response is much better than in the earlier results, Figure 5. The response compares very well for Tests 2 and 6; and is a little high for Test 8. This corresponds to a predicted value of  $Z$  that is above the actual value required plastic flow under the test conditions.

The calculated creep response is shown in Figure 10 with the creep curves determined in the experimental program. At the lower values of stress the agreement is good; however, at the higher values of stress the shape of the experimental and calculated curves do not agree. The experimental results are essentially tertiary creep whereas the model was developed to predict primary and secondary creep. This clearly shows that tertiary creep should be included in the constitutive model for application to IN100. Even though the calculated and experimental creep response for Tests 14, 15 and 10 appear to agree quite well, in these tests the calculated value for the secondary creep rate is below the experimental value. This also indicates that the value of  $Z$  is too high for the lowest value of stress.

The predicted stress relaxation response to a strain of 0.4% is shown in Figure 11 for time up to 1000 minutes. The overall level of the predicted response was good; however, the initial predicted rate of stress relaxation was too low. Also the model did not predict the change in the rate of relaxation starting at 500 minutes. It is possible that this change in response could be associated with the tertiary creep response.

The measured response to the combined strain history, Test 21, is shown in Figure 12 along with the calculated result. The strain history included reverse plastic flow with stress relaxation in compression. The model, which was limited to isotropic hardening, predicted the total stress range and total strain range of the hysteresis loop very well. The prediction of the shape of the compression side of the loop indicates that hardening rule may need some improvement. However, this is not unexpected since the coefficients in the model were determined from tests loaded only in tension.

## SECTION VI DISCUSSION OF THE RESULTS

In general the calculated response compares reasonably well with the observed experimental results. Most of the main features, such as the strain rate sensitivity in the tensile tests, low stress or short time creep response, and amount of stress relaxation up to 500 minutes were predicted adequately. The long time stress relaxation response and the tensile, tertiary creep response was not adequately predicted. In all cases, the observed change in response appeared late in the history or after significant deformation so that the onset of microstructural damage could have been a major contributing factor. This implies that the constitutive theory may need the modifications in Reference [6], to include damage in the representation.

A second modification may be necessary to adequately predict the response and very low values of stress. In both the tensile and creep calculations for low stress the value of hardness  $Z$  was too high. This produced an inelastic strain rate that was lower than the observed experimental value. The correct value of  $Z$  in these situations is much lower than the initial value of hardness,  $Z_0 = 6304$  MPa (915 KSI), determined from the high rate tensile test data by extrapolation to zero plastic work. Hence, it appears that the actual initial value for hardness is much lower than 6304 MPa (915 KSI) and the rate of hardening,  $Z$ , is very high initially. This result is essentially the same as observed in Rene 95 at 649°C (1200°F), Reference [10]. Further, Moteff, Reference [11], has shown that the initial development of the microstructure generally occurs rapidly in most metals. Thus the above conclusion appears to be reasonably consistent with observed response on both the microscopic and macroscopic levels.

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TABLE 1. SUMMARY OF THE EXPERIMENTAL PROGRAM

Test No.	Type of Test	Spec. No.	Date	Source	Control Variable	Observed Variable	Comments
1	Temp. Profile	T3	7/79	Mar Test	T=1350°F		
2	Tensile	G1	1980	AFWAL	$\dot{\epsilon}=1.42 \times 10^{-3} \text{ s}^{-1}$	=1116 MPa (162 KSI)	
3	Tensile	T1	4/78	AFWAL	$X=8.33 \times 10^{-4} \text{ s}^{-1}$		Const. Hd. Rate
4	Tensile	T3	7/79	Mar Test	$\dot{\epsilon}=8.33 \times 10^{-4} \text{ s}^{-1}$	=1068 MPa (155 KSI)	
5	Tensile	G2	1980	AFWAL	$\dot{\epsilon}=6.33 \times 10^{-5} \text{ s}^{-1}$	=951 MPa (138 KSI)	
6	Tensile	ENTEN 1	1980	AFWAL	$\dot{\epsilon}=5.5 \times 10^{-5} \text{ s}^{-1}$	=978 MPa (142 KSI)	
7	Tensile	GT7	12/80	Mar Test	$\dot{\epsilon}=1.33 \times 10^{-5} \text{ s}^{-1}$	=889 MPa (129 KSI)	
8	Tensile	ENTEN 4	1980	AFWAL	$\dot{\epsilon}=6.67 \times 10^{-6} \text{ s}^{-1}$	=841 MPa (122 KSI)	
9	Tensile	G3	1980	AFWAL	$\dot{\epsilon}=1.67 \times 10^{-6} \text{ s}^{-1}$		
10	Creep	C1	9/78	AFWAL	$\sigma=496 \text{ MPa}$ (72 KSI)	$=1.8 \times 10^{-8} \text{ s}^{-1}$	
11	Creep	C2	3/78	AFWAL	$\sigma=496 \text{ MPa}$ (72 KSI)		Ext. Slip
12	Creep	ENTEN 6	4/78	Mar Test	$\sigma=620 \text{ MPa}$ (90 KSI)		Temp. Failure
13	Creep	ENTEN 3	6/80	Mar Test	$\sigma=627 \text{ MPa}$ (91 KSI)		Temp. Failure
14	Creep	GT6	10/80	Mar Test	$\sigma=627 \text{ MPa}$ (91 KSI)	$=5.0 \times 10^{-8} \text{ s}^{-1}$	
15	Creep	GT5	11/80	Mar Test	$\sigma=620 \text{ MPa}$	$=1.2 \times 10^{-7} \text{ s}^{-1}$ (90 KSI)	

TABLE 1. SUMMARY OF THE EXPERIMENTAL PROGRAM (CONT.)

Test No.	Type of Test	Spec. No.	Date	Source	Control Variable	Observed Variable	Comments
16	Creep	C4	7/80	Mar Test	$\sigma=696$ MPa (101 KSI)		Relax. Obs.
17	Creep	ENTEN 5	4/80	Mar Test	$\sigma=758$ MPa (110 KSI)		Temp. Failure
18	Creep	GT4	11/80	Mar Test	$\sigma=827$ MPa (120 KSI)	$=4.5 \times 10^{-6} s^{-1}$	
19	Creep	C5	7/79	Mar Test	$\sigma=875$ MPa (127 KSI)	$=7.74 \times 10^{-6} s^{-1}$	
20	Creep	ENTEN 2	4/80	Mar Test	$\sigma=896$ MPa (130 KSI)	$=4.17 \times 10^{-6} s^{-1}$	
21	Combined History	C3	7/79	Mar Test	$\dot{\epsilon}=4.0 \times 10^{-3}$		Hyst. Loop

TABLE 2. COEFFICIENTS FOR IN100 AT 1350°F  
DETERMINED FROM THE LIMITED AND FULL DATA SETS.

