ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Technical Report

THE SHEAR MODULI OF INCONEL-X ALLOY AT TEMPERATURES FROM -120°F TO 1200°F

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ERI Project 2629

ASSOCIATED SPRING CORPORATION
PLYMOUTH, MICHIGAN

March 1958

Reprinted May 1958

NOTATIONS

σ_n	Unit normal stress on plane perpendicular to axis of test samples.
P	Axial load in lb.
A	Cross-sectional area of test samples in sq in.
ϵ_n	Unit normal strain.
E	Young's modulus of elasticity in psi.
G	Shear modulus of elasticity in psi.
I_o	Moment of inertia of torsional pendulum in lb-in./sec^2.
k	Torsional spring constant in lb-in.
d	Diameter of test samples in in.
I_p	Polar moment of inertia of cross-sectional area of test samples in in.^{4}
ℓ_e	Equivalent length of torsional spring in in.
$\ddot{\theta}$	Angular acceleration in radians per sec^2.
θ	Angular displacement in radians.
C	Constant depending upon initial conditions.
p	Circular frequency of motion.
ν	Poisson's ratio.
τ	Period of oscillation in sec.
ℓ_f	Free length of torsional spring in in.
δ	Additional length of torsional spring due to end effects.

ABSTRACT

Shear moduli of elasticity were determined for ten samples of Inconel X alloy over a temperature range of 70 to 1200°F. Duplicate specimens of heat-treated wire of 0.130-, 0.198-, and 0.298-in. diameter, and nonheat-treated wire of 0.198-, and 0.298-in. diameter were tested. In addition the heat-treated wire of 0.198-in. diameter was tested at subzero temperatures down to -120°F.

Young's moduli of elasticity were determined at room temperature on duplicate samples of the heat-treated wire of 0.298-in. diameter. Poisson's ratio was evaluated on this material, assuming a perfectly elastic isotropic material.

OBJECTIVE

The purpose of this investigation was to determine shear moduli of elasticity and Young's moduli of elasticity for ten samples of Inconel X alloy.

SUMMARY

Shear moduli of elasticity were determined on ten samples of Inconel X alloy over the temperature range of 70 to 1200°F. Six of these samples had been aged for 16 hours at 1325°F and the other four were in the nonaged condition. One specimen of aged material was tested at subzero temperatures down to -120°F. Young's modulus of elasticity was determined on the 0.298-in.-diameter wire in the aged condition at room temperature.

The elastic shear modulus of the aged material varies linearly with temperature up to 1000°F. The moduli obtained on the nonaged material were lower than those obtained on the aged material on initial testing but were essentially the same as those on the aged material at room temperature after testing at 1200°F.

One sample of aged 0.198-in.-diameter wire was tested at subzero temperatures down to -120°F. The resulting shear moduli values follow the straight line relationship noted at elevated temperatures.

MATERIALS

The materials used in this investigation were of the following composition:

	Wire Size		
	0.130	0.198	0.298
C	0.06	0.04	0.05
Mn	0.63	0.55	0.52
Si	0.35	0.30	0.35
Ni	72.85	73.15	73.35
Cr	15.0	15.48	15.44
Cu	—	0.06	0.05
Fe	7.2	7.13	6.59
Ti	2.2	2.24	2.21
Cb + Ta	—	0.81	0.74
Al	—	0.58	0.67

EXPERIMENTAL PROCEDURE

Stress-strain curves for the determination of Young's modulus of elasticity on the 0.298-in.-diameter wire were obtained using SR-4 strain gages. The results obtained on the smaller wires were unreliable due to the excessive curvature of the surface for the size of strain gages employed.

The elastic shear moduli were obtained from torsional pendulum test samples acting as torsional springs. The moment of inertia was 0.951 lb in. sec^2 for the 0.130-in. and 0.198-in.-diameter specimens and 4.353 lb in. sec^2 for the 0.298-in.-diameter specimen. With lengths of test samples of approximately 10.3 in., this gave periods of oscillations ranging from .45 to 1.2 sec, which allowed measurements of periods by means of a stop watch covering 100 complete oscillations. In each case three separate and consecutive readings were made, and the accuracy was found to be about 0.001 sec on the period. Details of the attachment of the test sample to the pendulum and to the foundation are shown in Fig. 1. This design was adopted to facilitate the insertion of the test samples into the furnace. The use of a piece of ferritic stainless steel of 0.75-in.-diameter shrunk on to both ends of the test sample made it possible to determine the effective length of the sample with great accuracy.

The amplitude of oscillations were held within 10-15° to each side. Within this range the period was found to be independent of amplitude. Figure 2 shows the assembly of the pendulum, test sample, and chucks, with the thermocouples attached to the sample for temperature readings during testing.

