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Air Force Materials Laboratory

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FOREWORD

This report was prepared by the Strength and Dynamics Branch, Metals and Ceramics Division, under Project Number 7351, "Metallic Materials", Task Number 735106, "Behavior of Metals", Subtask 735106-043, "Fatigue and Reliability of Aerospace Materials". The research work was conducted in the AF Materials Laboratory, Wright-Patterson Air Force Base, Ohio, by Dr. W. H Reimann of AFML.

This report covers work performed from May 1967 to February 1968.

This manuscript was released by the author June 1968 for publication as an Technical Report.

This technical report has been reviewed and is approved.

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ABSTRACT

Recent investigations have emphasized that Ti-6Al-4V can show appreciable amounts of creep at room temperature. The present study was conducted in an attempt to establish the design limitations imposed by this behavior. It was concluded that as long as the applied stresses remain below the limit of proportionality the alloy exhibits no instability. However after plastic deformation, and under reversed loading, the alloy shows drastic dimensional instability at very low stresses. It is essential therefore that after forming, a component be given adequate stress relief prior to being put into service.

LIST OF ILLUSTRATIONS

I. INTRODUCTION

Recent investigations by Wood (Refs 1, 2) have shown that Ti-6Al-4V can exhibit appreciable amounts of creep at room temperature. Furthermore this creep can take place at stresses below the nominal yield point of the material.

The phenomenon of room temperature creep in titanium and its alloys is not new. Adenstedt (Ref 3) in 1949 was the first to show this for pure titanium and since then a number of other workers have obtained similar results for titanium alloys (Refs 4, 5, 6, 7). Of the common titanium alloys Ti-6Al-4V appears to show the least amount of room temperature creep.

The significant feature of Woods study has been to point out that the creep observed is very dependent on the loading method. The earlier investigations were restricted to uniaxial loading; however Wood has clearly shown that under torsional loading, the room temperature creep observed is far greater and takes place at stresses much lower than those required to initiate creep under simple tensile loading.

In view of the existing and planned wide-spread use of titanium alloys for aerospace applications where stability over long time periods is of vital concern, it is necessary that this creep phenomenon be fully understood and design limitations established. It was with this in mind that the AF Materials Lab undertook the following investigation.

II. PROCEDURES

All specimens tested were of Ti-6Al-4V. The specimens were tested in two standard heat-treated conditions - mill annealed and STA.

Two series of tests were performed, one series using uniaxial loading and the other using torsional loading. Figs. 1 and 2 show the specimen configurations used in each case. For the torsional tests some additional tubular specimens were made by drilling a 3/16" dia. hole along the axis of the specimen. After machining the specimens were heat treated prior to testing.

For the uniaxial testing a standard MTS testing machine was used. Initially an Instron clip-on extensometer was used to measure strains; however this was not successful because the long testing times involved in some of the tests permitted too much "drift" in the zero point of the strain measuring circuit. For these tests extensions were measured by a Tuckerman optical strain gage. This allowed extensions to be determined with an accuracy of better than 5 microinches, but had the disadvantage that the results could not be automatically recorded.

It was felt that the probability of observing creep would be greater for very low strain rates, therefore slow loading rates were used in most of the tests. The actual strain rates during the loading part of each test are shown on the respective figures.

In addition to simple load/hold tests, some specimens were subjected to cyclic load/unload and load/hold/unload testing. For these last tests the load-time profile shown in Fig. 3 was enscribed on the data track of the MTS testing machine. It was considered that this profile would approximate many expected aerospace service conditions.

For the torsion tests a special testing rig was designed and built which incorporated an optical torsional strain measuring systems. An overall view of the test set-up is shown in Fig. 4. The specimen forms a link between two shafts, one of which is rigidly restrained while the other is free to rotate. The specimen grips contain wedge blocks which bear against machined flats on the specimen and thus ensure that there is no slippage between specimen and grip. Rigidly attached to the end of the rotating shaft is a 8" dia. pulley with cable and pan so that the specimen may be dead loaded and the applied torque will remain constant with deflection.

To measure the resulting torsional strains, two mirros are fixed to two collars which clamp directly onto the test section by means of pointed positioning screws. By using a spacer attachment these collars can be clamped on to give an accurate 1" gage length. A close up view of the specimen with the collars in place is shown in Fig. 5. Deflections are observed by means of a telescope with cross hair eyepiece which focuses on the images of two vertical scales in the two mirrors. Deflections as small as $0^{\circ}02'$ can be readily observed by this method. For the strain calculations deflections were determined as the deflection of the movable end minus the deflection of the "fixed" end of the gage length. In this way elastic deflections in the test rig itself can be eliminated. These elastic deflections turned out to be quite appreciable. For small angles of twist this proved to be a very accurate method. For larger angles of twist (>10°) the accuracy decreased somewhat because the mirrors had to be periodically rezeroed. The error introduced by the fact that the two mirrors do not lie along the axis of the specimen may be ignored as long as the mirror-scale distance is kept large.

The method for determining the torsional stress-strain data was as follows. After the specimen was set in the testing rig the zero point for each of the mirrors was read. A dead load was then applied and the deflections of each of the mirrors again noted. If after 1 - 2 hours no further deflection was observed the specimen was unloaded and the zero rechecked. The load was then increased by one step and the process repeated. If the specimen started to creep under the applied torque, the load was maintained constant until the specimen had again come to rest. This proved to be very time consuming since 25 - 50 hours were frequently required. At the highest stress levels used the specimen did not come to rest but continued to creep although at a decreasing rate. In these cases the load was maintained for a period of 150 - 300 hours and then removed.