Material Parameter	Description	Limited Data Set	Full Data Set
E	Elastic modulus	$1.72 \times 10^5$ MPa ( $25.0 \times 10^3$ KSI)	$1.50 \times 10^5$ Mpa ( $21.3 \times 10^3$ KSI)
n	Strain rate exponent	3.5	0.7
$D_0$	Limiting value strain rate	$10^4 \text{ sec}^{-1}$	$10^4 \text{ sec}^{-1}$
$Z_0$	Initial value of hardness	1546 MPa (224.4 KSI)	6304 MPa (915.0 KSI)
$Z_1$	Maximum value of hardness	1733 MPa (251.5 KSI)	6993 MPa (1015.0 KSI)
$Z_2$	Minimum value of hardness	689 MPa (100.0 KSI)	4134 MPa (600.0 KSI)
m	Hardening rate exponent	$25.9 \text{ MPa}^{-1}$ ( $3.75 \text{ KSI}^{-1}$ )	$17.7 \text{ MPa}^{-1}$ ( $2.57 \text{ KSI}^{-1}$ )
A	Hardening recovery coefficient	$8.77 \times 10^{-4} \text{ sec}^{-1}$	$1.9 \times 10^{-3} \text{ sec}^{-1}$
r	Hardening recovery exponent	4.30	2.66

TABLE 3. EVALUATION OF THE HARDNESS VARIABLE  
Z FOR THE CONDITIONS OF SECONDARY CREEP

Test No.	Stress , MPa (KSI)	Min. Creep Rate $\dot{\epsilon}$ min <sup>-1</sup> sec <sup>-1</sup>	Hardness Z, MPa (KSI)
10	496 (72)	$1.8 \times 10^{-8}$	4568 (663)
14	627 (91)	$5.0 \times 10^{-8}$	5615 (815)
15	620 (90)	$1.2 \times 10^{-7}$	5422 (787)
18	827 (120)	$4.5 \times 10^{-6}$	6477 (940)
19	827 (127)	$7.7 \times 10^{-6}$	6731 (977)
20	896 (130)	$4.2 \times 10^{-6}$	7028 (1020)

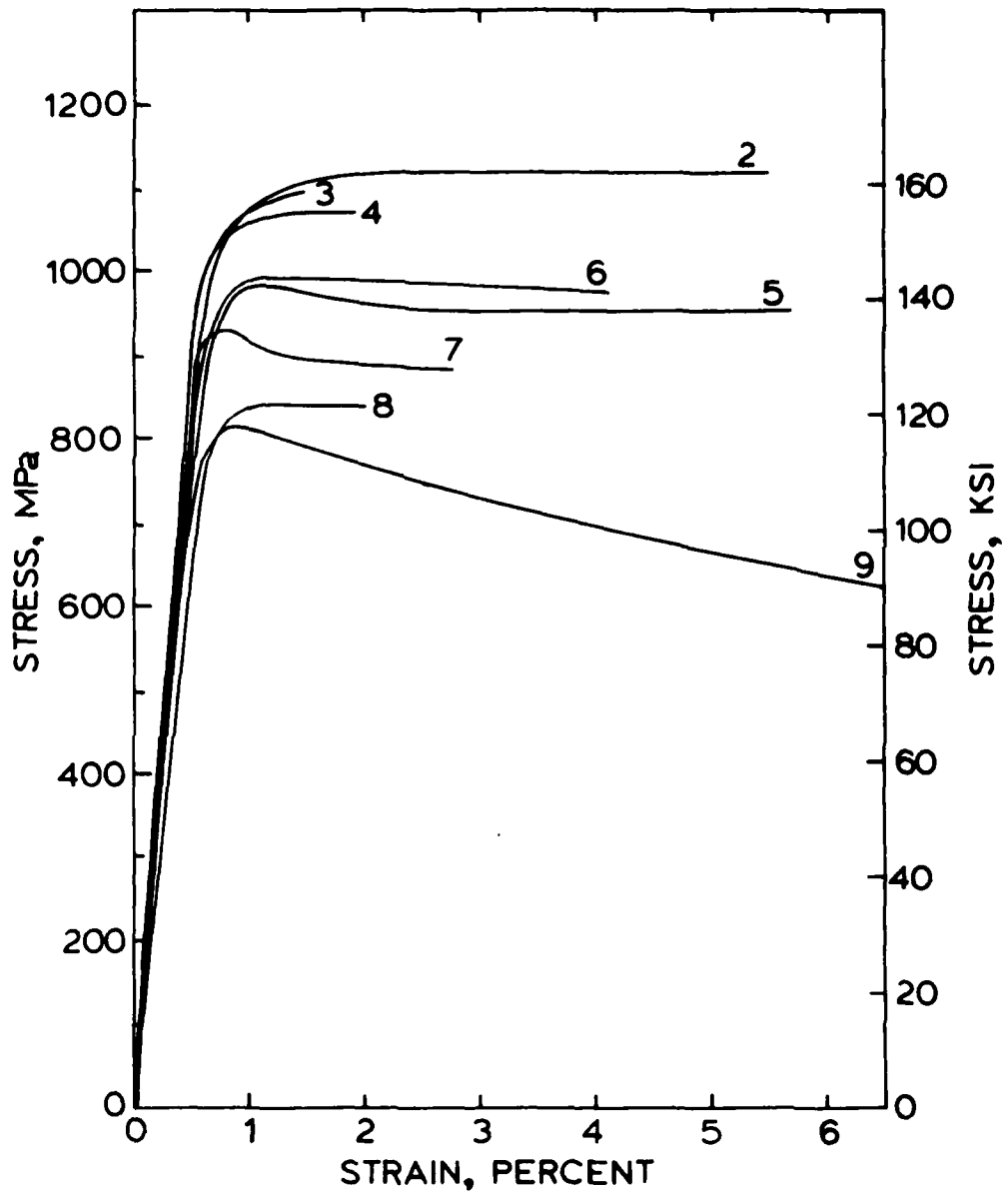


Figure 1. Tensile response of IN100 at 732°C to eight values of strain rate from  $1.42 \times 10^{-3} \text{ sec}^{-1}$  to  $1.67 \times 10^{-6} \text{ sec}^{-1}$ . Test numbers refer to Table 1.