Figure 3 shows the furnace used for tests at elevated temperatures with the sample and the pendulum in place. The length of the furnace was 36 in. and its inside diameter 2 in. The furnace was wired with three coils in series. The variable outside shunt was connected across the terminals of the upper two coils, thus providing a means of regulating the temperature distribution in the furnace at various temperature levels.

Maximum temperature variation in the furnace over the length of the test sample was found to be about 20°F. Due to the linear variations of shear modulus with temperature, a mean temperature can be used, and the mean temperature can be determined within ± 2°F.

The subzero tests were accomplished by constructing an insulated chamber as shown in Figs. 4 and 4a and utilizing liquid nitrogen for lowering the temperature. The liquid nitrogen was introduced into the space surrounding the test sample and then allowed to vaproize completely prior to the test to maintain a constant weight and, therefore, constant moment of inertia of the of the pendulum. The test temperatures were determined with iron-constantan thermocouples.

ANALYSIS OF DATA

Figure 5 shows the stress-strain diagram obtained from the two samples of heat-treated material of 0.298-in. diameter, tested at room temperature. The tensile stress is assumed to be uniformly distributed across the cross section; hence

$$\sigma_n = \frac{P}{A} , \tag{1}$$

all other stress components being equal to zero. Hooke's law then becomes

$$\sigma_n = E \times \epsilon_n \quad \text{or} \quad E = \frac{\sigma_n}{\epsilon_n} , \tag{2}$$

i.e., the slope of the stress-strain curve.

The equation of motion for a torsional pendulum is given by

$$I_o \ddot{\Theta} + k\Theta = 0 , \tag{3}$$

where, for a circular shaft,

$$k = \frac{G I_p}{\ell_e} = \frac{G\pi d^4}{32\ell_e} \tag{4}$$

Depending upon the initial conditions, the angular displacement of a pendulum as a function of time can therefore be expressed as

$$\Theta = C \sin pt , \tag{5}$$

where

$$p^2 = \frac{k}{I_o} = \frac{G\pi d^4}{32 I_o \ell_e} . \tag{6}$$

For this harmonic motion the period of oscillation is

$$\tau = 2\pi\sqrt{\frac{I_o}{k}} \quad . \tag{7}$$

From Eq. (7),

$$k = I_o\left(\frac{2\pi}{\tau}\right)^2 \tag{8}$$

Equating Eq. (4) and (8),

$$\frac{G\pi d^4}{32\ell_e} = I_o\left(\frac{2\pi}{\tau}\right)^2 \quad , \tag{9}$$

or

$$G = \frac{128\,\pi\,\ell_e}{d^4\tau^2}\, I_o \quad .$$

Where

$$\ell_e = \ell_f + \delta \quad ,$$

and δ is determined from end conditions of the test sample.

Since, from Eq. (9), G is a function of diameter to the fourth power, small variations in the diameter will become significant. The following average diameters were obtained from measurements of test samples.

Number	Nominal Diam, in.	Actual Diam, in.
1	.298	.2975
2	.298	.2975
1	.198	.1994
2	.198	.1997
1	.130	.1301
6	.130	.1301

These diameters have been used in the evaluation of the elastic shear moduli.

The effect of temperature on the shear modulus of Inconel X are shown in Figs. 6,7, and 8. The results obtained on the 0.298-in. wire in both the aged and nonaged condition are shown in Fig. 6. The results of tests on nonaged material are somewhat erratic and lower than those obtained from tests on the aged material. Sample No. 2 of the nonaged material was tested up to

600°F, cooled down overnight, and then heated to 900°F the next morning for further evaluation. The shear modulus obtained on this specimen from 900 to 1200°F then equaled the values obtained on the aged material. The modulus on this specimen at room temperature after testing at 1200°F was also equal to the room-temperature modulus of the aged material. This indicates that age-hardening of the alloy is taking place during testing. The small difference in the results on the check samples of aged material could be due to either difference in the samples themselves, experimental error, or both.

Figure 7 shows the results on the 0.198-in. wire. The wire in the nonaged condition also produced erratic results while the age material only showed a slight difference between the check samples. This size wire was tested down to -120°F and shows a continuation of the straight line relationship existing at elevated temperatures.

Figure 8 shows the results obtained on the 0.130-in.-diameter wire of aged material. No material of this size was tested in the nonaged condition.

