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AN ANALYSIS OF THE TIME AND TEMPERATURE DEPENDENCE OF THE UPPER YIELD POINT IN IRON

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FOREWORD

This report was prepared by the Department of Theoretical and Applied Mechanics under USAF Contract No. AF 33(616)-5153 with Professor G. M. Sinclair as principal investigator. The project number is 7024, "Mechanisms of Ductility and Fracture," and the task number is 70666, "The Kinetics and Energies of Crack Initiation, Crack Propagation, and Fracture." The research was administered by the Aeronautical Research Laboratory, Directorate of Laboratories, Wright Air Development Division, with Dr. H. A. Lipsitt as cognizant scientist.

ABSTRACT

The influence of temperature and strain rate on the upper yield point of ingot iron was studied. Torsion tests were conducted using strain rates of 12.5/sec., .25/sec., and .0001/sec. over the temperature range 77°K to 525°K.

The upper yield point showed a rapid increase as the temperature was lowered. An increase in the strain rate also caused an increase in the yield point.

An apparent activation energy can be associated with the strain rate and temperature dependence of the yield point. This energy is influenced by stress level, and it appears from the present study that the relationship can be described by an equation of the form

$$\Delta H = \overline{\Delta H}\left(\frac{\bar{\tau} - \tau}{\bar{\tau}}\right)^b .$$

If this relationship is substituted for ΔH in a modification of the Boltzman relation, the following result is obtained:

$$\log\left(\frac{\dot{\gamma}}{\dot{\gamma}_1}\right) = M\,\frac{\overline{\Delta H}}{RT_1}\left(\frac{\bar{\tau} - \tau_1}{\bar{\tau}}\right)^b \left[1 - \frac{T_1}{T}\left(\frac{\bar{\tau} - \tau}{\bar{\tau} - \tau_1}\right)^b\right] .$$

This equation describes the experimental data within $\pm$3000 psi.

The results of this investigation compared with tensile test data from other investigators show that state of stress is an important factor in determining whether a material will behave in a ductile or brittle fashion.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

Most metals show an increase in strength as their temperature is lowered below room temperature. (1)* In some metals, the change is very gradual and is of little significance. In others a very large change in strength can be noted over a narrow temperature range. This short range is often referred to as the transition range, for in this temperature region, it is possible that the metal's behavior can be changed from ductile to brittle by only a slight temperature decrease.

Metals with the body centered cubic lattice structure exhibit a transition temperature. (2, 3, 4, 5, 6) Another common characteristic of this group is an upper yield point exhibited in a stress-strain curve. Dislocation theory suggests a common explanation for both effects. (7, 8, 9)

The analysis of the problem on the basis of energy concepts should be possible. It is reasonable to assume that a certain amount of energy is necessary to dislodge a dislocation from its pinning atmosphere. It is possible that mechanical energy in terms of stress as well as thermal energy can contribute to the total. If this concept is correct, the total or activation energy necessary to dislodge dislocations and produce yielding may be composed of these two forms. This would mean that the thermal activation energy may be a function of stress level. Experimental results suggest that stress level does influence the thermal activation energy. (10, 11) It would appear from the magnitudes of nominal stresses involved that some stress multiplication mechanism (possibly dislocation pileup) is necessary for the large effect that stress has on the thermal activation energy.

The yield point of body centered cubic metals is dependent on strain rate as well as temperature. (12, 13) For a constant temperature, an increase in the loading rate causes the observed yield point to increase. This phenomenon can be examined on the basis of a probability function. (14) High strain rates involve small time intervals which reduce the probability of slip occurring. The observed effect is that a higher yield stress is reached for high strain rates than for low ones.

The dependence of the yield strength of these metals on time and temperature is important in many engineering applications. It appears that there is a critical tensile stress above which a microcrack initiated by yielding will propagate. (15) If the temperature and loading conditions are such that the yield stress exceeds this value, brittle fracture will occur. Since time and temperature influence the yield strength, they are involved in the transition from ductile to brittle behavior.

The concept of a limiting tensile stress fits in with the effect of state of stress on the material's behavior. If the state of stress is such that shearing stresses are low in comparison with the tensile stresses, plastic flow is restricted, and brittle fracture is more likely to occur. (16) By the time the

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* Numbers in parentheses refer to list of references.

shear stress has reached a value high enough to cause yielding, a high tensile stress has been reached, which, if higher than the critical stress, will cause brittle fracture. The act of yielding can initiate the crack (17, 18, 19) which may propagate at a high level of tensile stress.

II. OBJECT AND SCOPE

This investigation was conducted to extend previously developed concepts of the time and temperature dependence of the upper yield point of metals having the body centered cubic lattice structure. Ingot iron was tested in torsion over a range of strain rates from 10^{-4}/sec. to 10/sec. and over a temperature range from that of liquid nitrogen to a temperature sufficient to cause a disappearance of the upper yield point effect.

Of major interest in this investigation was the determination of a relationship between yield stress, strain rate, and temperature. It was also desired to determine if an activation energy could be associated with the time and temperature dependence of the yield point in iron.

Another objective of this investigation was to determine, if possible, which interstitial atoms are responsible for the upper yield point and the embrittlement phenomenon in iron.

III. MATERIALS, PREPARATION OF SPECIMENS, AND APPARATUS

A. Materials

The specimens used in this investigation were made of ingot iron. The material in the as received condition was a hot-rolled, 5/8-in. diameter rod. Its chemical composition follows in weight per cent: C, 0.012; Mn, 0.017; P, 0.005; S, 0.025; and Fe the remainder. The average grain diameter of the iron in its final condition was .28 mm or ASTM No. 4. A photomicrograph of the iron in this condition is illustrated in Fig. 1.

B. Preparation of Specimens

Tubular torsion specimens, Fig. 2, were machined from the as received rod. Critical dimensions, such as wall thickness, were held within $\pm$.003-in. The inside diameter was finish reamed to produce a smooth surface. A 1-in. length was undercut 0.020-in. in the center of the specimen to prevent fracture at the gradual radii. The final wall thickness was chosen as a compromise between two factors. A thin wall was desired in order to simplify the stress analysis and minimize the stress gradient, but a thicker wall was necessary in order to prevent failure by plastic buckling. By compromising between these two conditions, a wall thickness of 0.070-in. was chosen.

After machining, the specimens were annealed in a vacuum at 923°K for 24 hours. This relieved machining stresses and allowed precipitation of excess carbides to the grain boundaries.

C. Apparatus

(1) General Description

The testing apparatus is illustrated in Fig. 3. This testing machine applied a pure torsional load to one end of the specimen while the other end was held fixed in a torque weighbar. Either motor M_1 or M_2 applied the torque, depending upon the desired strain rate. The specimen was mounted as indicated by S in the figure.

The wire resistance strain gages were mounted on the torque weighbar and are indicated by G in the figure. The signal from these gages was amplified by means of the amplifier indicated by A, and this signal was sent to one recording galvanometer of the 6 channel Hathaway S14-A oscillograph. Here a continuous record of torque was recorded.

Another channel of the oscillograph was used to record twist over the interval of the test. Due to the large range in strain rates, two separate twist recording devices were used. At high speeds, a gear was mounted in series with the specimen. As its teeth passed a magnetic pickup, a signal was induced which produced a sawtooth wave on the record. The number of peaks produced per revolution was the same as the number of teeth on the gear. For slower tests, a high resistance wire was mounted on the periphery of a lucite disk. A potential was impressed across the wire at two points, 180^o apart. This disk was mounted in series with the specimen, and a potential that was proportional to the angular displacement of the disk was picked off the wire. The signal was fed to a galvanometer whose deflection was then proportional to the angle of twist.

The temperature of the specimen was controlled by means of a furnace or cold chamber which was mounted over the specimen. By using these, any temperature between 77^oK and 800^oK could be obtained.

One of the advantages of this torsion apparatus was its wide range of strain rates. In the present test program, strain rates of 12.5/sec., 0.25/sec., and .0001/sec. were used. This covers a range of more than five orders of magnitude.

(2) High Speed Tests

Referring again to Fig. 3, motor M_1 was used to obtain a strain rate of 12.5/sec. This motor was used to accelerate the flywheel F to the proper speed. This speed was determined by balancing a known frequency from oscillator 0 with the signal from the magnetic pickup previously described. When the proper speed was obtained, the control unit C was actuated, which in turn started the oscillograph and then engaged the flywheel with the specimen. This control unit eliminated the waste of photographic paper which would occur if the operations were manual. Continuous torque and angle of twist curves were obtained up to fracture, after which an automatic shut-off switch stopped the oscillograph.

(3) Medium Speed Tests

At the strain rate of 0.25/sec., motor M_2 was used in conjunction with gear reducer G_2. This set up was used as a direct drive on the specimen, with torque and angle of twist recorded on the oscillograph.

(4) Slow Speed Tests

For a strain rate of 0.0001/sec., motor M_2 was used to drive the specimen through three gear reducers. An autographic X-Y recorder was used to record torque and angle of twist in this case. The torque signal from the strain gages was fed into the X coordinate of the recorder, while the resistance wire pickup signal was fed into the Y axis as an indication of strain. The X-Y recorder then plotted a continuous curve of torque versus angle of twist.

Work and Dolan have given a more detailed description of this apparatus. (20)

IV. RESULTS

Figure 4, shows test results relating shearing stress at yield point, τ, strain rate, $\dot{\gamma}$, and temperature, T. These curves exhibit the general qualitative behavior that would be expected from "body centered cubic" metals. That is, the yield stress increased at increased strain rates for a constant temperature, while it also increased as the temperature was decreased, at a constant strain rate.