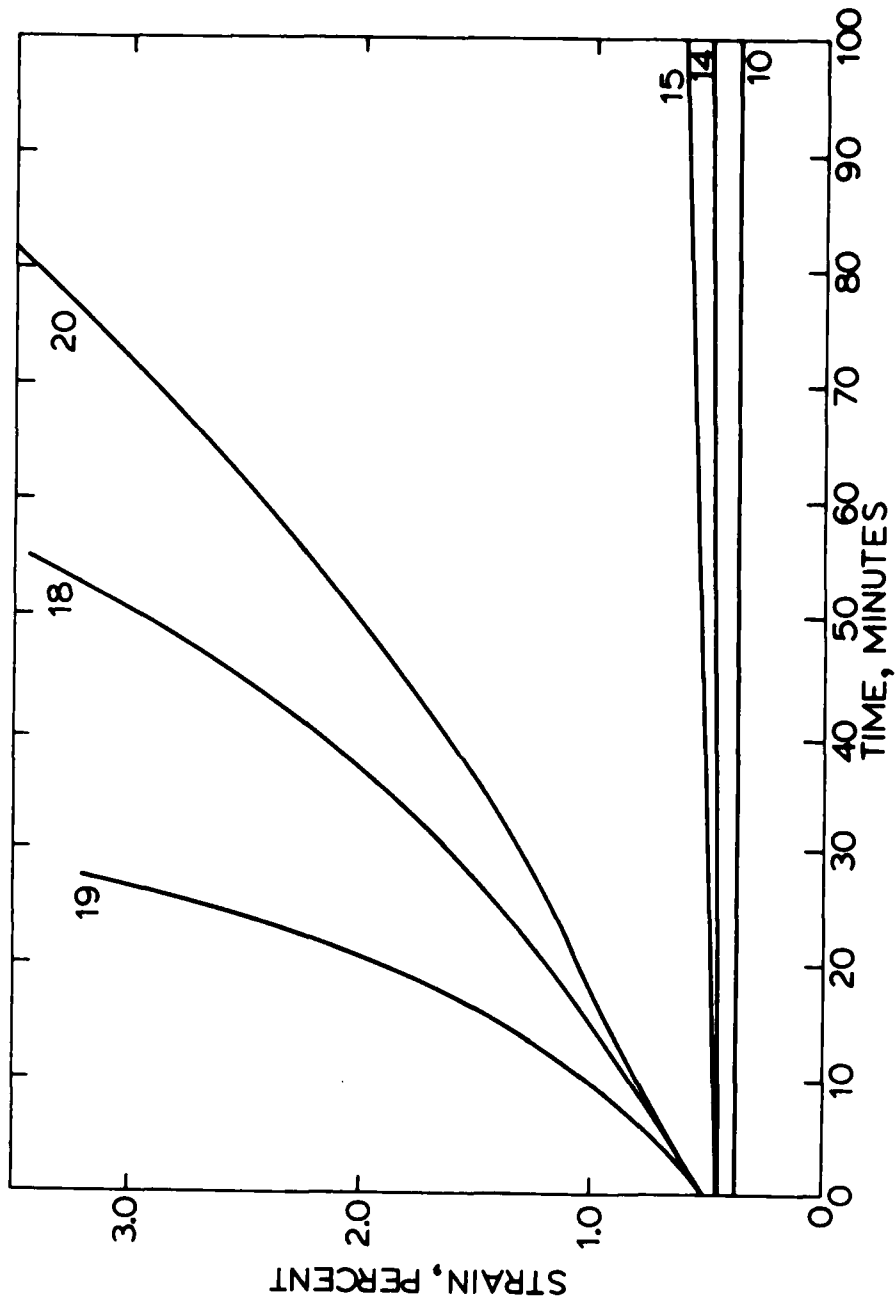


Figure 2. Short time creep response of IN100 at 732°C to five values of stress from 496MPa to 875MPa. Test numbers refer to Table 1.

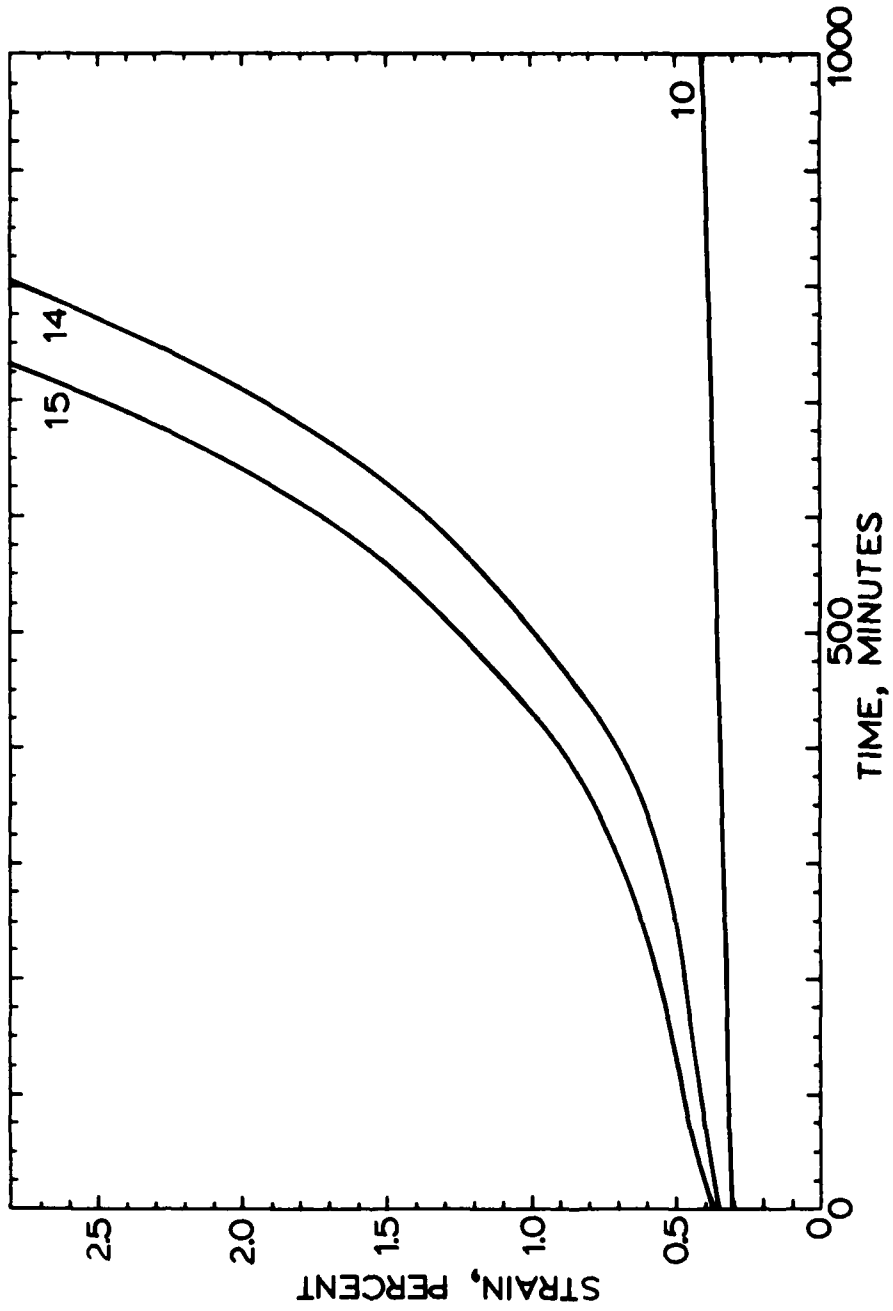


Figure 3. Long time creep response of IN100 at 732°C to two values of stress, 620MPa and 496MPa. Test numbers refer to Table 1.