Torsional stresses and strains were calculated from the following standard equations:

$$\text{Shear strain } \gamma = \frac{r\theta}{L}$$

Where r = specimen test section radius

θ = angle of twist (radians)

L = gage length

Maximum shear stress

$$\tau_{max} = \frac{16\ M_T}{\pi\ D^3} \text{ (solid specimen)}$$

$$\tau_{max} = \frac{16\ M_T\ D_1}{\pi (D_1^4 - D_2^4)} \text{ (tubular specimen)}$$

Where M_T = applied torque (in-lb)

D, D_1 = outside diameter

D_2 = inside diameter of tube

III. RESULTS

A. Uniaxial Loading

Prior to any other testing, one specimen from each heat treated condition was pulled in simple tension to determine the 0.2% yield strength and the limit of proportionality. The values obtained are shown below:

	0.2% Y.S.	L.P.
Mill annealed	133.4 ksi	119 ksi
STA	152.0 ksi	127.5 ksi

Figs. 6 and 7 show the effect of simple incremental loading with a 30 minute hold time at each level. It can be seen that under these conditions no creep is observed below the limit of proportionality of the alloy.

The result of cyclically loading the specimen can be seen in Figs. 8 and 9. Each specimen was subjected to 100 cycles zero to maximum stress at a frequency of 0.5 Hz. Again it is clear that no strain accumulation takes place below the limit of proportionality.

Fig. 10 summarizes the results obtained from using the load-time profile shown in Fig. 3. Again it can be seen that even at 90% of the yield stress the strain accumulation with cycling is very small.

Although not shown in Fig. 10, one more test for each heat treated condition was run, in which the load was cycled from +80% to -40% of the yield stress. Again, no creep was observed.

All of the above results confirm the early published data which indicate that room temperature creep in titanium alloys does not take place below about 85% of the yield stress (e.g. Ref 7). Therefore it was concluded that under uniaxial loading, room temperature instability of titanium alloys does not present a design problem; nor is there any reason to doubt the validity of the published data.

B. Torsional Loading

The stress-strain relationships obtained from simple dead-weight torsional loading are shown in Figs. 11 and 12.

It was felt that the best reference point to study instability effects would again be the limit of proportionality, which was taken as the first observable departure from the elastic line. The values of the torsional limit of proportionality for the two heat treated conditions were determined to be 62.5 ksi for the mill annealed conditions and 72.0 ksi for the STA condition.

Fig. 13 is the equivalent stress strain relation for a mill annealed thin walled tubular specimen and it can be seen that the behavior is essentially identical. The value of 61.0 ksi for the limit of proportionality is in good agreement with that obtained from the solid specimen.

Fig. 14 illustrated some typical torsional creep curves. As was the case in the uniaxial tests, it can be seen that under simple torsional loading, no instability is observed below the limit of proportionality.

Fig. 15 shows the effect on a mill annealed tubular specimen of interrupted and reversed torsional loading. The specimen was loaded to the point where continuous torsional creep occurred and allowed to creep extensively (to a plastic shear strain of approximately 0.03). After this creep the specimen was unloaded and allowed to rest for 50 hours under zero load. During this rest period a very small amount (.0009 shear strain) of reverse plastic creep was observed. The specimen was then reloaded in the same direction. No creep was observed until the previously applied maximum load was reached, when the specimen again exhibited instability. At this stage the specimen was unloaded again and loaded in the reverse direction. As can be seen from Fig. 15 this had a very drastic effect on the creep. The specimen started creeping as soon as the load was reversed and there was no clearly defined elastic region. This exaggerated Bauschinger effect has already been emphasized by Wood (Ref 2) and the present results merely confirm it. Upon reversing the load again back to the original direction the same effect took place with the specimen exhibiting instability as soon as the load went through zero. After this symmetrical hysteresis loop was established, the specimen was removed from the testing machine and reheat treated to the mill anneal condition before reloading. The effect of this heat treatment on the loading can be seen in Fig. 16. It is clear that the effects of the prior plastic deformation have been completely eliminated, and the specimen follows the initial loading curve.

The specimen was taken just into the creep region (a shear strain of approximately 0.003 as against 0.03 initially) and then the load was reversed again. It is clear from Fig. 16 that again the specimen exhibits instability at stresses far below the original limit of proportionality. However a comparison of Figs. 15 and 16 show that the amount of creep at any intermediate load is much smaller in the second case. This would appear to indicate that the instability observed upon load reversal is a function of the prior plastic strain.

IV. DISCUSSION

The above results re-emphasize the well known fact that titanium alloys can exhibit appreciable amounts of creep at room temperature. However the point of concern at present is the influence of this phenomenon on the applications for which these alloys are being considered.

For the present applications at least there does not appear to be any real instability problem. It is clear that as long as the stresses to which the component will be subjected remain within the elastic range, whether those stresses are steady or cyclic, the alloy will not exhibit creep. The design loads used in the various applications all lie well within this region.

The marked Bauschinger effect shown by this alloy is a very significant feature that must be taken into consideration. This Bauschinger effect occurs where the load is reversed after prior plastic deformation. As already stated the design loads are well within the elastic range and therefore would not produce this effect. However two cases come to mind where it could be significant.

The first of these is the common practice of creep-forming large titanium sheet components. It is imperative that after creep forming, components that will be subjected to reversed loadings be given adequate stress-relief treatments to ensure stability (see Ref 2).

The second case to be considered is the possibility of plastic overloads resulting from gust loading, severe maneuvers or clear air turbulence. This case is not as simple as the first, nor is the solution as readily available. More investigation is required before quantitative answers can be supplied but it is probable that this also is not as severe a problem as it might appear at first glance. It must be remembered that the results shown in this investigation and the observations of Wood (Ref 2) were obtained by dead weight loading where the specimen was given every opportunity to deform by maintaining the load for a period of many hours. The overloads resulting from gust etc. take place at very high loading rates. The plastic deformation experienced would be extremely small (if any) and therefore the induced instability upon any load reversal would also be correspondingly small.