It should be noted that at elevated temperatures, (300-500°K) the yield strength becomes relatively insensitive to changes in temperature and strain rate.

Another observation that can be made from the data is the apparent convergence of the curves to a limiting stress value at very low temperatures.

All of the specimens failed in a ductile manner, including those at the highest strain rate and the lowest temperatures. This can be seen in Fig. 5, where ductility is plotted as a function of temperature. A typical ductile fracture is illustrated in Fig. 6. These ductility data were obtained for only the higher two strain rates. Specimens at the lowest strain rate were not tested to fracture, as in many cases it would have taken several days for fracture to occur. The yield point was of major interest in this investigation, and it was not believed that this ductility curve justified the time required to obtain it. These two curves illustrate the great dependence of ductility on temperature and strain rate.

In summary, the data illustrated the tendency for embrittlement of iron at reduced temperatures and increased strain rates as shown by the increase in yield strength and the decrease in ductility under these conditions. It also shows that brittle behavior of ingot iron is not likely to be exhibited under the state of stress existing in torsion.

V. DISCUSSION AND ANALYSIS OF RESULTS

If the maximum principal tensile stress at yielding was increased over that which occurs in torsion, it is very likely that ingot iron would fail in a brittle manner. Brittle fracture is associated with a tensile stress. It has been observed that brittle fracture propagates along planes normal to the principal tension stress. (10, 16) This suggests that there may be a critical value of tension stress which will propagate a microcrack nucleated by yielding. A stress state in which the ratio of maximum principal tensile stress to shear stress is large increases the tendency for brittle behavior. This can be illustrated by referring to Fig. 7, where the octahedral shear stress is plotted against the maximum principal tensile stress for several states of stress. In this figure, a critical fracture stress is assumed and represented by a horizontal line. If two states of stress are examined, tension and torsion, for example, it can be seen that, for a given value of octahedral shear stress to be reached, the maximum principal tensile stress is proportionately greater in the tension test. This state of stress would then be more conducive to brittle fracture. A criterion for brittle fracture, then, must take into account the effect of state of stress.

For this reason the yield point data of Fig. 4 were converted to octahedral shear values and plotted in Fig. 7. By means of a plot such as this, yield data from any state of stress may be compared. From these curves it is possible to obtain the value of octahedral shear at yield point for a given strain rate and temperature. With a knowledge of the state of stress, the maximum principal tensile stress can be calculated. If the critical value of tensile stress is known for the material, brittle behavior might be predicted. The behavior would be brittle if the maximum principal tensile stress exceeded the critical value, and ductile if it were lower.

Weinstein (10) observed yield points in molybdenum which exceeded the value of stress necessary to cause brittle fracture. Cottrell (21) has proposed a model which requires yielding to precede fracture. This model suggests that yielding causes dislocations to pile up on an obstacle such as a grain boundary, thus initiating a crack. If the fracture strength of the material is exceeded, the crack will propagate, producing a brittle fracture. This would explain observed yield points above the proposed fracture strength without contradicting the idea of a critical fracture stress.

It is possible to analyze for an apparent activation energy necessary to produce slip by means of Boltzman's relationship. This relationship states that the probability, p, of an atom acquiring an energy ΔH in time interval t is inversely proportional to $e^{-\Delta H/RT}$; that is $1/t = Ae^{-\Delta H/RT}$. If the stress induced short range diffusion of interstitial atoms is considered to be the rate controlling mechanism for yielding, the time interval of interest would be that necessary to allow dislocations to be torn away from interstitial atmospheres. A reasonable estimate of this time interval is obtained by measuring the time delay for yielding at stress levels above the static yield point.

In recent years, Clark and Wood (22, 23, 24) have measured this delay time in body centered cubic metals. They did this by rapidly loading to a desired stress level and then measuring the time interval until yielding took place. The results of their work on a low carbon steel are shown in Fig. 9. The results of this investigation are plotted on this same figure. In order to make this plot, the shearing yield stress values of this test program were converted to tensile stresses which would give the same value of octahedral shear in tensile tests as were obtained in the present torsion tests. The time interval plotted was that necessary to reach the yield stress at the stress rate used. The two curves are parallel which suggests the same mechanism is described. It was believed that the two different types of loading accounted for the difference in positioning the curves. In Clark and Wood's work, the stress was raised to the desired level in a very short time interval and held constant. In this way the entire test essentially was conducted at a constant elevated stress. In the present investigation the stress was constantly increasing until yielding occurred. A comparison of these two types of loading is illustrated in Fig. 10.

In an attempt to relate these time intervals, it was assumed that the criterion for yielding depended upon some function of the time that a given stress was maintained. It was further assumed that the time spent at stress levels below the static yield point of the material had little significance and could be neglected. A first approximation of these assumptions would lead to

$$\int_0^{t_{1y}} (\sigma_{1y} - \sigma_s)\,dt = \int_{t_2'}^{t_{ay}} (\sigma_2 - \sigma_s)\,dt \qquad (1)$$

where: $\sigma_{1y} = \sigma_{2y} = \sigma_y$ = constant stress level considered for yielding in both test series

σ_s = static yield point of the material

σ_2 = $(d\sigma/dt)t$

and $d\sigma/dt = \sigma_s/t_2' = \sigma_y/t_{2y}$

t_{1y} = time for yielding to occur at a stress level of σ_y in Clark and Wood's tests.

t_{2y} = time for yielding to occur at a stress level of σ_y in the present test series

t_2' = time to reach a stress level of σ_s in the present test series

This equation results in the following relation between t_{1y} and t_{2y}.

$$t_{1y} = \frac{t_{2y}}{2} \left[\frac{\sigma_y - \sigma_s}{\sigma_y} \right] \qquad (2)$$

If Eq. 2 is used to transform the data from Clark and Wood's curve to time intervals comparable to that of the present investigation, the third curve of Fig. 9 is obtained.

Equation 2 can be rewritten in the form,

$$t_{1y} = \frac{1}{2E\dot{\epsilon}} \left[\sigma_y - \sigma_s \right] \qquad (3)$$

and for a constant stress level,

$$t_{1y} = \frac{K}{\dot{\epsilon}} \qquad (4)$$

Since it is likely that t_{1y} is a measure of the probability of slip occurring at a given stress level, its use in Boltzman's equation appears justified. Equation 4 then suggests that $K/\dot{\epsilon}$ may be used interchangeably with t_{1y} in the Boltzman relation. Since the present tests were conducted in torsion, $K/\dot{\gamma}$ will be used. The following equation results from this approach:

$$\dot{\gamma} = Ae^{-\frac{\Delta H}{RT}} \qquad (5)$$

where $\dot{\gamma}$ is the strain rate, R is the gas constant, T is the absolute temperature, ΔH is the activation energy, and A is a constant. For strain rates 1 and 2, the same equation can be written. By combining the equations for strain rates 1 and 2, the following equation is obtained:

$$\Delta H = \frac{RT_1 \ T_2 \ \ln\left(\frac{\dot{\gamma}_1}{\dot{\gamma}_2}\right)}{T_1 - T_2} \qquad (6)$$

From the plot of Fig. 4, for constant values of shearing stress, temperatures T_1 and T_2 can be obtained. This makes possible the calculation of ΔH for any stress level. In Fig. 11, these calculated values of ΔH are plotted as a function of the shearing stress for the three combinations of strain rates. The experimental points could be measured with an accuracy of about ± 3000 psi.

The values of log ΔH from this curve were plotted against $\log(\bar{\tau} - \tau)/\bar{\tau}$ in Fig. 12, in an attempt to linearize the data. The extrapolated value of yield stress at a temperature of absolute zero is $\bar{\tau}$. The plot of Fig. 12, is essentially a straight line and leads to the relationship

$$\Delta H = \overline{\Delta H}\left(\frac{\bar{\tau} - \tau}{\bar{\tau}}\right)^{b} \tag{7}$$

where: $\overline{\Delta H}$ = 18,000 cal/gm. mol, the thermal activation energy at zero stress

$\bar{\tau}$ = 80,000 psi., the stress necessary for yielding at a temperature of absolute zero, and

b = .57, the slope of the line in Fig. 12.

This equation indicates that the thermal activation energy is a function of the stress level. As the stress level is increased, the corresponding values of thermal activation energy decrease. The value of ΔH = 18,000 cal/gm. mol at zero stress agrees very well with values of ΔH for carbon and nitrogen in iron. By means of internal friction measurements, Wert (25) found that ΔH for carbon in iron was 20,100 cal/gm. mol and was 18,200 cal/gm. mol for nitrogen in iron. This strongly suggests that either carbon or nitrogen or both are the interstitial atoms responsible for the embrittlement effect in iron. Weinstein (10) concluded that these same two atoms may be responsible for the ductile-brittle transition in molybdenum.

By substituting Eq. 7 into Eq. 5 the following relationship is obtained:

$$\dot{\gamma} = Ae^{-\frac{\overline{\Delta H}\left(\frac{\bar{\tau} - \tau}{\bar{\tau}}\right)^{b}}{RT}} \tag{8}$$

The constant A can be evaluated by making a single test at $\dot{\gamma} = \dot{\gamma}_1$, $T = T_1$, and $\tau = \tau_1$. This leads to an equation relating yield stress, strain rate, and temperature of the form

$$\log\left(\frac{\dot{\gamma}}{\dot{\gamma}_1}\right) = \frac{M\,\overline{\Delta H}}{RT_1}\left(\frac{\bar{\tau} - \tau_1}{\bar{\tau}}\right)^{b}\left[1 - \frac{T_1}{T}\left(\frac{\bar{\tau} - \tau}{\bar{\tau} - \tau_1}\right)^{b}\right] \tag{9}$$

where M = .4343, the constant of conversion between natural and common logarithms. Calculated curves based on Eq. 9 are plotted in Figs. 4 and 8. These curves describe the experimental points very well for stresses above 30,000 psi. The maximum deviation of the experimental curves from the theoretical curves is about 2,000 psi., which is within the experimental accuracy of the tests.