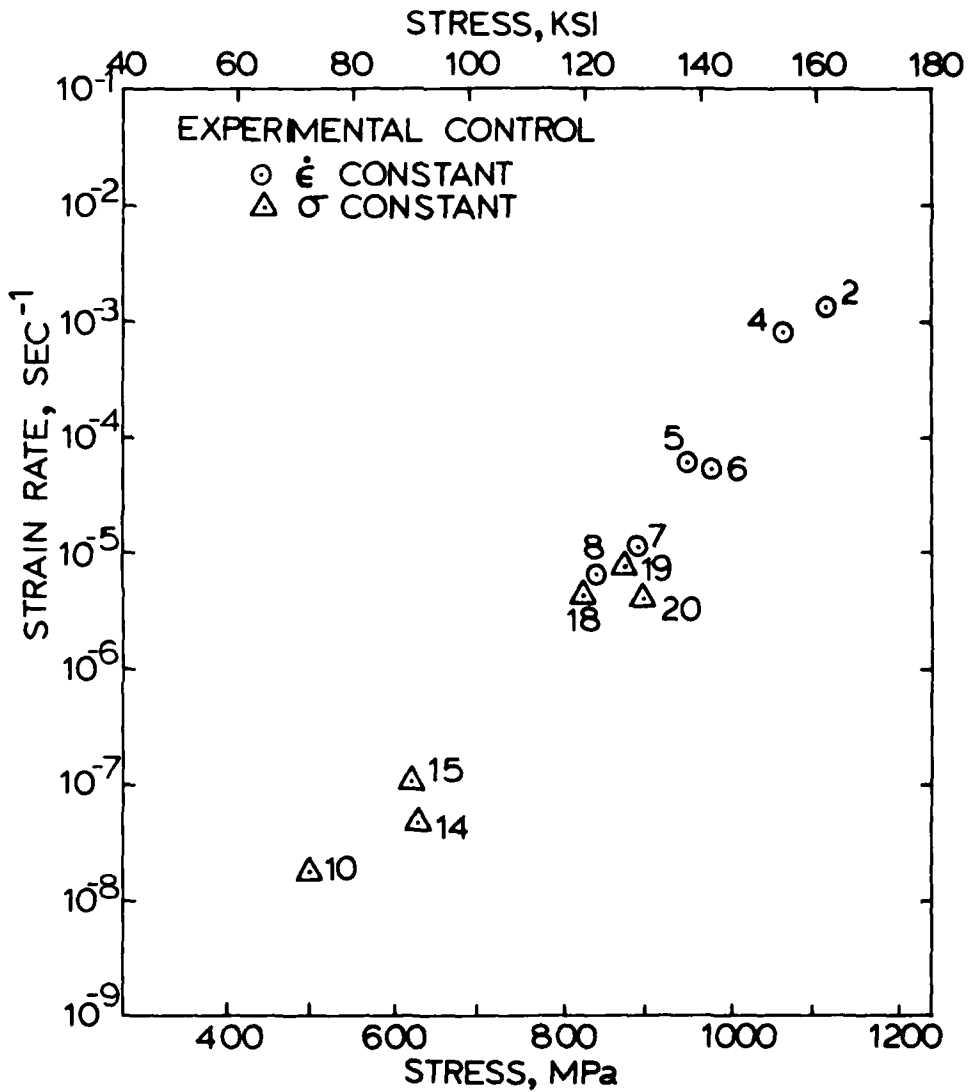


Figure 4. Stable values of stress and strain rate from both tensile and creep experiments. Test numbers refer to Table 1.