It would be of interest to determine the extent of the Bauschinger effect under reversed uniaxial loading. Unfortunately the present test facility did not permit this to be done as any attempt to apply plastic compressive loads resulted in severe buckling problems so that the measurements were rather meaningless. However there is no reason to suppose that the same effects would not take place under simple uniaxial loading.

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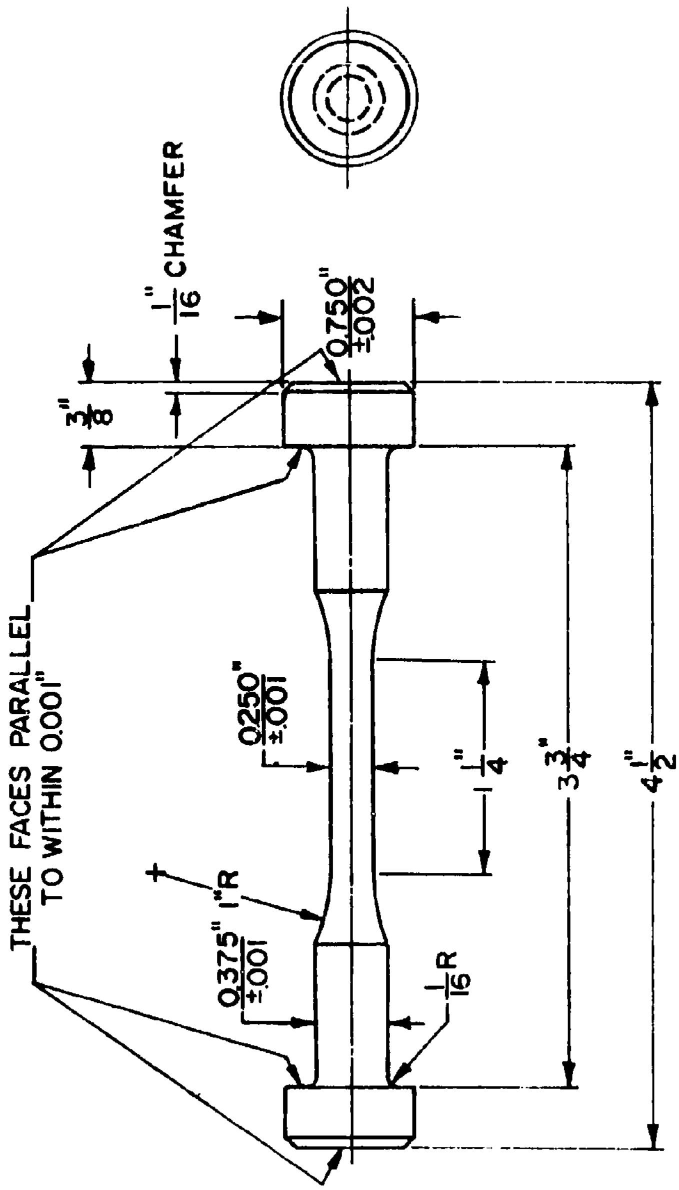

Figure 1. Tensile specimen configuration.