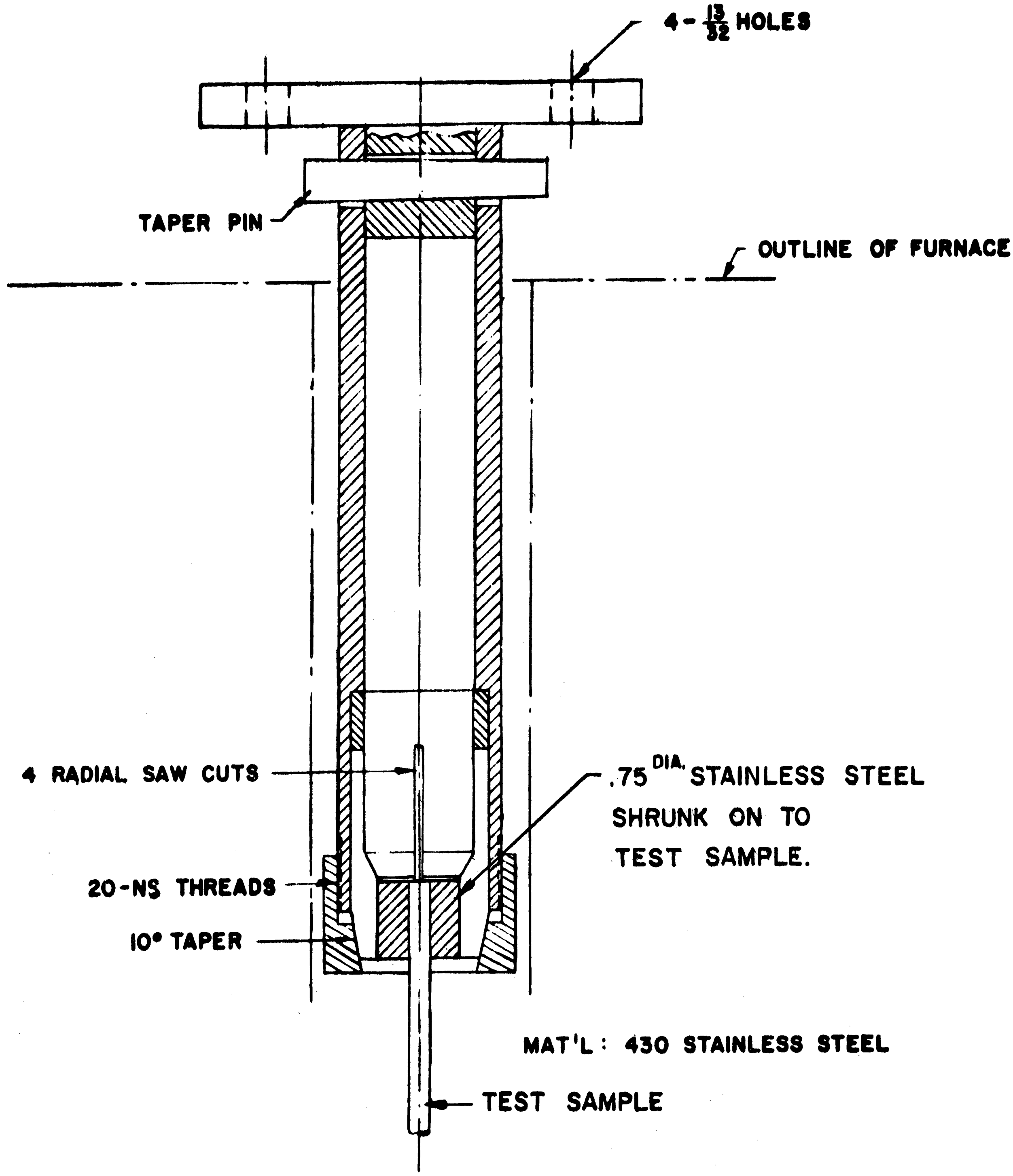

Fig. 1. Detail of chuck for torsional pendulum.

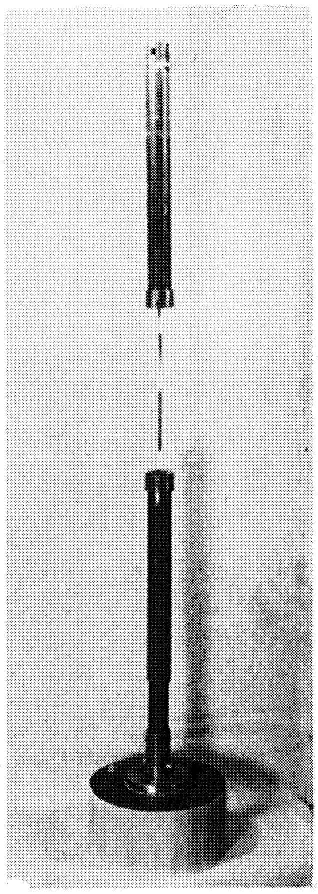

Fig. 2. Pendulum, test sample, and chucks assembled.