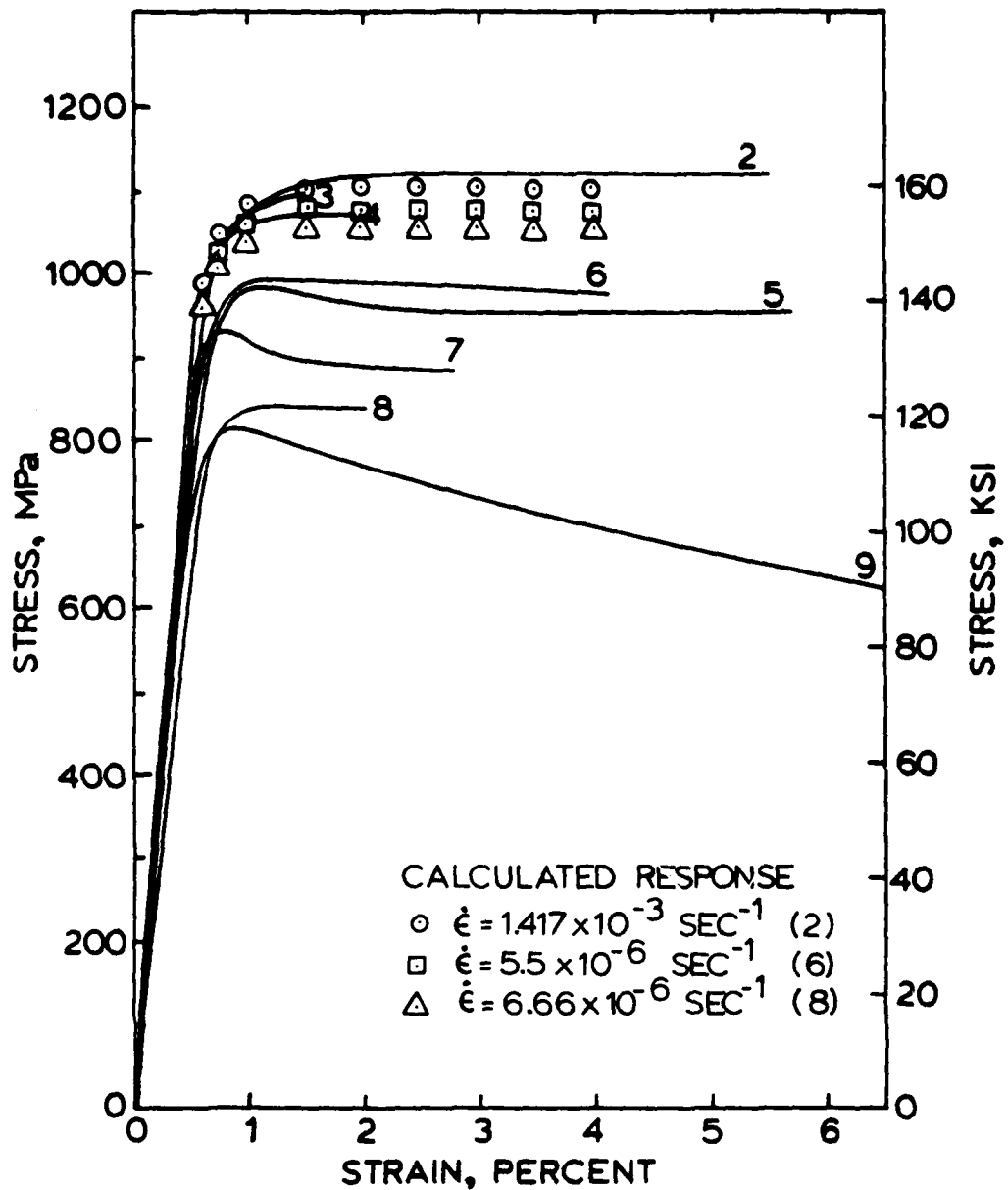


Figure 5. Experimental tensile response of IN100 at 732°C. compared to calculated response using assumed value of n. Test numbers refer to Table 1.

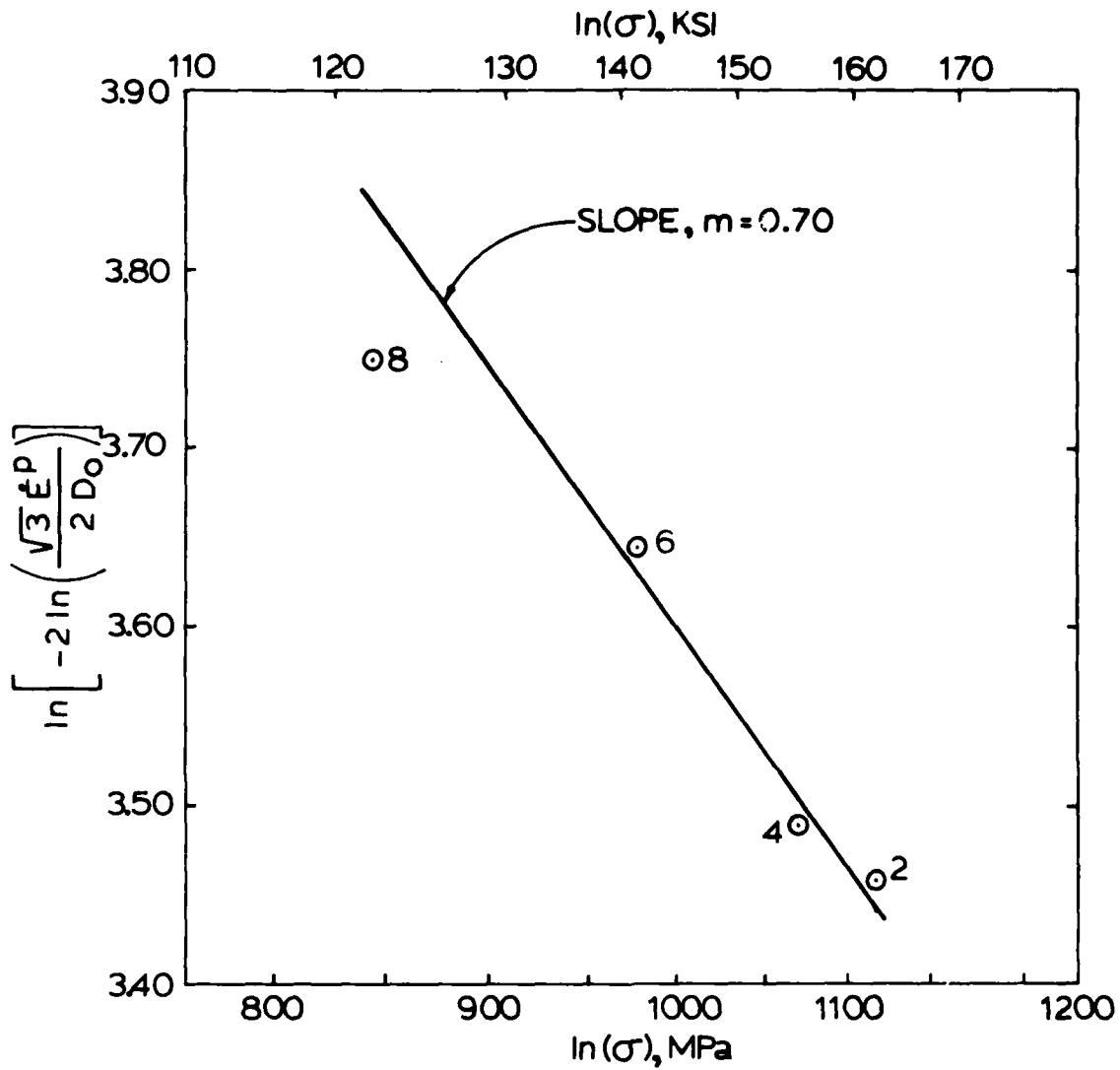


Figure 6. Evaluation of strain rate exponent  $n$  for IN100 at  $732^{\circ}\text{C}$ .  
 Test numbers refer to Table 1.