It should be noted that at stress levels below about 30,000 psi., Eq. 9 no longer describes the stress, temperature, and strain rate relationship. It is quite obvious from the experimental data that at stress levels below about 30,000 psi., a new mechanism has become dominant. The combination of elevated temperatures and low strain rates, which lead to yield points below 30,000 psi., give the pinning atoms sufficient energy and time to move freely through the lattice. They no longer pin the dislocations effectively, so the embrittlement phenomenon disappears. The yield stress then shows a gradual decrease as the temperature is increased, as would be expected in normal metal behavior. Equation 9 then describes the time and temperature dependence of the yield point in the temperature range where interstitial locking is effective.

At very low temperatures the yield stress values appear to reach an upper limiting value, as seen in Fig. 4. This upper limit may be the result of twinning which takes place at these low temperatures and high stress levels. Metallographic examination of specimens tested in this region show that extensive twinning has taken place. Figure 13 shows a photomicrograph of one of these specimens.

Equation 9 may be considered as a relationship between two parameters; $\log(\dot{\gamma}/\dot{\gamma}_1)$ and $(T_1/T)(\bar{\tau}-\tau/\bar{\tau}-\tau_1)^b$. In Fig. 14, these two parameters plot as a straight line. By means of the relationship shown, it appears possible that a quantitative estimate of critical temperatures and strain rates leading to brittle fracture may be made. The accuracy of this determination is within 2, 000 psi. It should be noted that this curve applies only to a certain composition iron with a given grain size. These factors must be considered when other materials are used, but this is beyond the scope of this paper.

Equation 9 can be solved for τ explicitly. This yields the relation

$$\frac{\tau}{\bar{\tau}} = 1 - \left[\frac{T}{T_1}\left(1 - \frac{\tau_1}{\bar{\tau}}\right) - \frac{\log\left(\frac{\dot{\gamma}}{\dot{\gamma}_1}\right) RT^2 \left(1 - \frac{\tau_1}{\bar{\tau}}\right)^{1-b}}{MT_1 \ \overline{\Delta H}} \right]^{1/b}$$

which move readily lends itself to engineering estimates, since the dependent variable is given as a function of the independent variables.

The three variables in this relation can be represented as a surface in space, which is shown schematically in Fig. 15. This surface representation is equivalent to the curves of Figs. 4 and 8, for if planes of constant strain rate cut this surface, these curves are obtained.

If the surface is cut by a plane of constant temperature, a stress-strain rate curve is obtained. If this strain rate is modified by Eq. 4, the equivalent of Clark and Wood's delay time data is obtained.

The surface representation then gives a good qualitative picture of the relationship between yield stress, temperature, and time in the embrittlement region.

VI. SUMMARY

Torsion tests were conducted on ingot iron using strain rates of 12. 5, . 25, and .0001/sec. over a temperature range of 77°K to 525°K. The magnitude of the upper yield point shear stress was the dependent variable in all of the tests.

The results of the tests are shown in Fig. 4. They show that the yield strength exhibits a rapid increase as the temperature is lowered. The yield strength also increases as the strain rate is increased. The dependence of the yield point on strain rate and temperature can be explained on the basis of a locking interstitial mechanism.

An activation energy ΔH can be associated with this embrittlement mechanism. This energy is influenced by stress and it appears from these tests that this relationship can be described by an equation of the form

$$\Delta H = \overline{\Delta H}\left(\frac{\overline{\tau} - \tau}{\overline{\tau}}\right)^b$$

If this relation is used in conjunction with a modification of the Boltzman equation, the following result is obtained:

$$\log\left(\frac{\dot{\gamma}}{\dot{\gamma}_1}\right) = M \frac{\overline{\Delta H}}{RT_1}\left(\frac{\overline{\tau} - \tau_1}{\overline{\tau}}\right)^b \left[1 - \frac{T_1}{T}\left(\frac{\overline{\tau} - \tau}{\overline{\tau} - \tau_1}\right)^b\right]$$

This equation quite accurately describes the experimental data as can be seen in Fig. 4.

In all of the torsion tests conducted on ingot iron, the fracture occurred in a ductile manner. From these results and the tests conducted by Weinstein (10) on molybdenum, it appears that there is a critical tensile stress which must be exceeded before brittle fracture can occur. The state of stress is an important factor in determining whether this tensile stress can be reached before yielding takes place. Torsion tests effectively reduce the tensile stress in comparison with the shear stress and thus enhance the chances for ductile behavior.

At sufficiently elevated temperatures, the embrittlement mechanism no longer holds and the yield stress loses its strong time and temperature dependence. This is reasonable if the dependence is assumed to be a consequence of a locking mechanism. At elevated temperatures the interstitial atoms have sufficient energy to move freely through the lattice and no longer effectively lock dislocations.

VII. CONCLUSIONS

1. The activation energy necessary for plastic deformation is stress dependent. This suggests that both thermal and mechanical energy may contribute to the total energy necessary to cause slip.

2. From the results of the present tests, it appears that the influence of stress on the activation energy can be described by a relationship of the form

$$\Delta H = \overline{\Delta H}\left(\frac{\bar{\tau} - \tau}{\bar{\tau}}\right)^b$$

3. A modification of Boltzman's relationship describes the experimental data very well. It is of the form

$$\log\left(\frac{\dot{\gamma}}{\dot{\gamma}_1}\right) = M \frac{\overline{\Delta H}}{RT_1}\left(\frac{\bar{\tau} - \tau_1}{\bar{\tau}}\right)^b \left[1 - \frac{T_1}{T}\left(\frac{\bar{\tau} - \tau}{\bar{\tau} - \tau_1}\right)^b\right]$$

4. The thermal activation energy for the embrittlement mechanism was found to be approximately 18,000 cal/gm. mol. by extrapolation of the curves in Fig. 11 to zero stress. This suggests that a diffusion process controls the embrittlement mechanism and the responsible interstitial atoms are carbon or nitrogen, or both.

5. The state of stress has a significant effect on the brittle behavior of a material. In torsion tests such as utilized in the present investigation, the probability of brittle fracture occurring is relatively low since the ratio of the maximum principal tension stress to the shear stress is small.

6. It appears that there is some critical value of maximum principal tension stress which must be exceeded before a brittle fracture can occur. It is not possible to exceed this stress in ingot iron when tested in torsion at temperatures above 77°K .

7. The extreme dependence of the yield point on temperature and strain rate no longer exists when the temperature is elevated to a sufficiently high value. It is likely that at these elevated temperatures the interstitial atoms have sufficient thermal energy to diffuse readily through the lattice and no longer effectively pin dislocations.

8. It appears that there is a limiting stress value at absolute zero that is approached no matter what strain rate is applied. In the case of ingot iron tested in torsion, this limiting value of shearing yield stress appeared to be approximately 80,000 psi.

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Fig.1 Photomicrograph of 0.012 Per Cent Carbon Ingot Iron (X100)