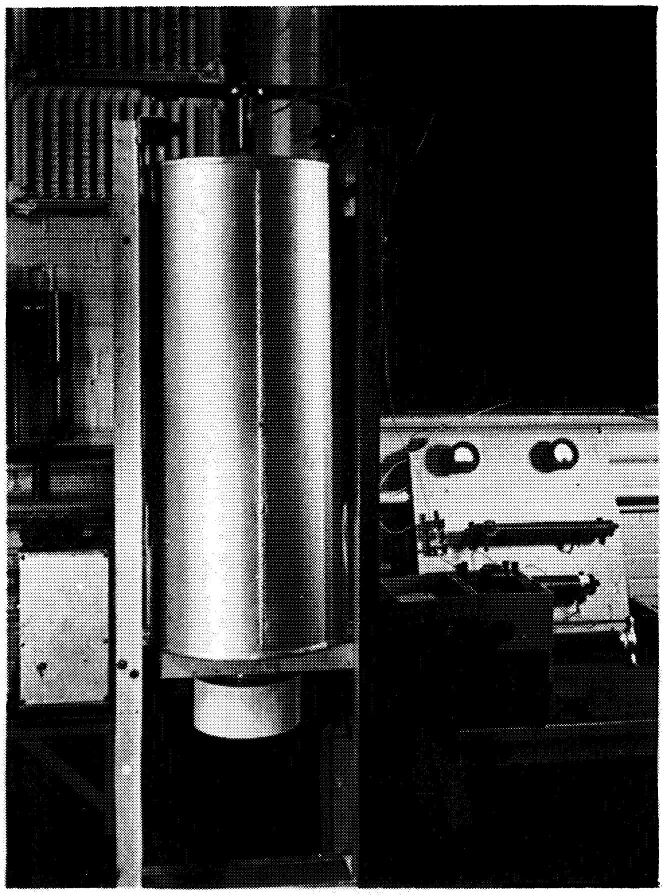

Fig. 3. Furnace with test sample in place.

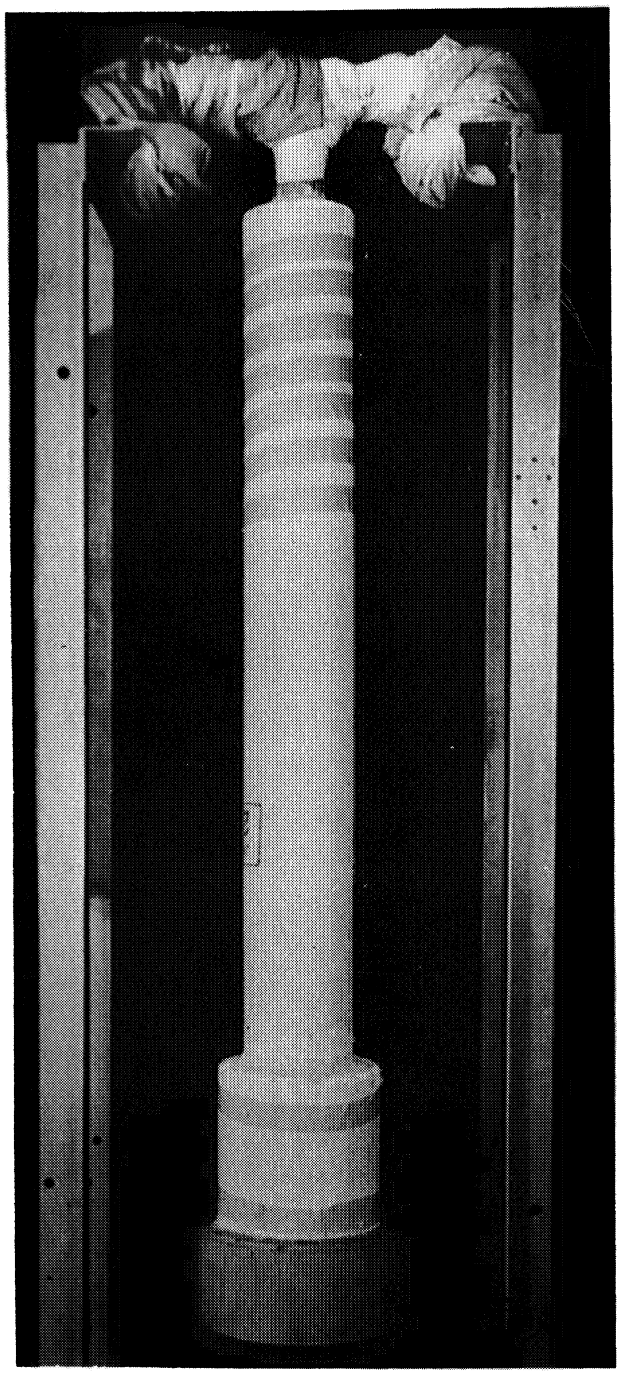

Fig. 4. Pendulum and test sample in place ready for low-temperature testing.