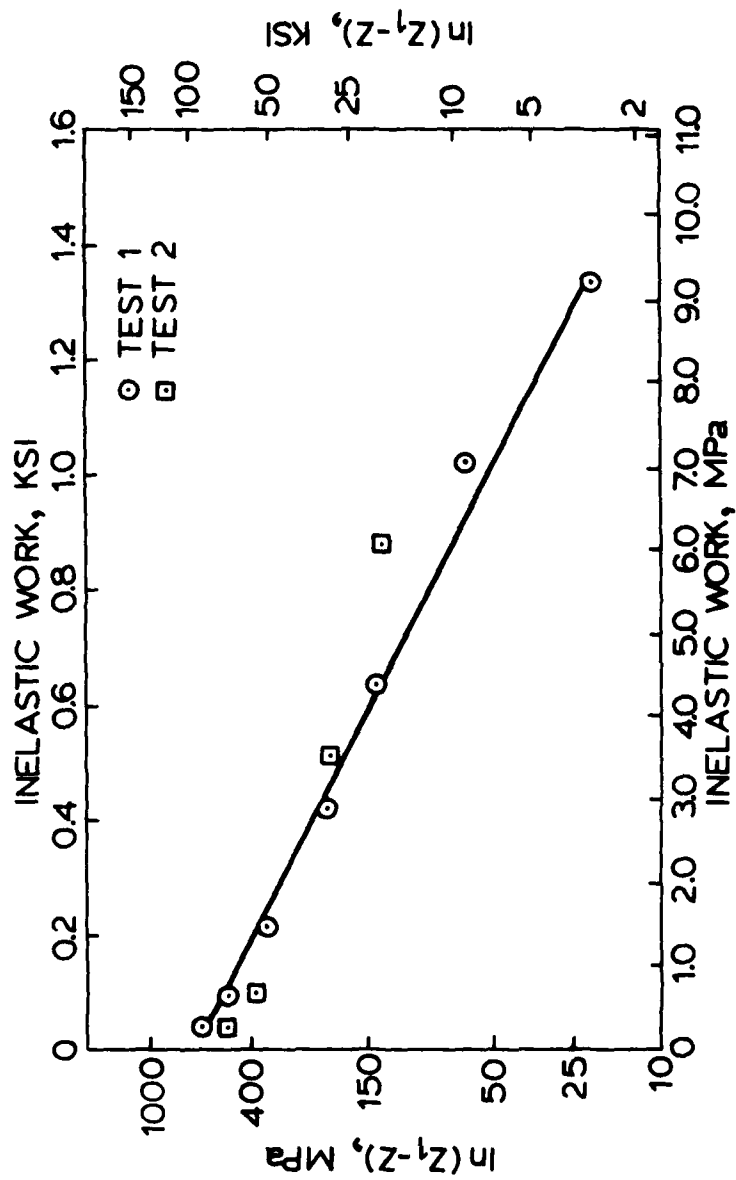


Figure 7. Evaluation of hardening parameters for In100 at 732°C. Test numbers refer to Table 1.

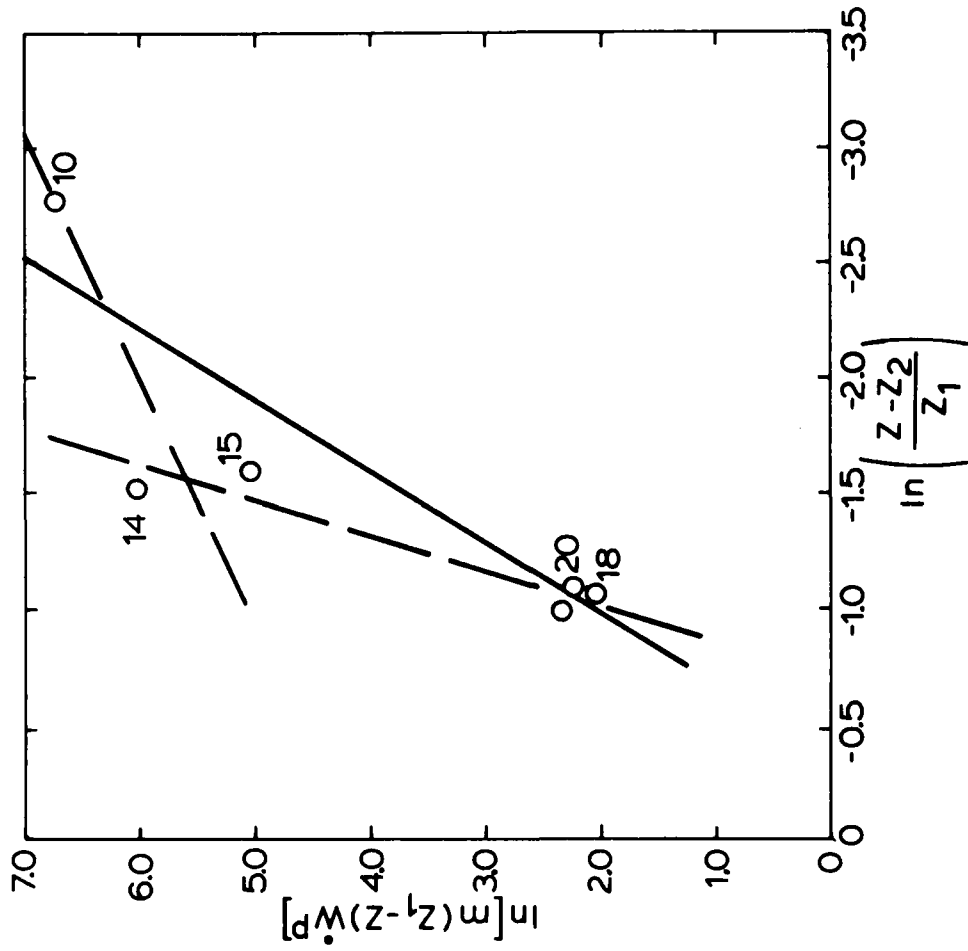


Figure 8. Evaluation of the hardening recovering parameters for IN100. Test numbers refer to Table 1.