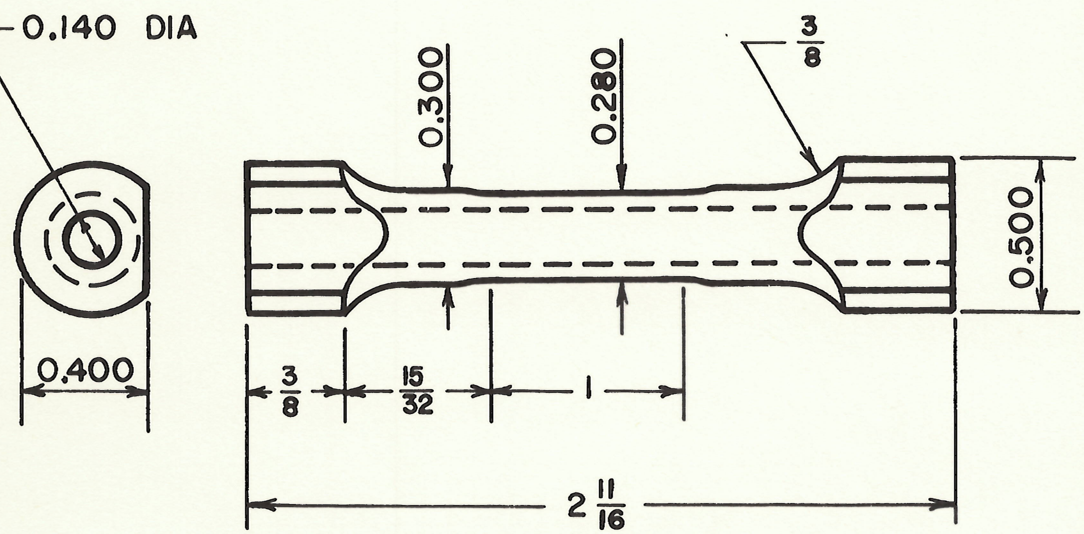


FIG. 2 TUBULAR TORSION SPECIMEN

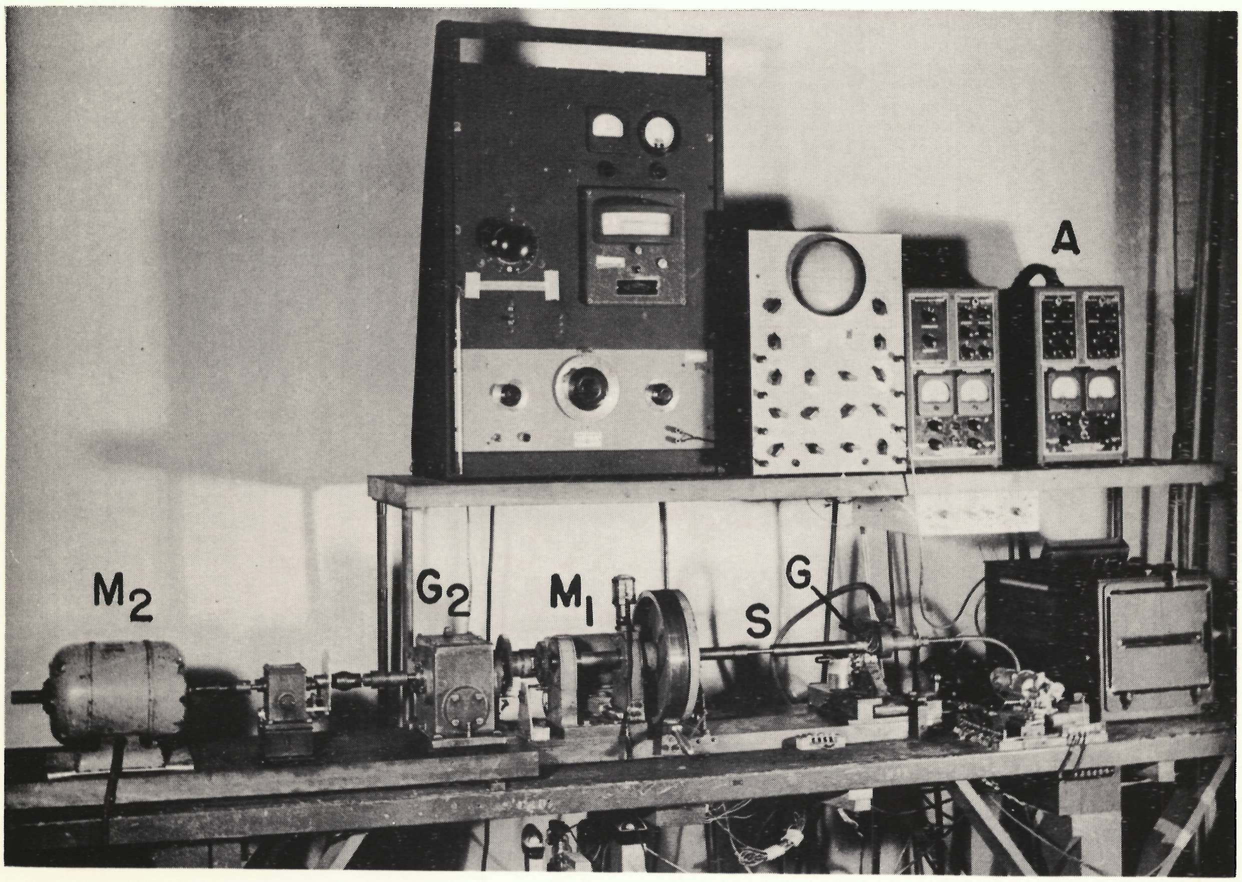


Fig. 3 Torsion Testing Apparatus

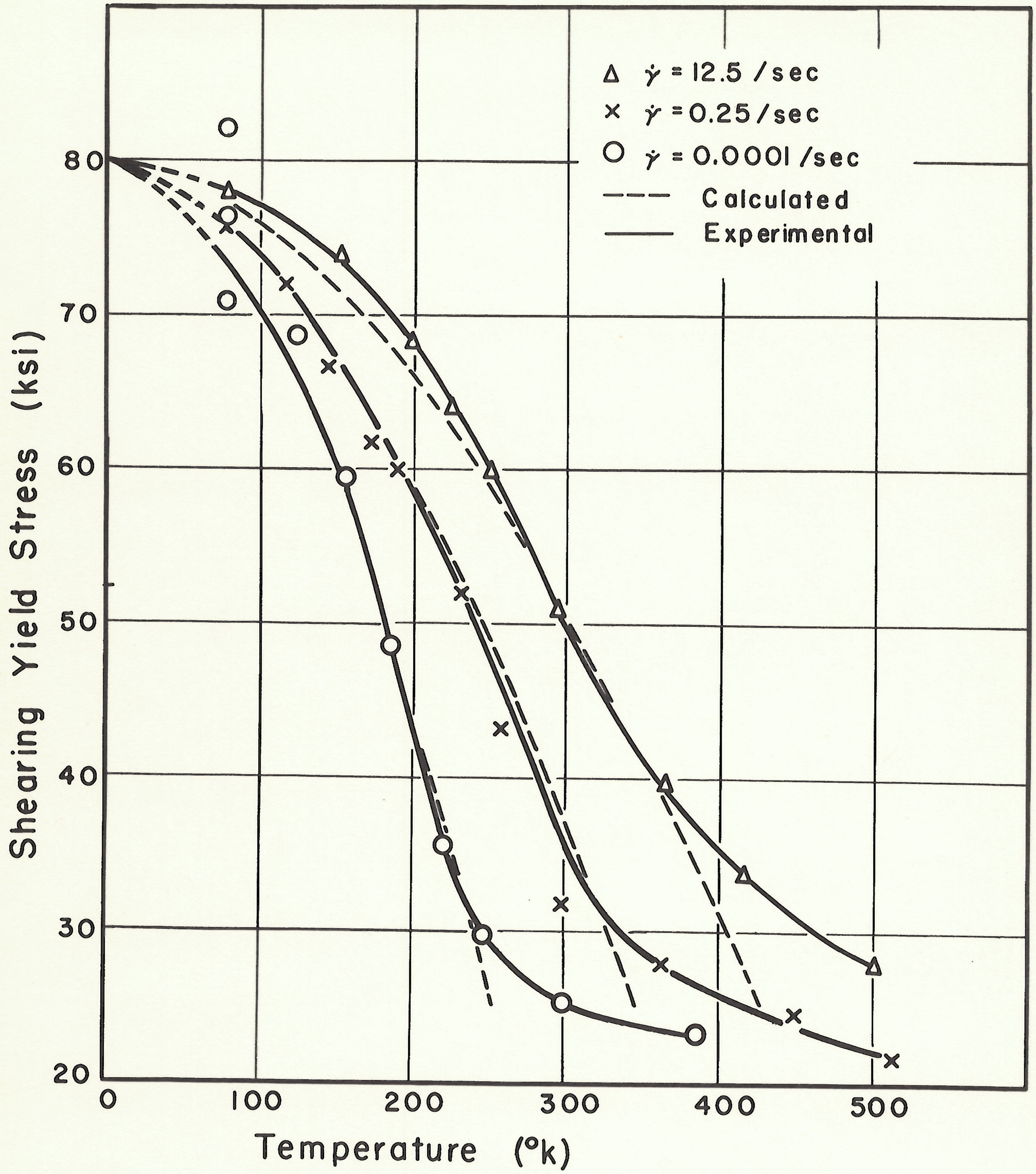


FIG. 4 Comparison Of Computed And Observed Values Of Upper Yield Stress

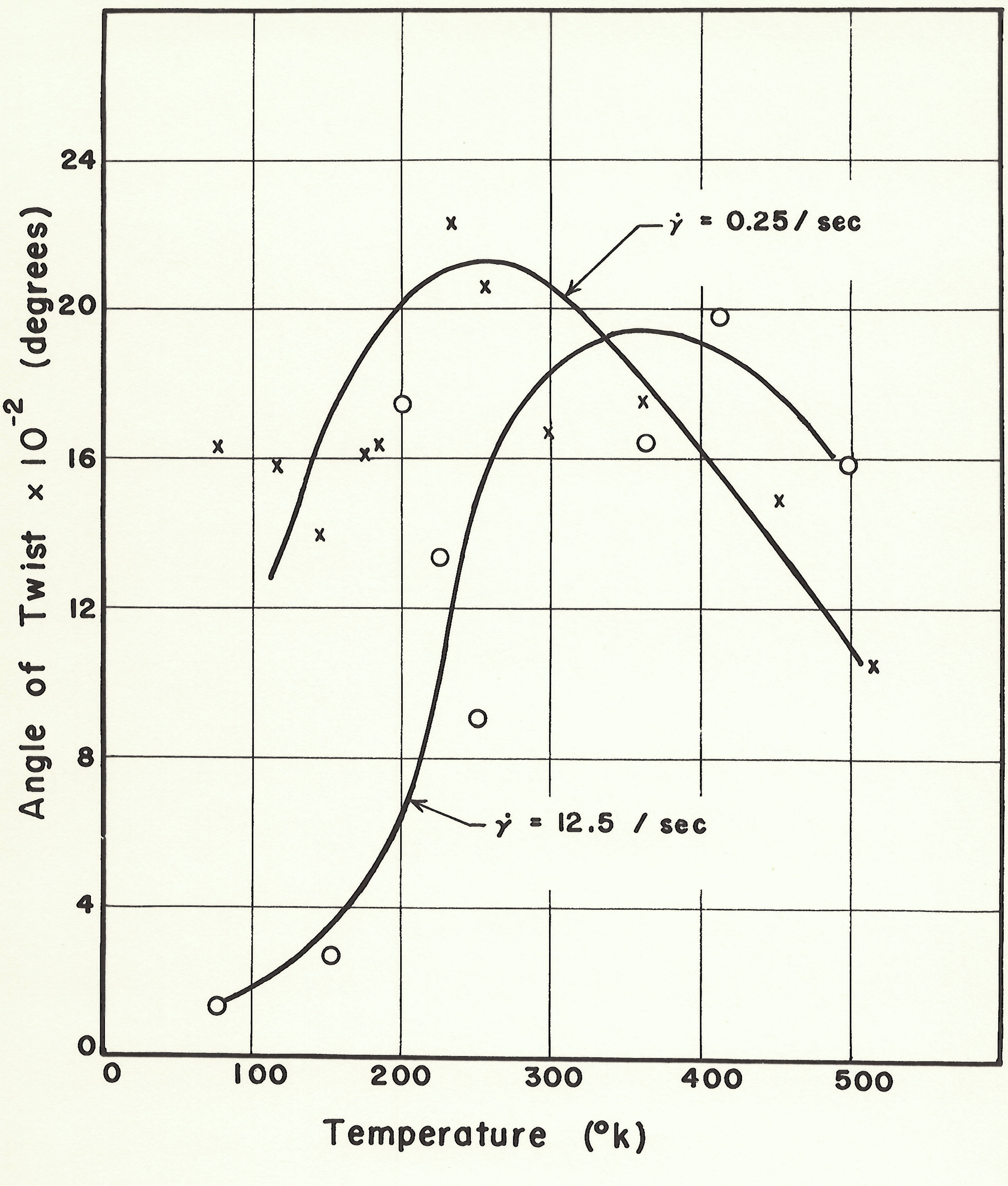