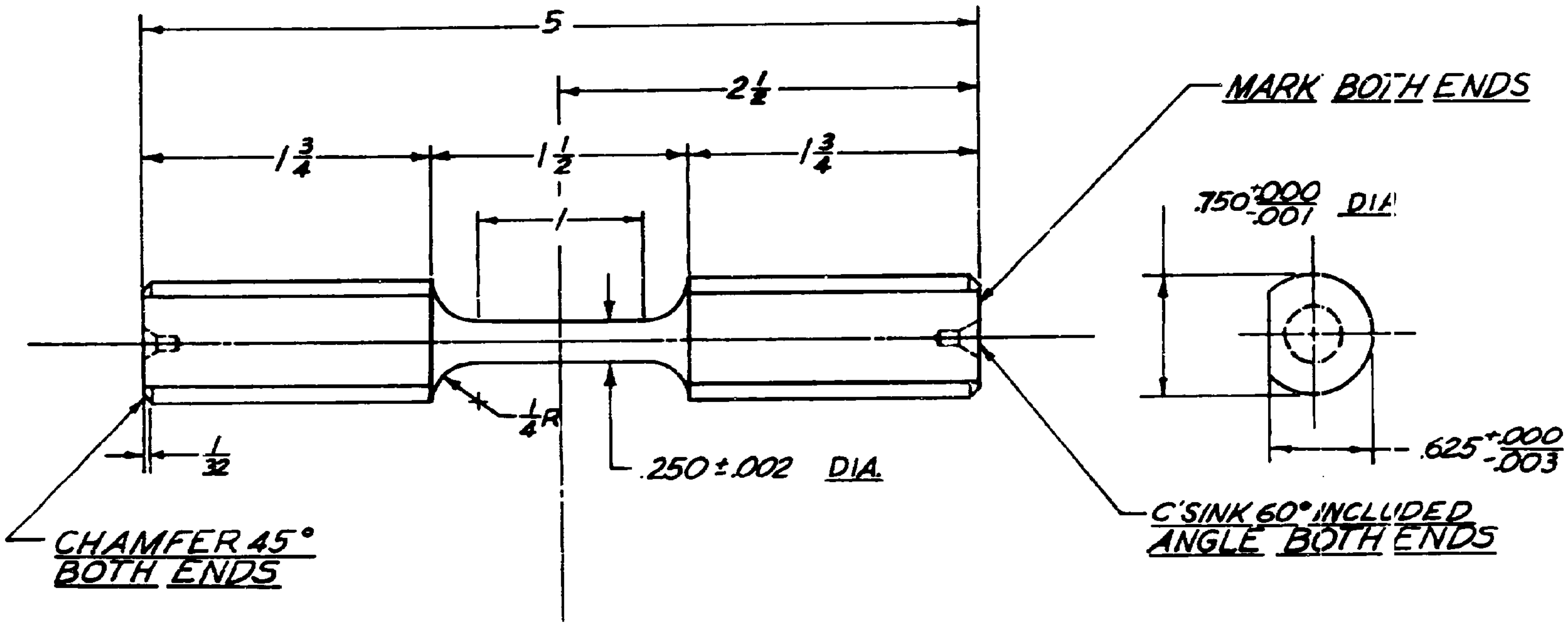

Figure 2. Torsion specimen configuration.

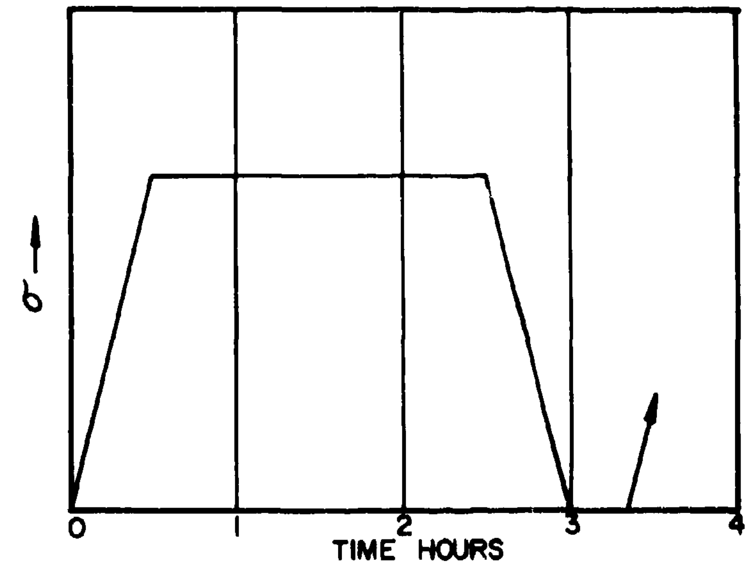

Figure 3. Load-time profile used in slow cycle tensile tests.

Figure 4. Overall view of torsional straining test rig.

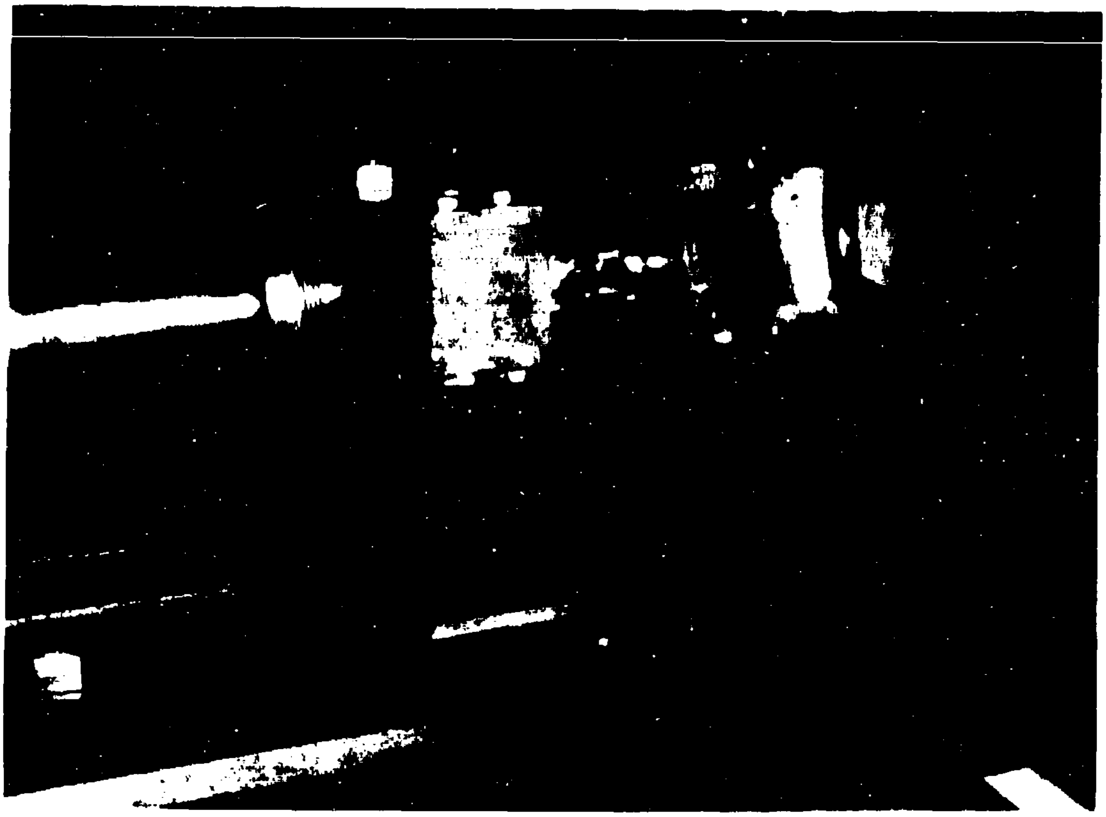

Figure 5. Close up view of specimen with mirror collars in place.