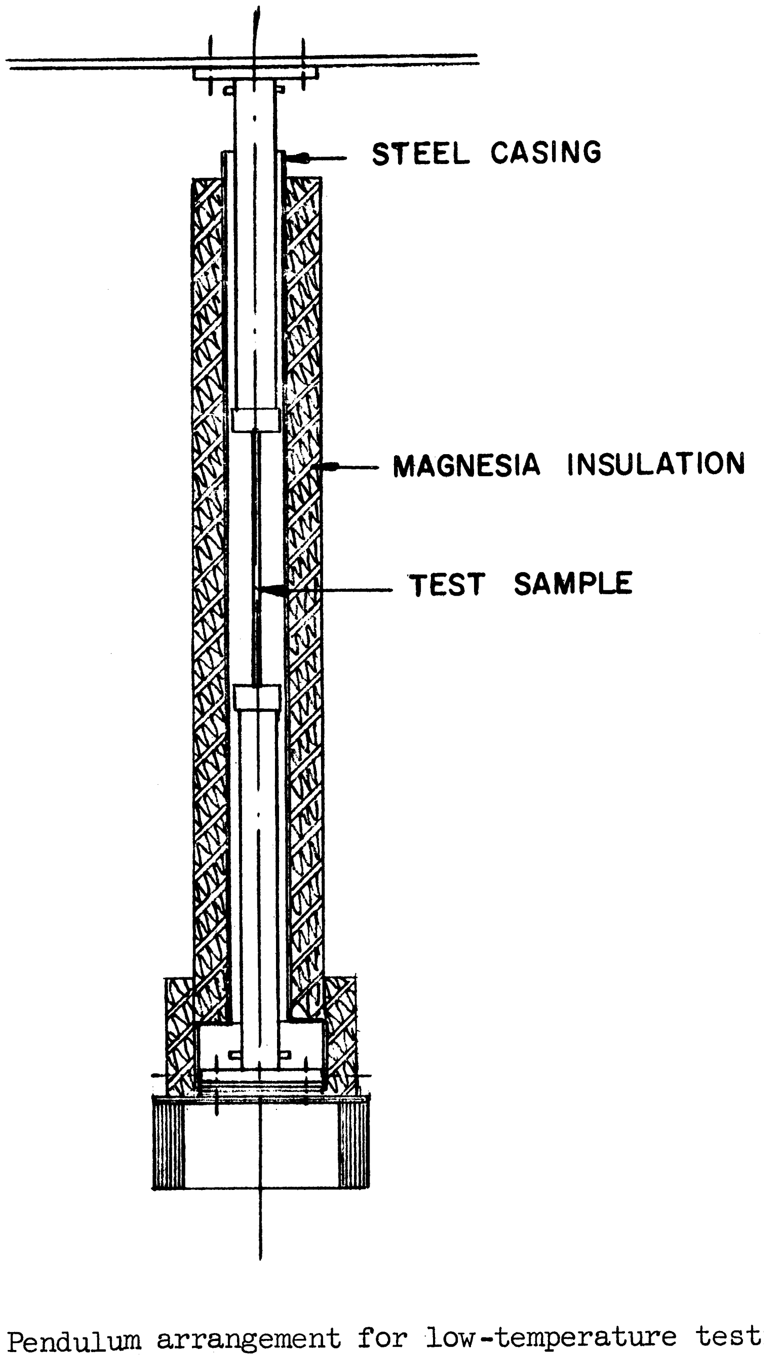

Fig. 4a. Pendulum arrangement for low-temperature testing.