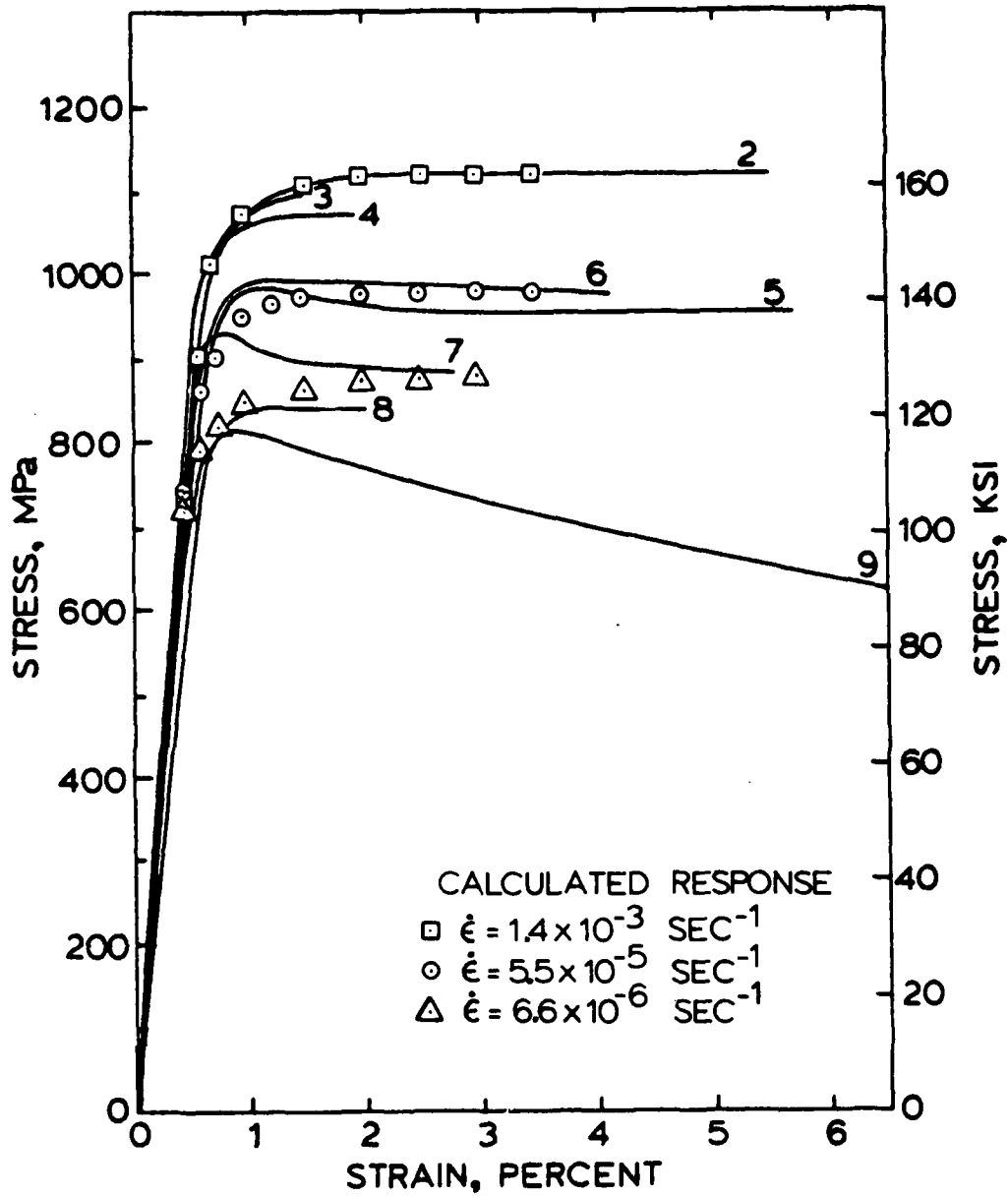


Figure 9. Calculated and experimental tensile response of IN100. using the revised material parameters. Test numbers refer to Table 1.

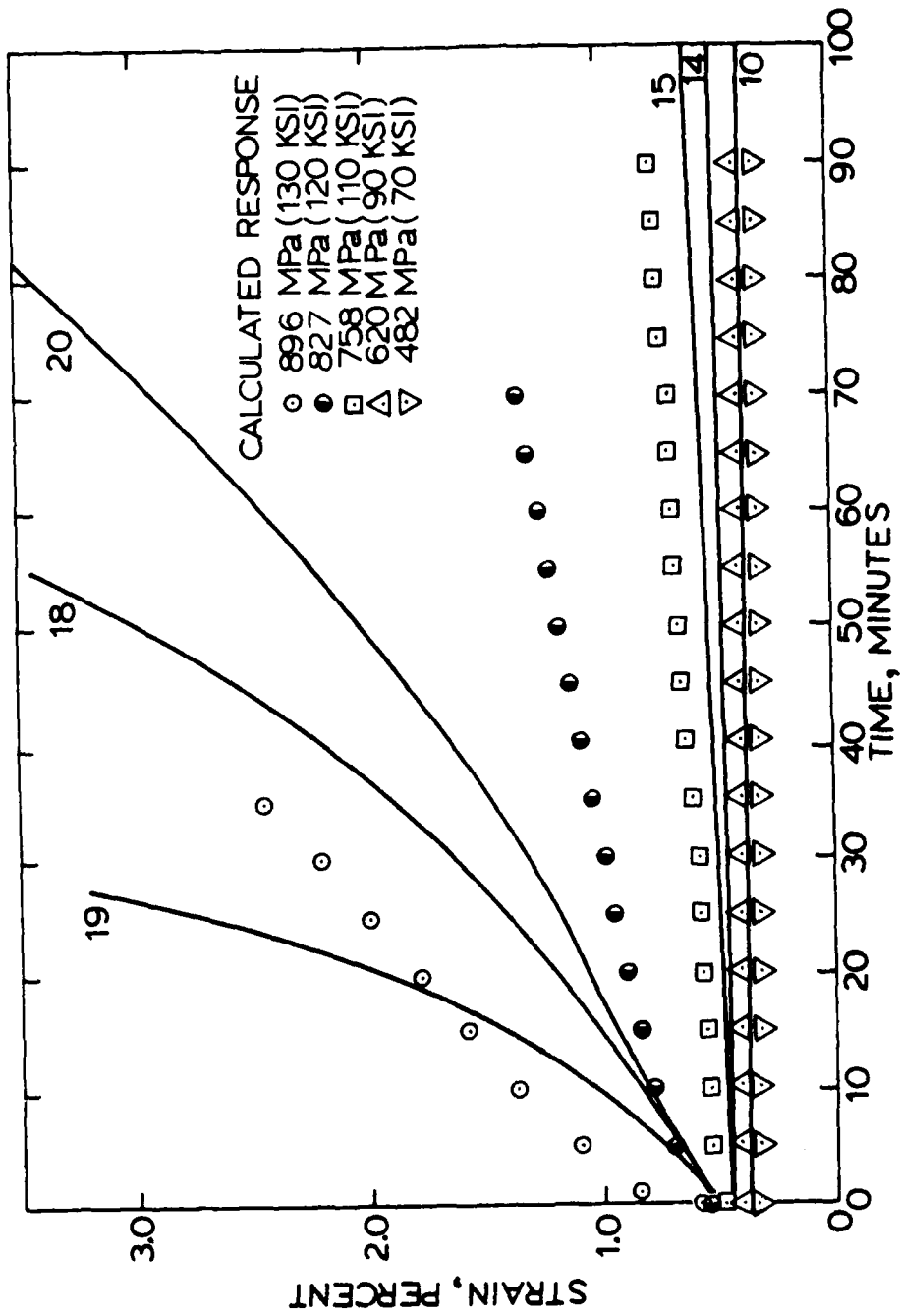


Figure 10. Calculated and experimental creep response for IN100 using the revised material parameters. Test numbers refer to Table 1.