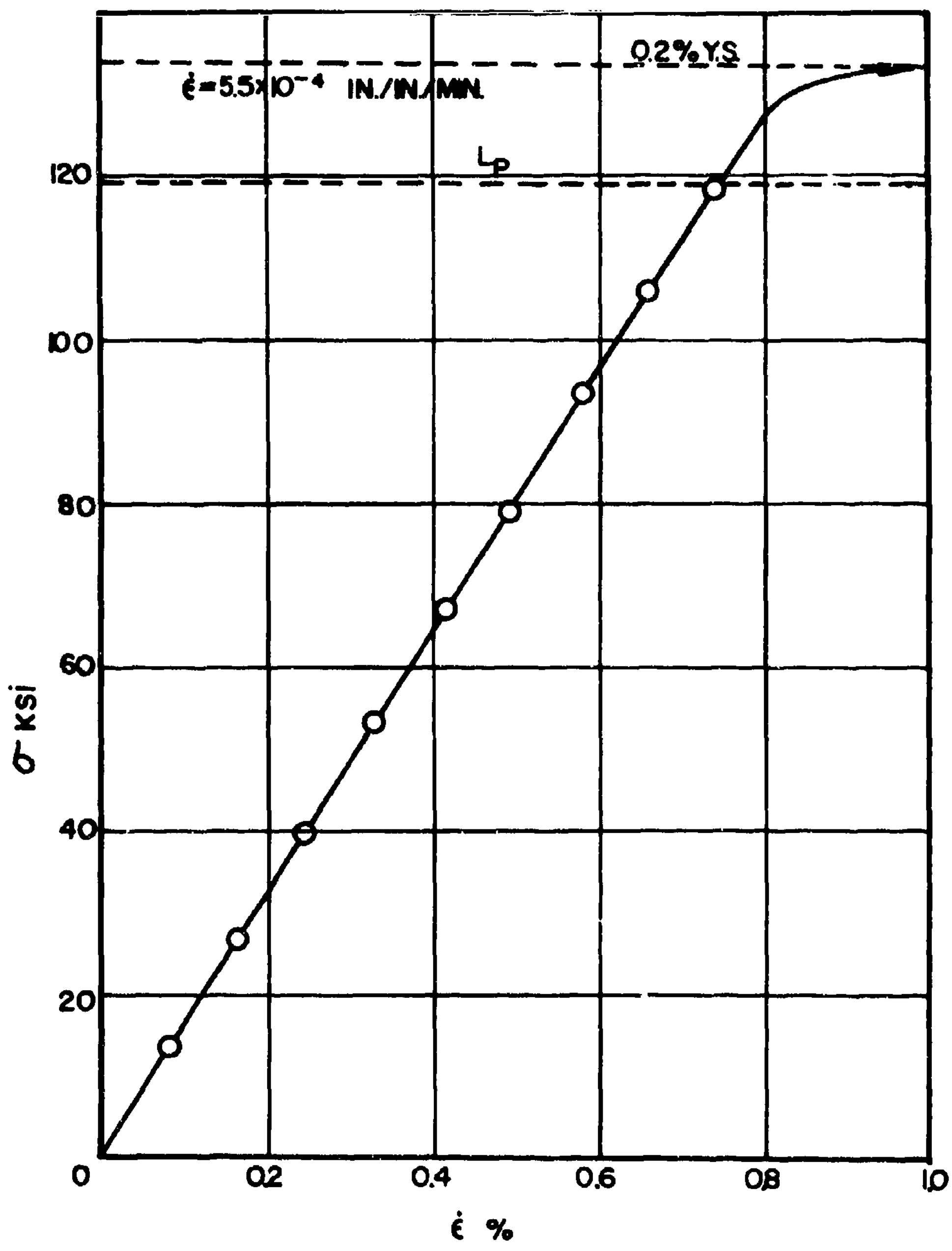

Figure 6. Incremental loading with 30 minute hold time (mill annealed condition).