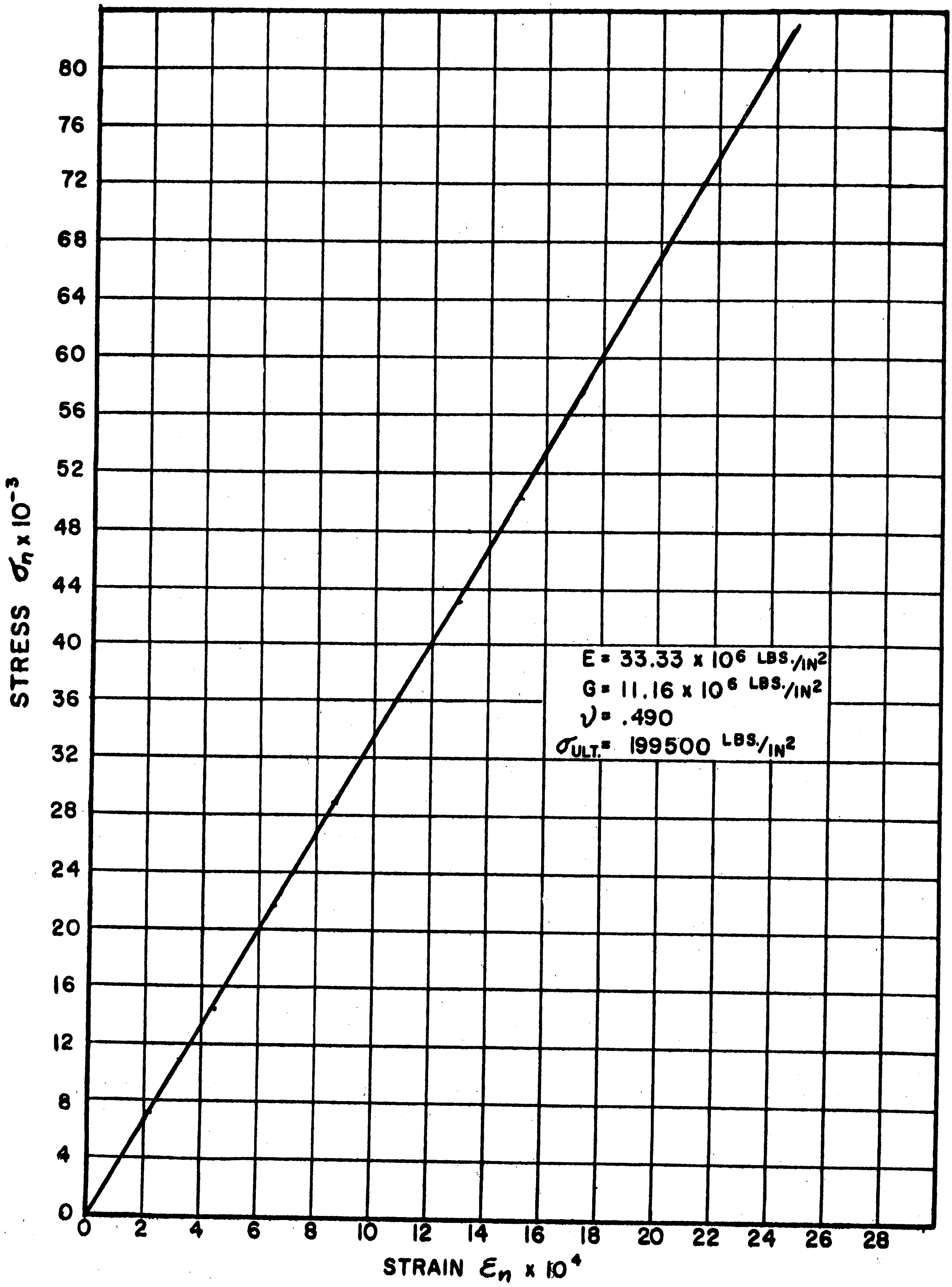

Fig. 5. Stress-strain diagram for .298-diam heat-treated Inconel X alloy.