FIG. 5 EFFECT OF TEMPERATURE AND STRAIN RATE ON DUCTILITY

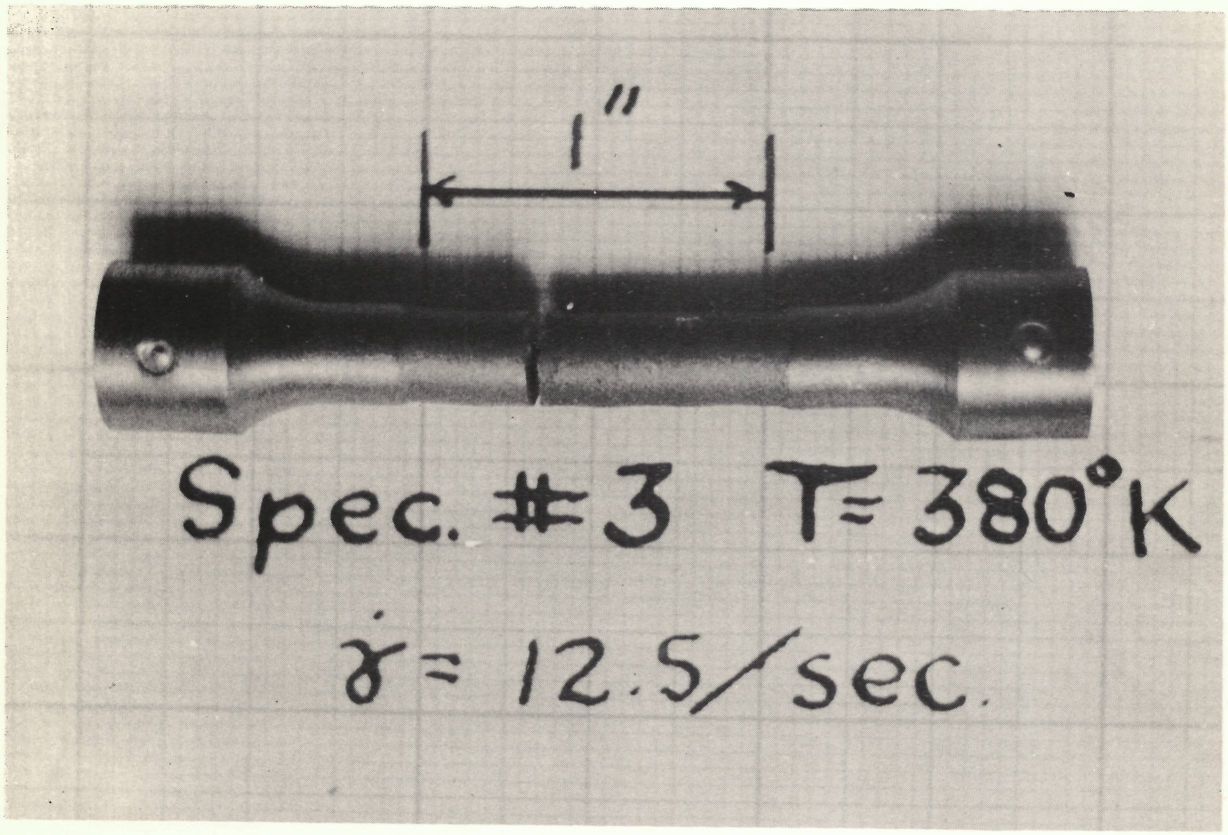


FIG. 6 Typical Ductile Fracture Of A Torsion Specimen

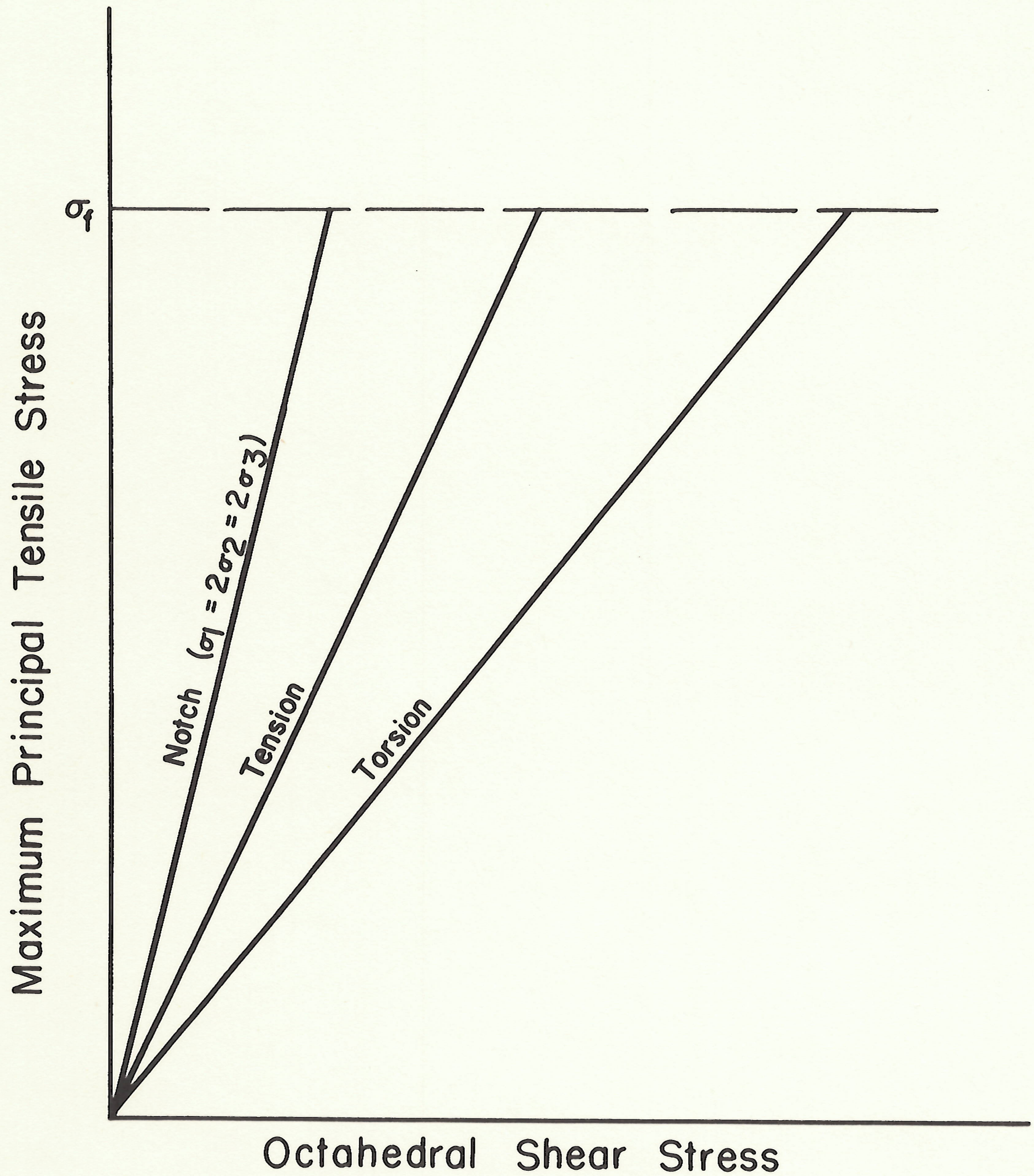


FIG. 7 Effect Of State Of Stress On Relation Between Shear And Normal Stresses