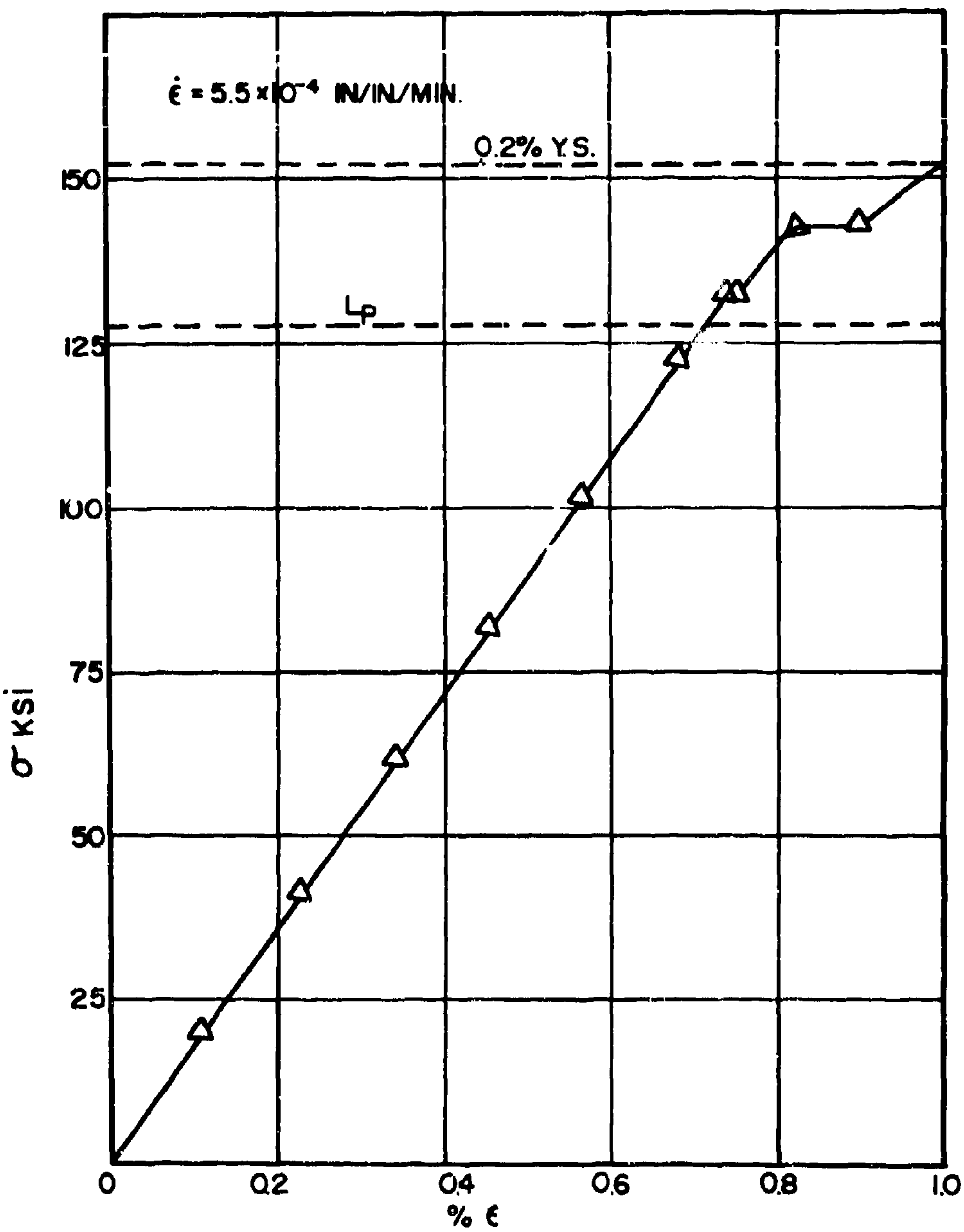

Figure 7. Incremental loading with 30 minute hold time (STA condition).

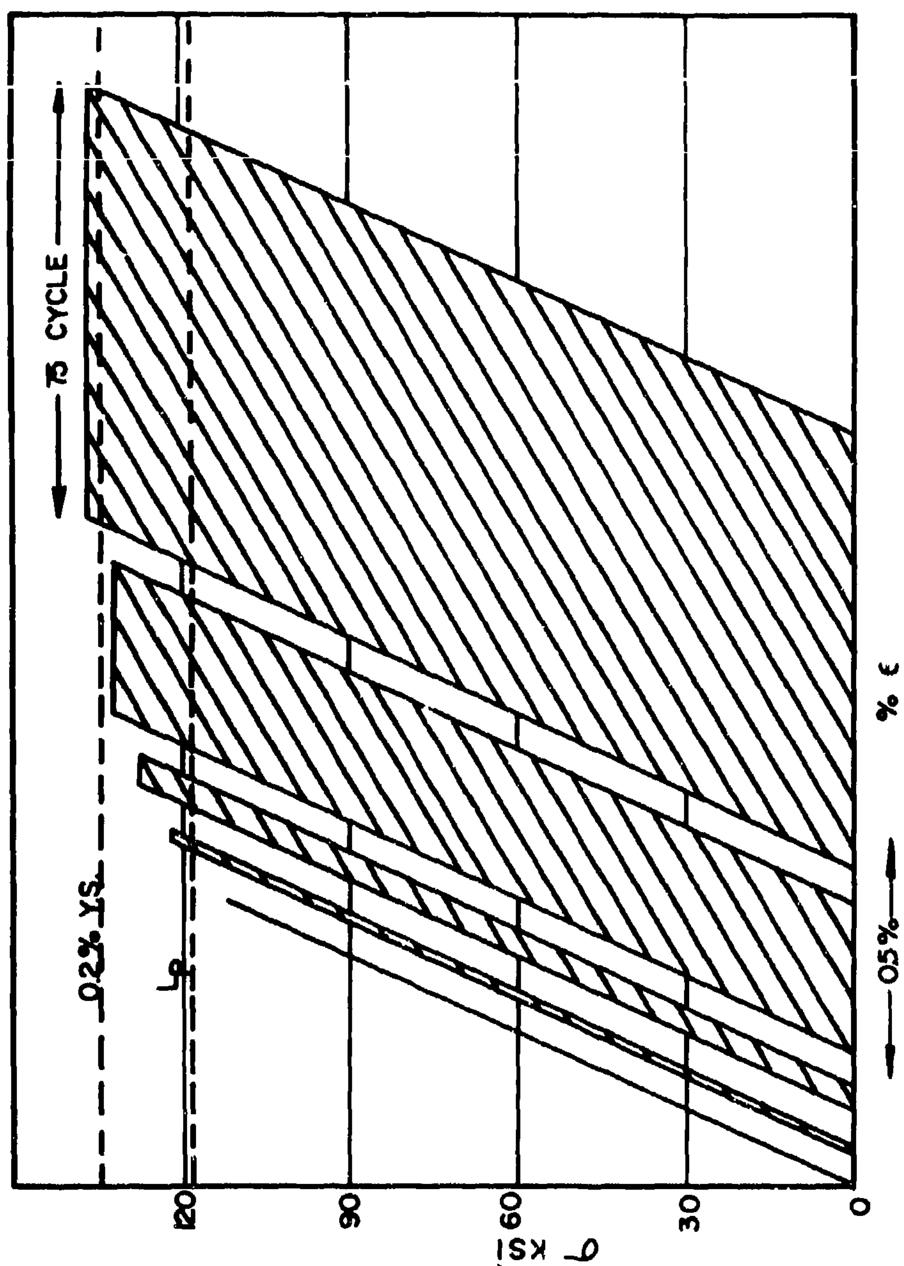

Figure 8. Effect of 100 0-σ_{max} load cycles at a frequency of 0.5 Hz. (mill annealed condition)