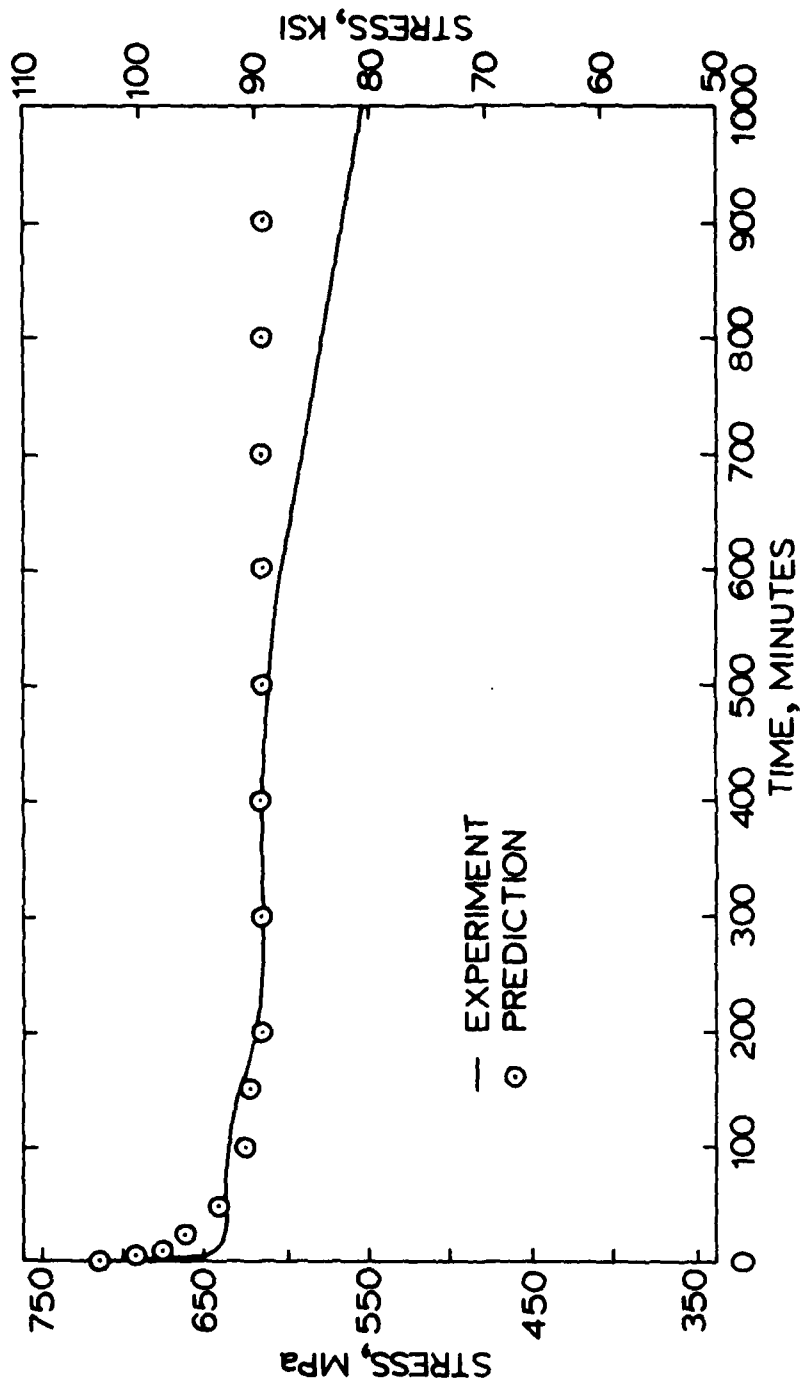


Figure 11. Predicted and experimental stress relaxation response for IN100 for Test 16 in Table 1.

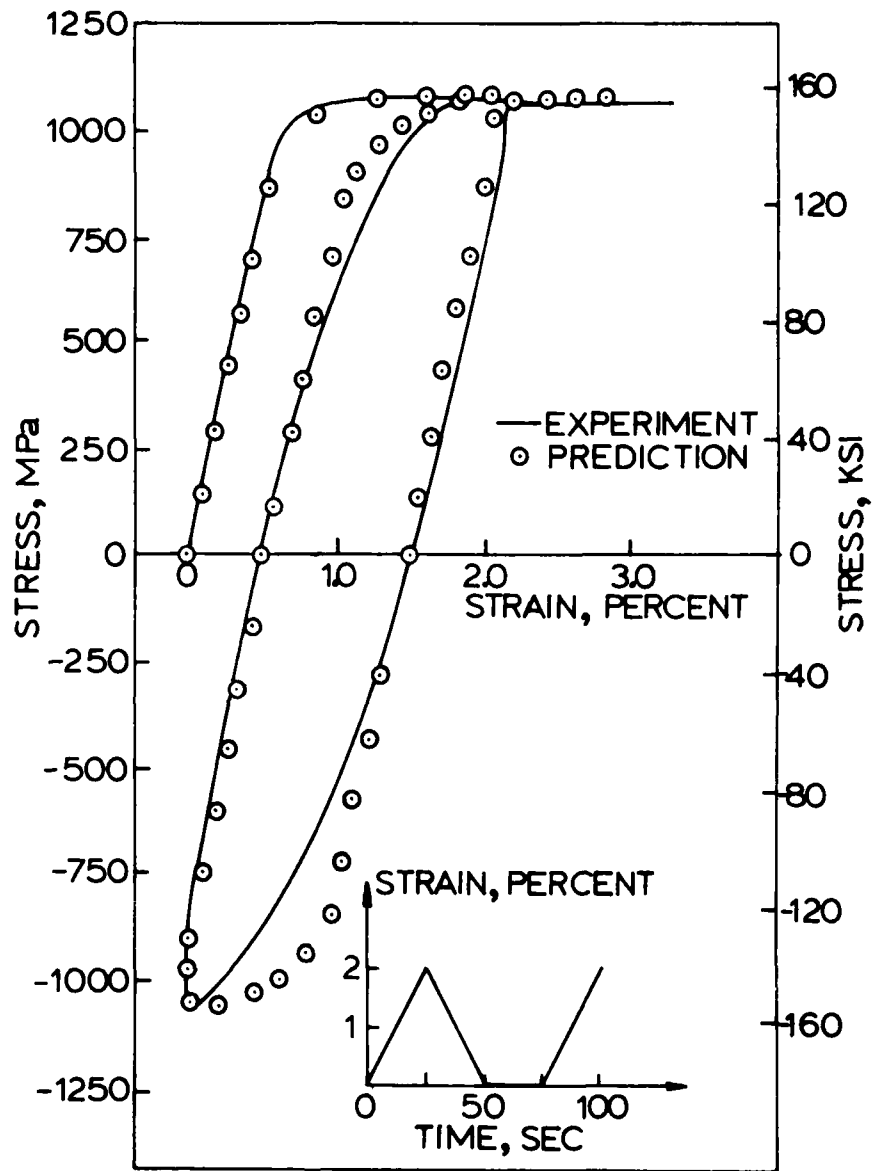


Figure 12. Predicted and experimental response of a fatigue loop with stress relaxation in compression. Test 21 in Table 1.