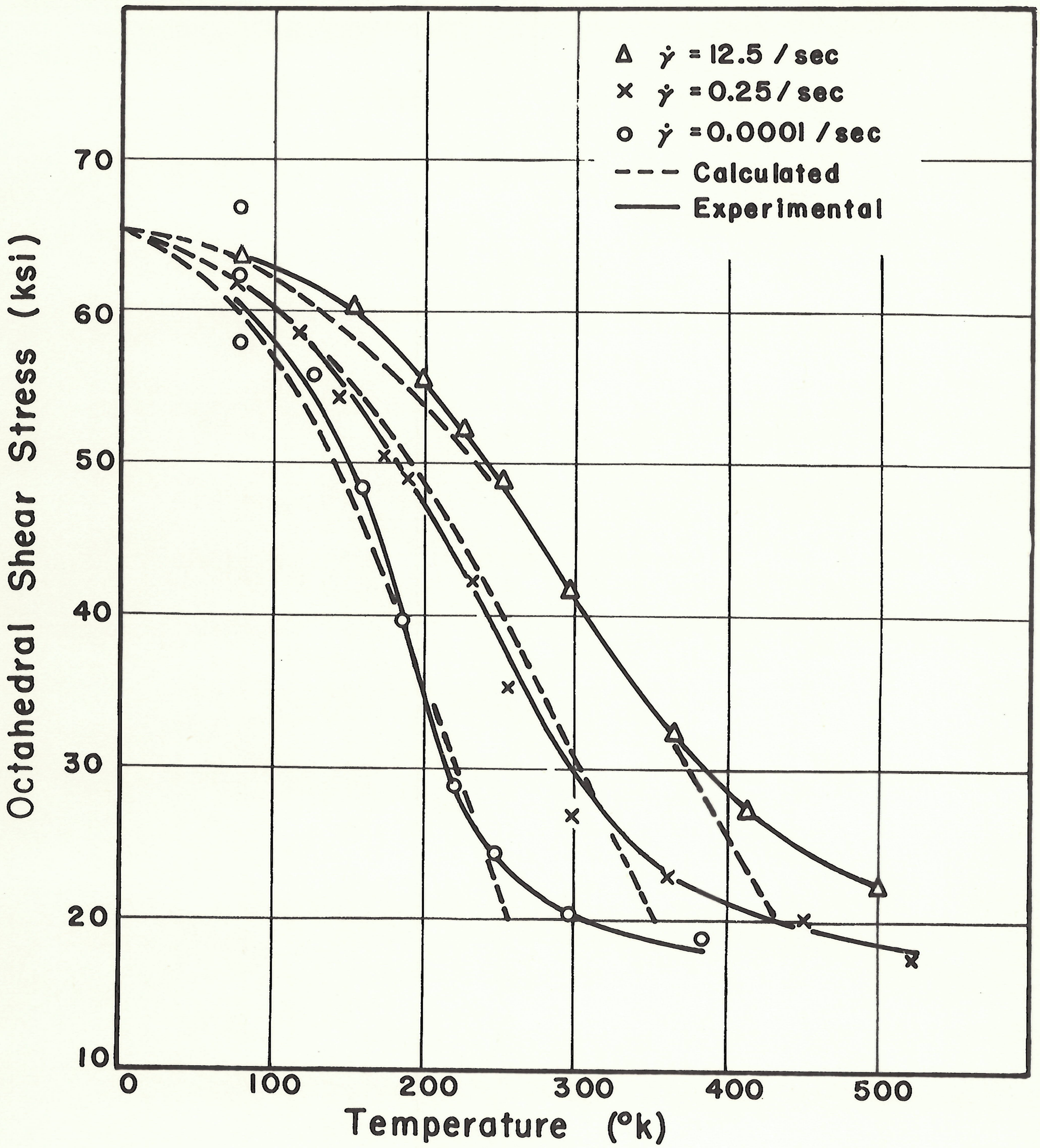


FIG. 8 Comparison Of Computed And Observed Values Of Upper Yield Stress In Terms Of Octahedral Shear

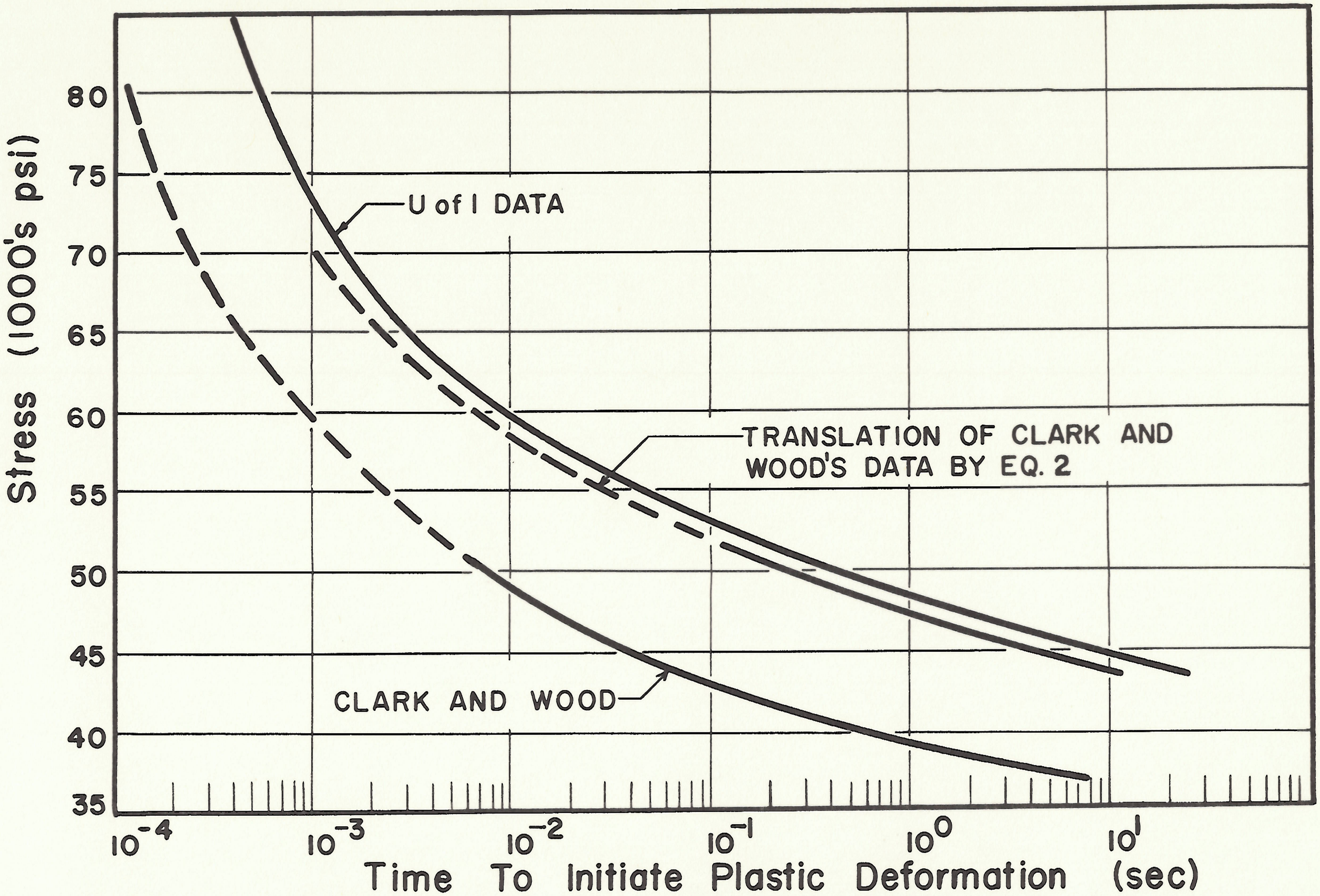
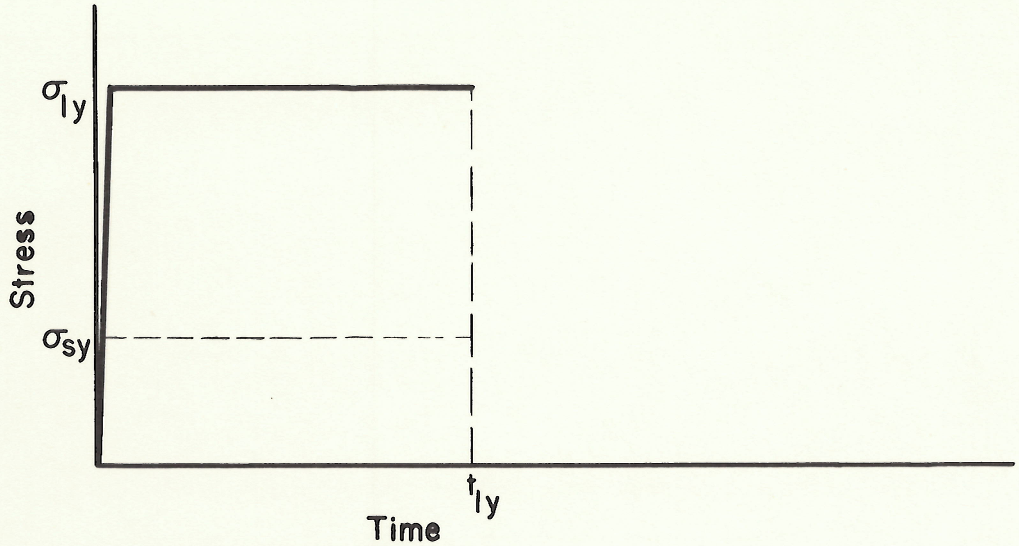


FIG. 9 Comparison Of Data From This Investigation With Clark And Wood's Delay Time Data