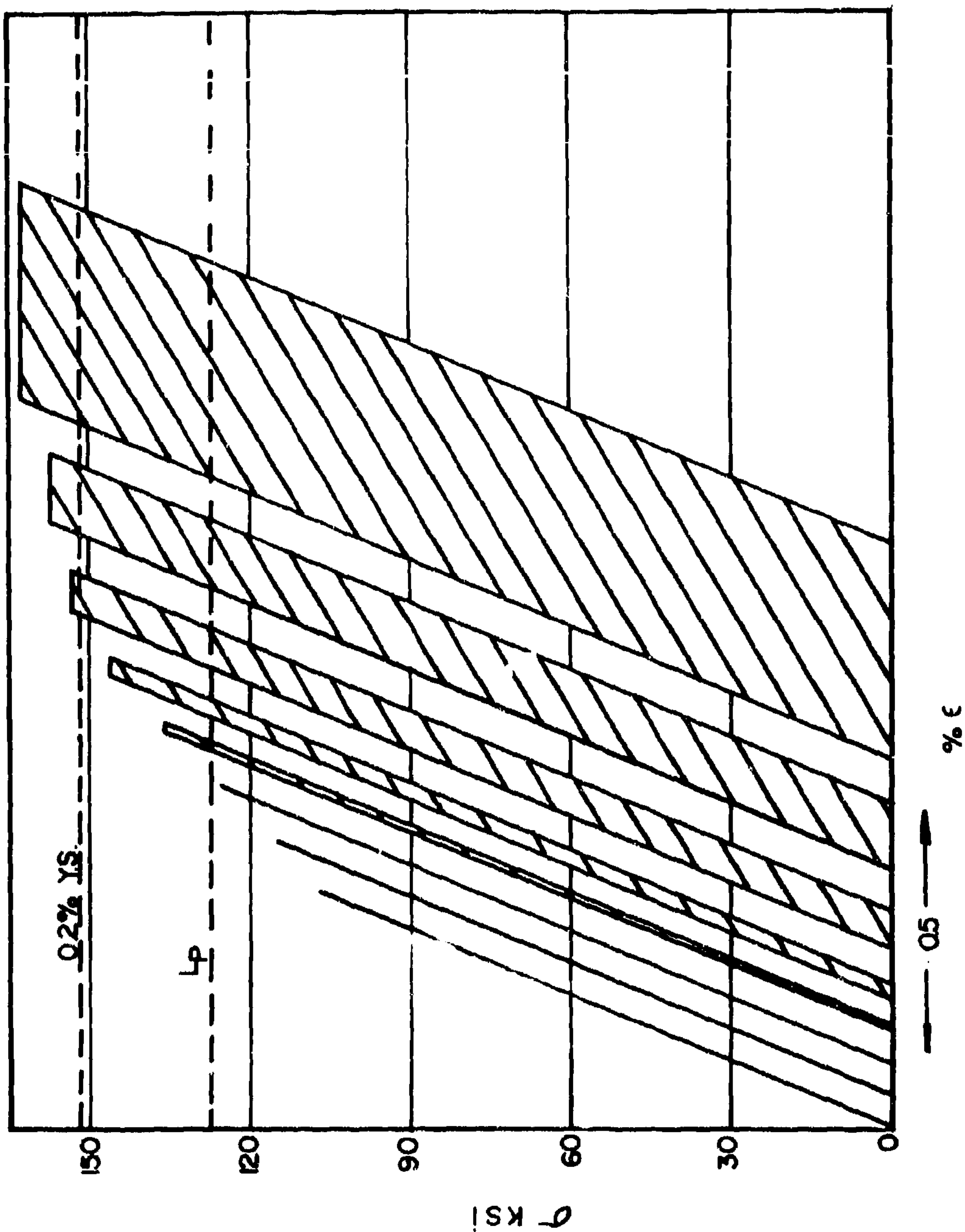

Figure 9. Effect of 100 $0-\sigma_{max}$ load cycles at a frequency of 0.5 Hz. (STA condition)