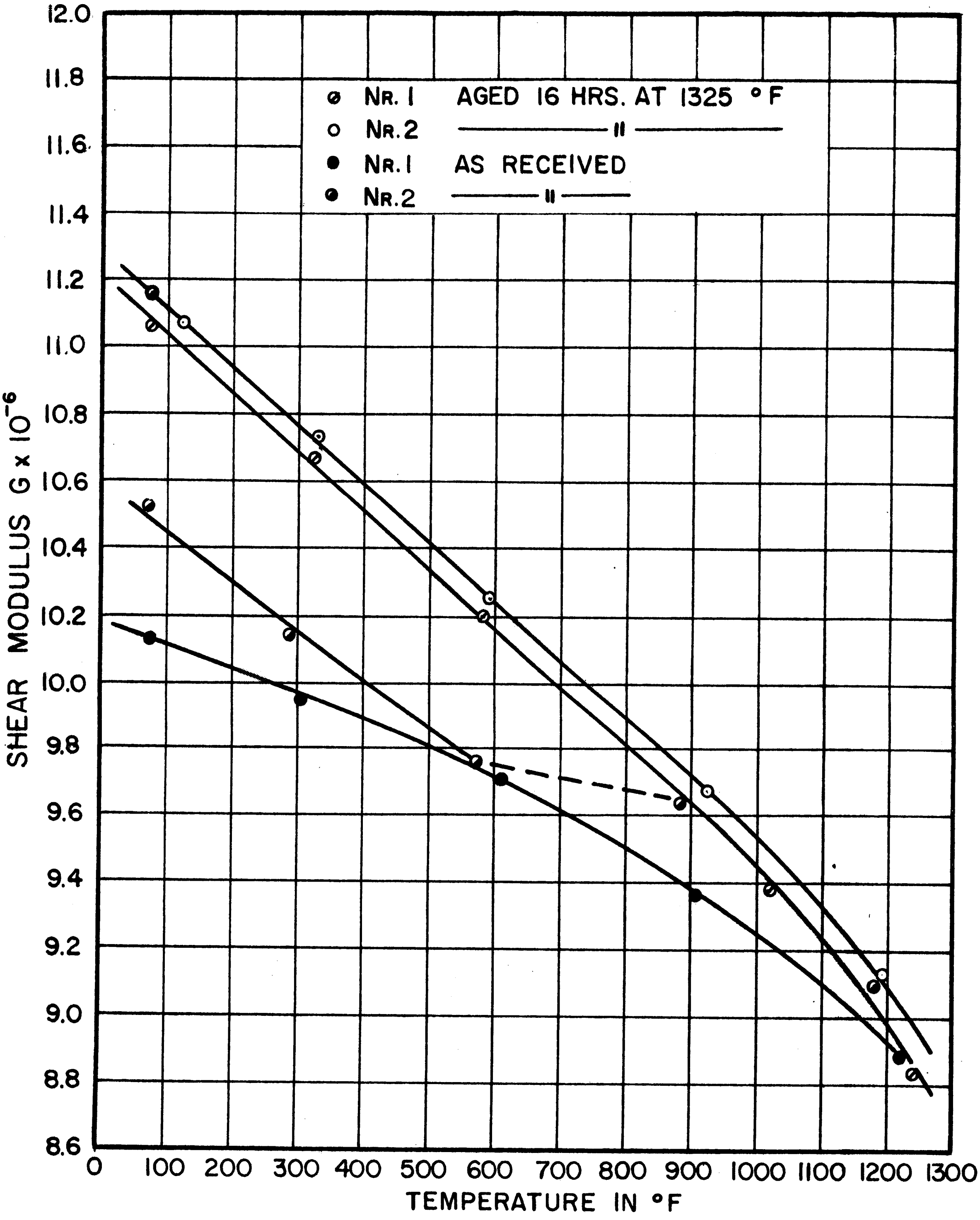

Fig. 6. Elastic shear modulus versus temperature for .298-diam Inconel X alloy.