CLARK AND WOOD

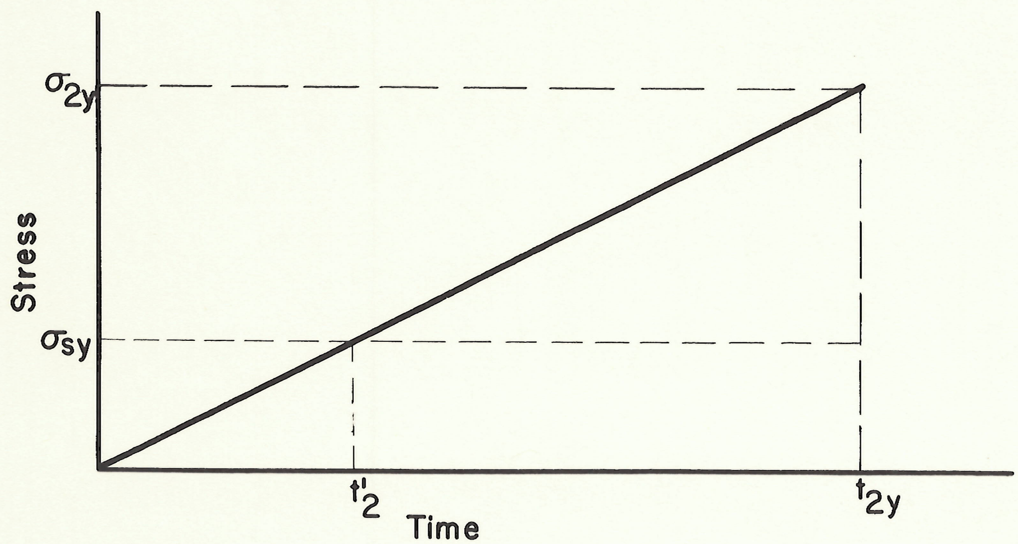


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FIG. 10 Comparison Of The Type Of Loading Used In This Investigation With That Of Clark And Wood

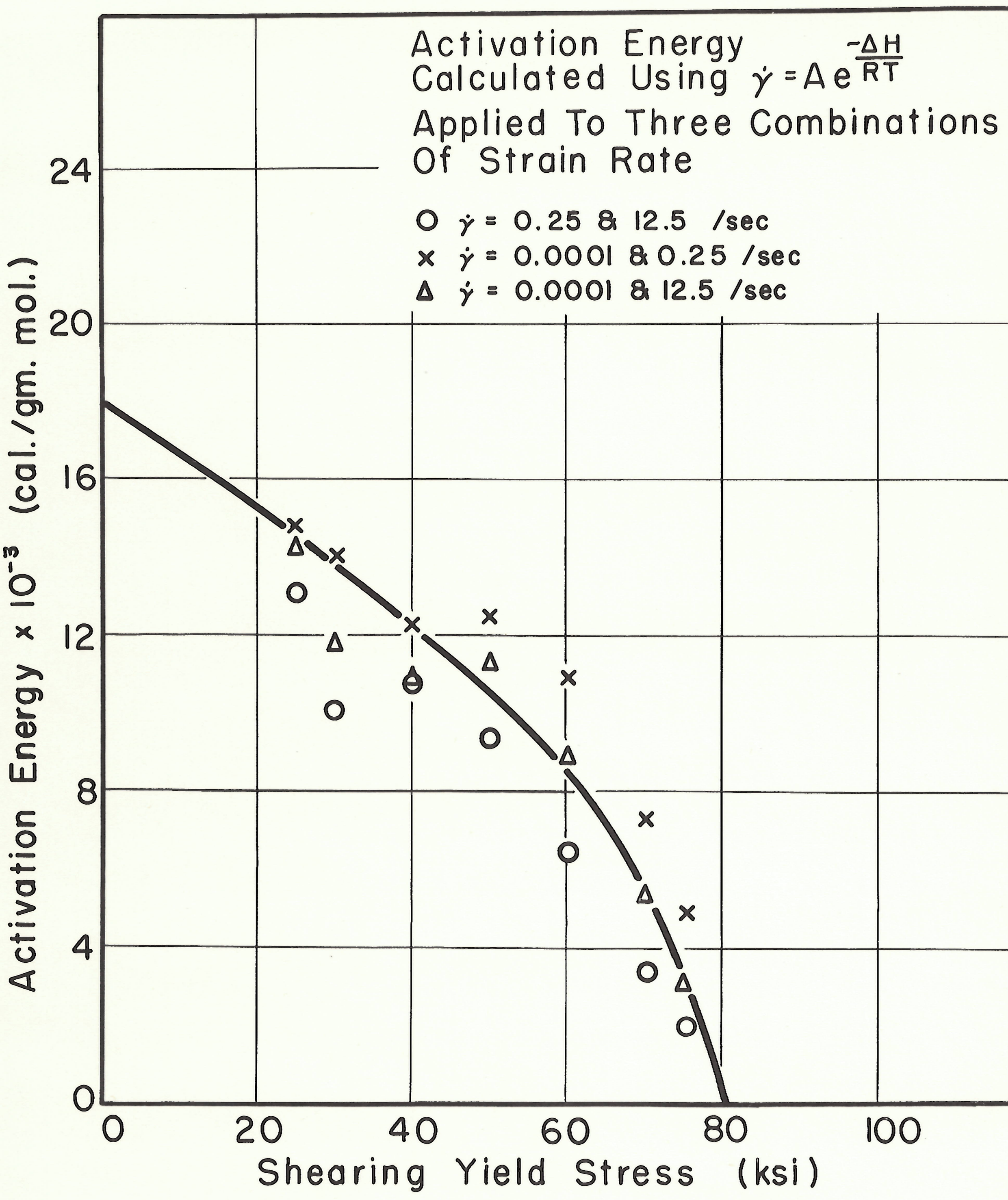

FIG. 11 EFFECT OF STRESS LEVEL ON THERMAL ACTIVATION ENERGY

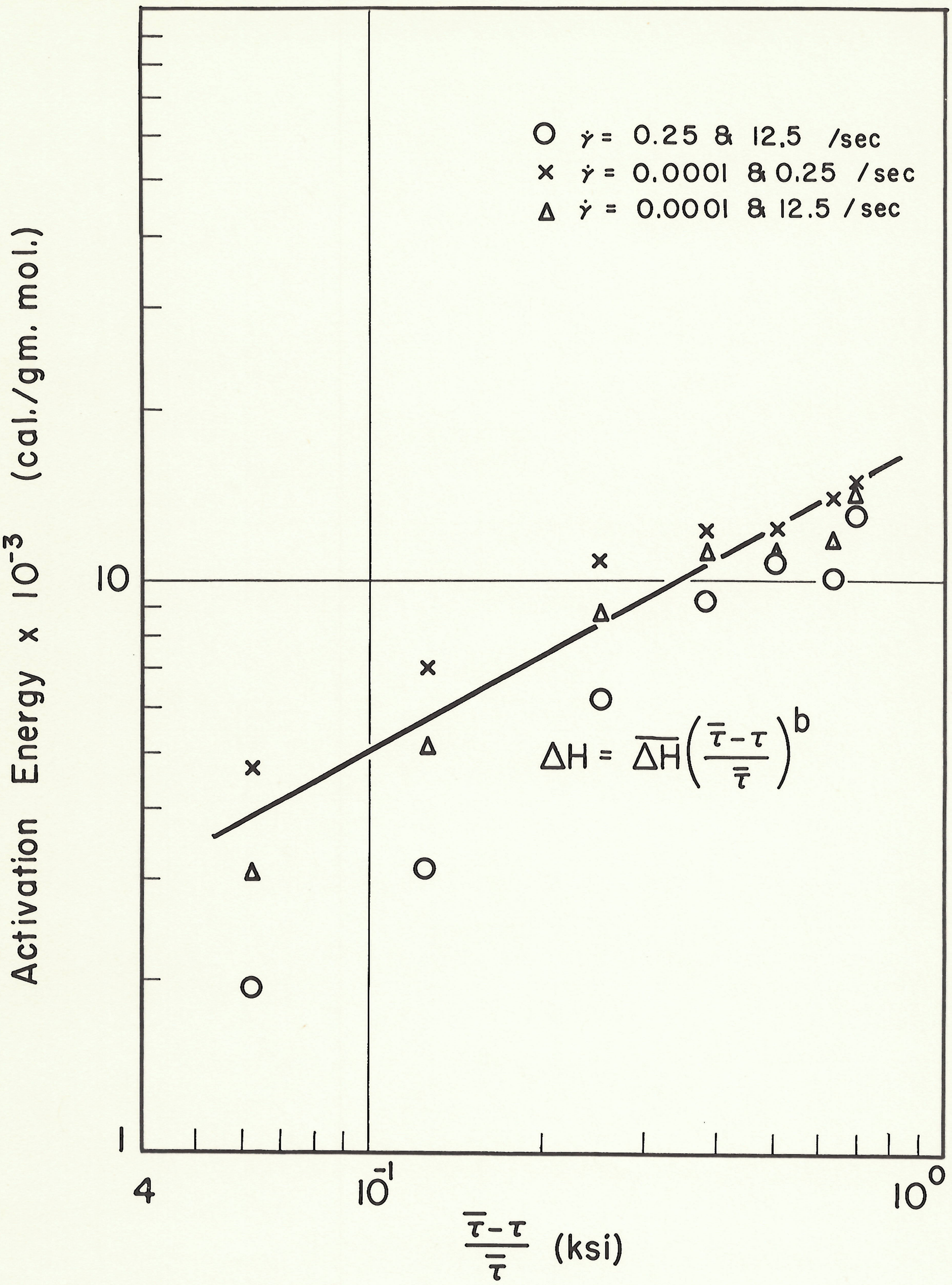

FIG. 12 DETERMINATION OF b USING DATA FROM FIG. 11

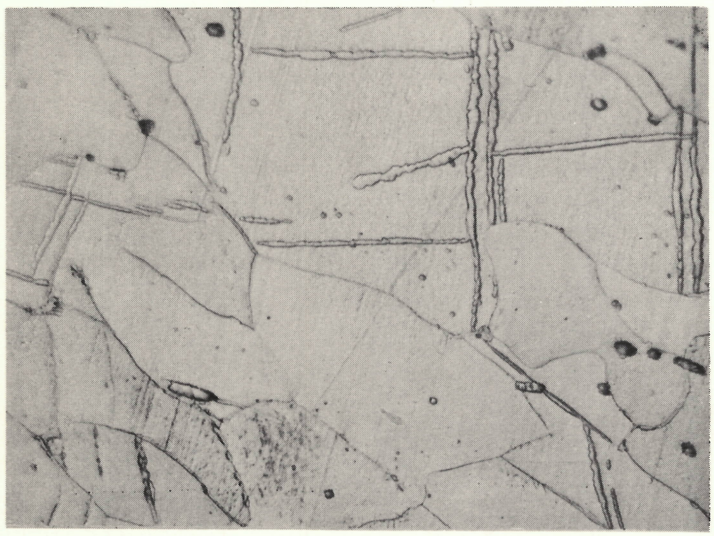

FIG. 13 Photomicrograph Of Specimen After Loading At $\dot{\gamma}$=12.5/sec., T=77°K (X400)

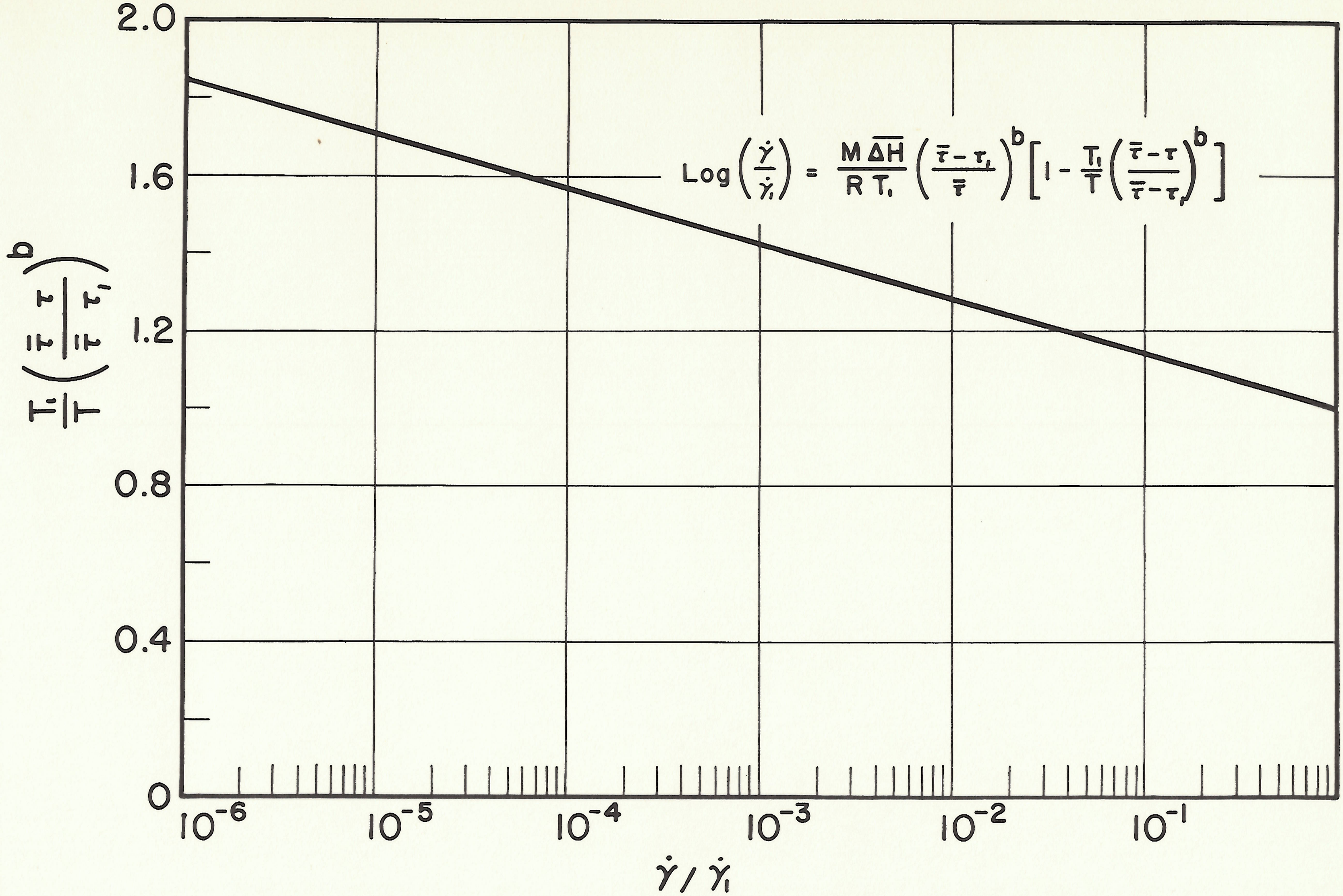

FIG. 14 Parametric Representation Of Theoretical Dependance Of Yield Stress On Temperature And Strain Rate

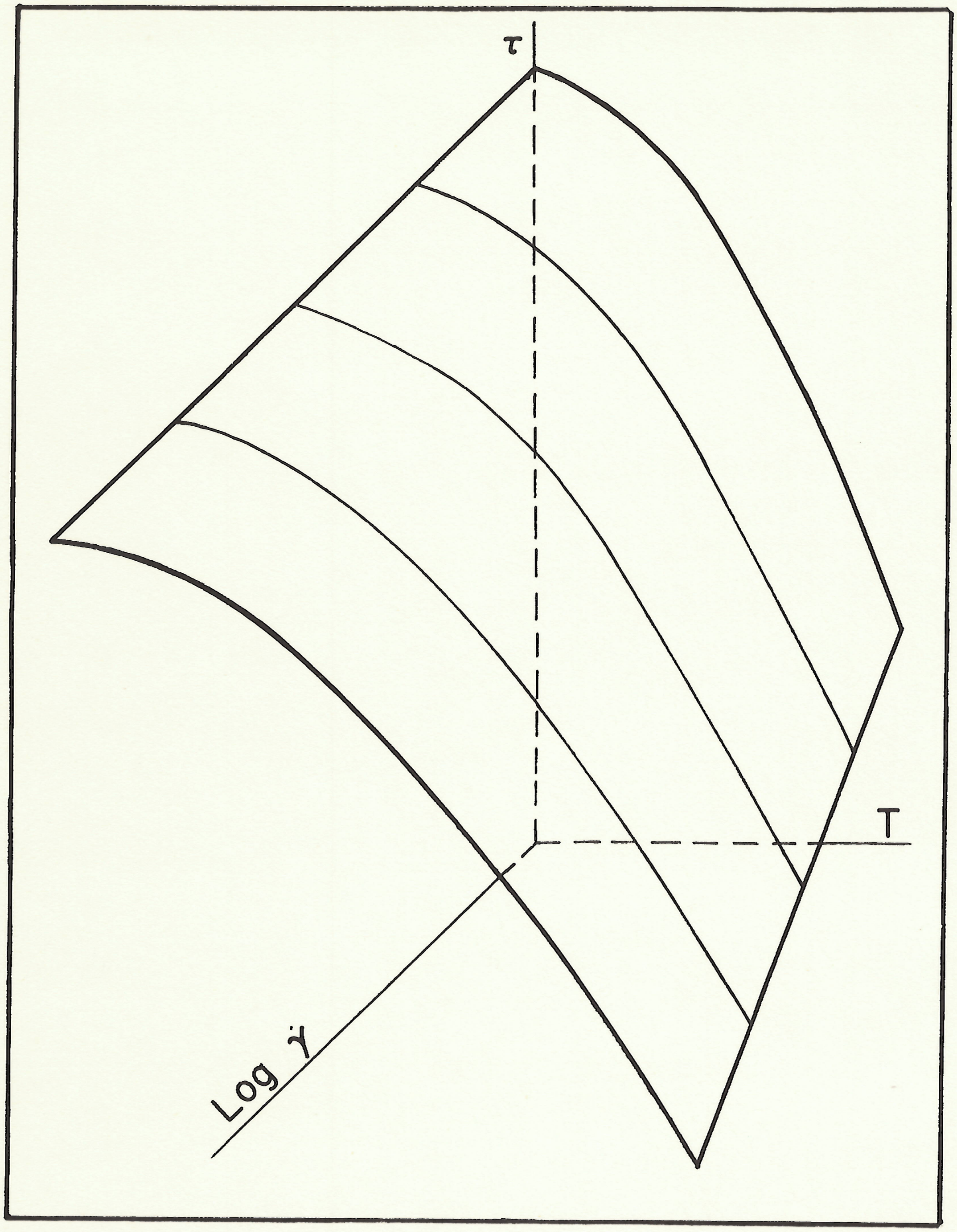

FIG. 15 Schematic Surface Representation Of Yield Stress, Temperature And Strain Rate Relationship