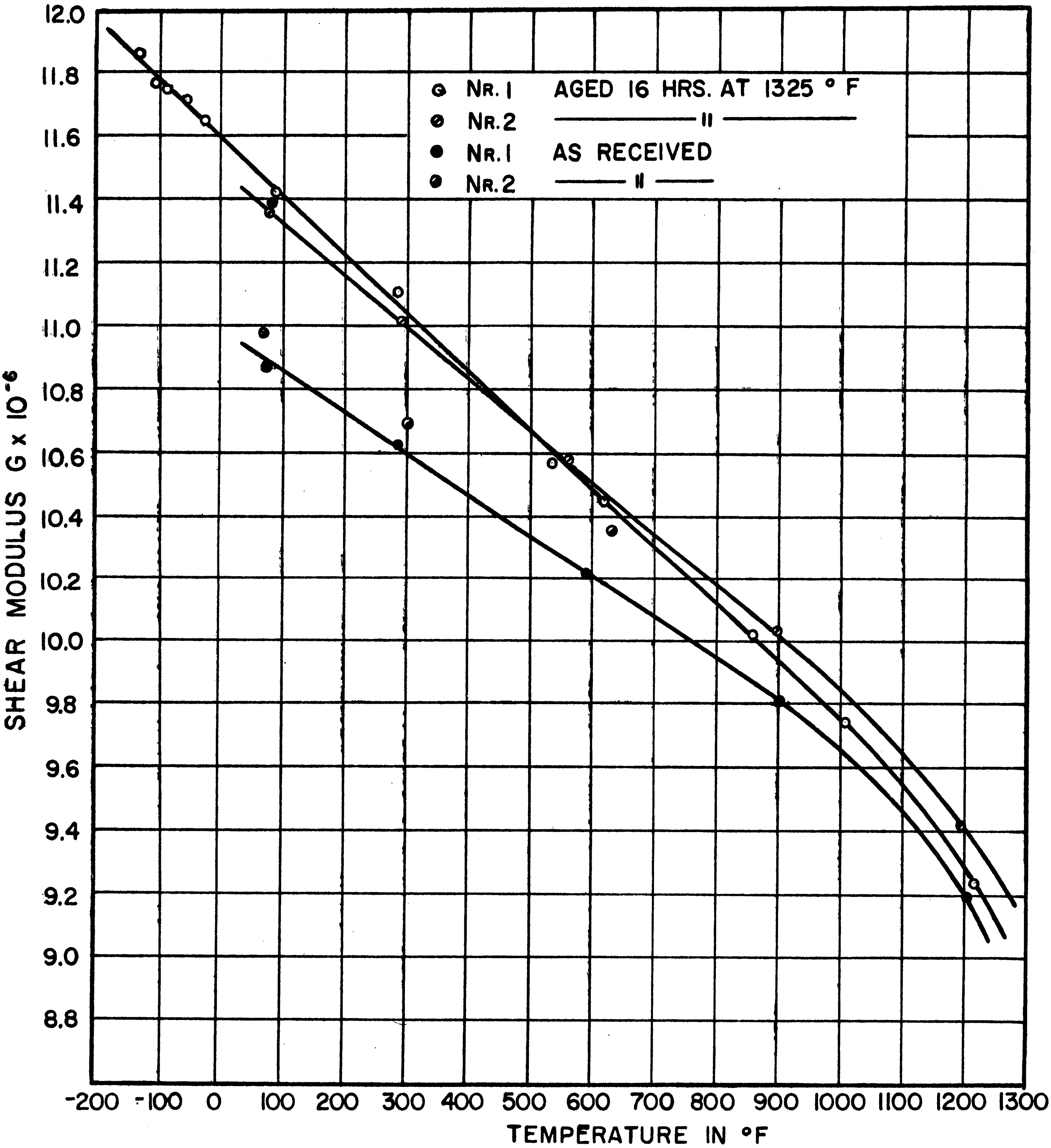

Fig. 7. Elastic shear modulus versus temperature for .198-diam Inconel X alloy.

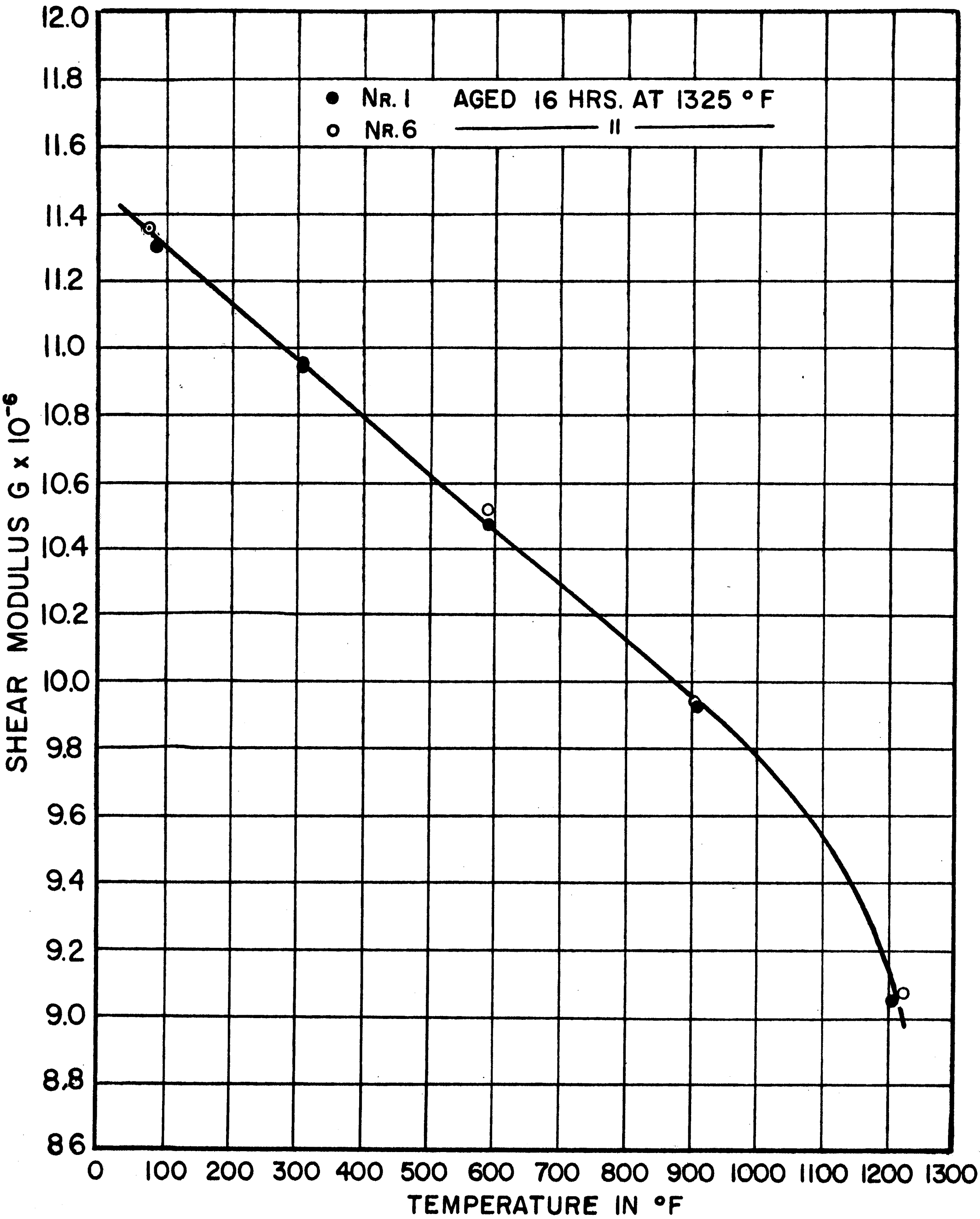

Fig. 8. Elastic shear modulus versus temperature for 130-diam Inconel X alloy.