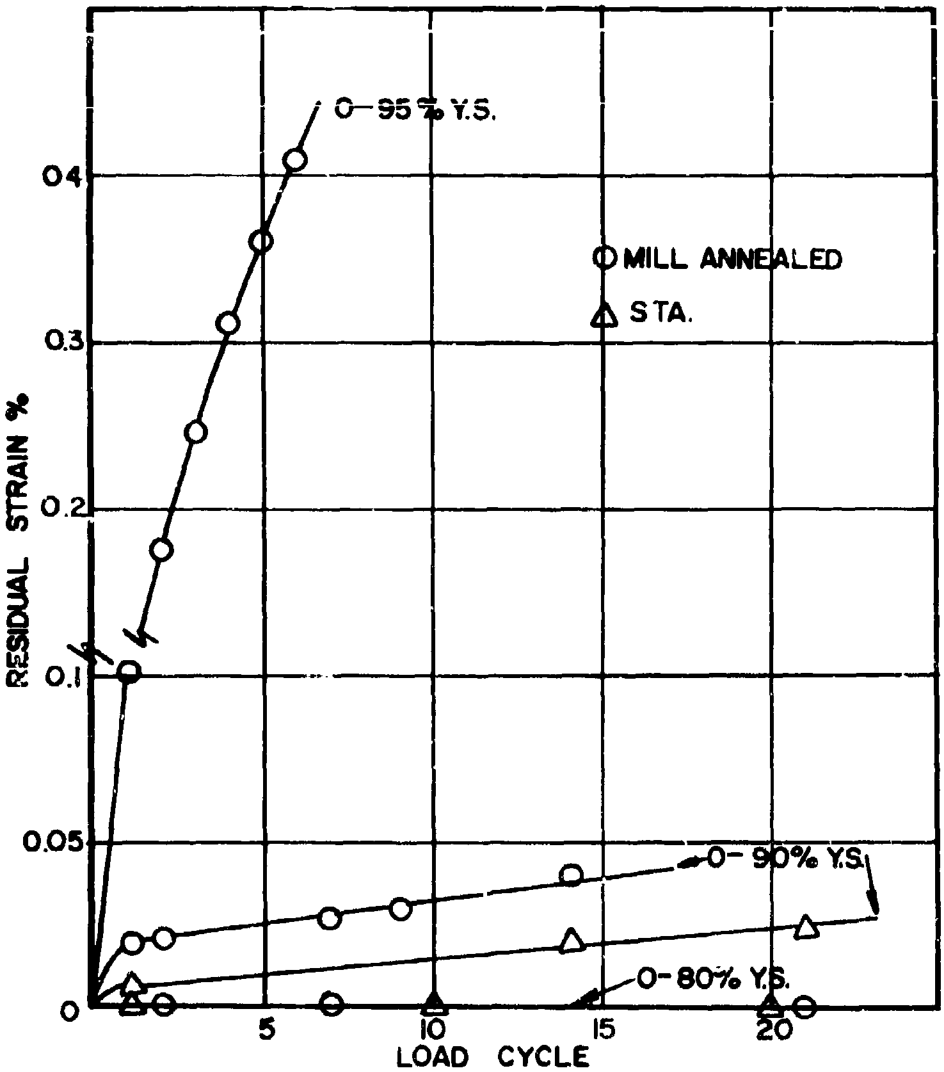

Figure 10. Effect of slow cycling with hold time on the two heat treated conditions.

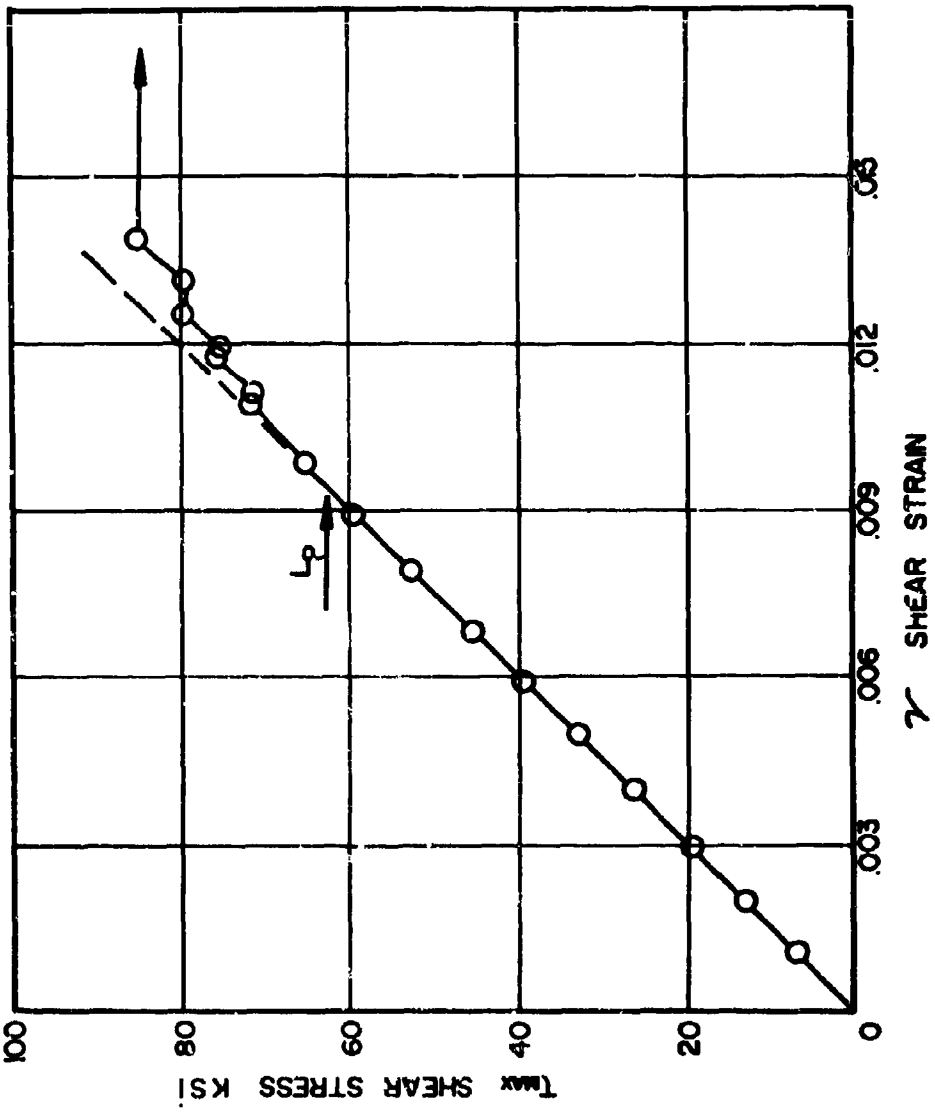

Figure 11. Torsional stress-strain diagram for solid mill annealed specimen.

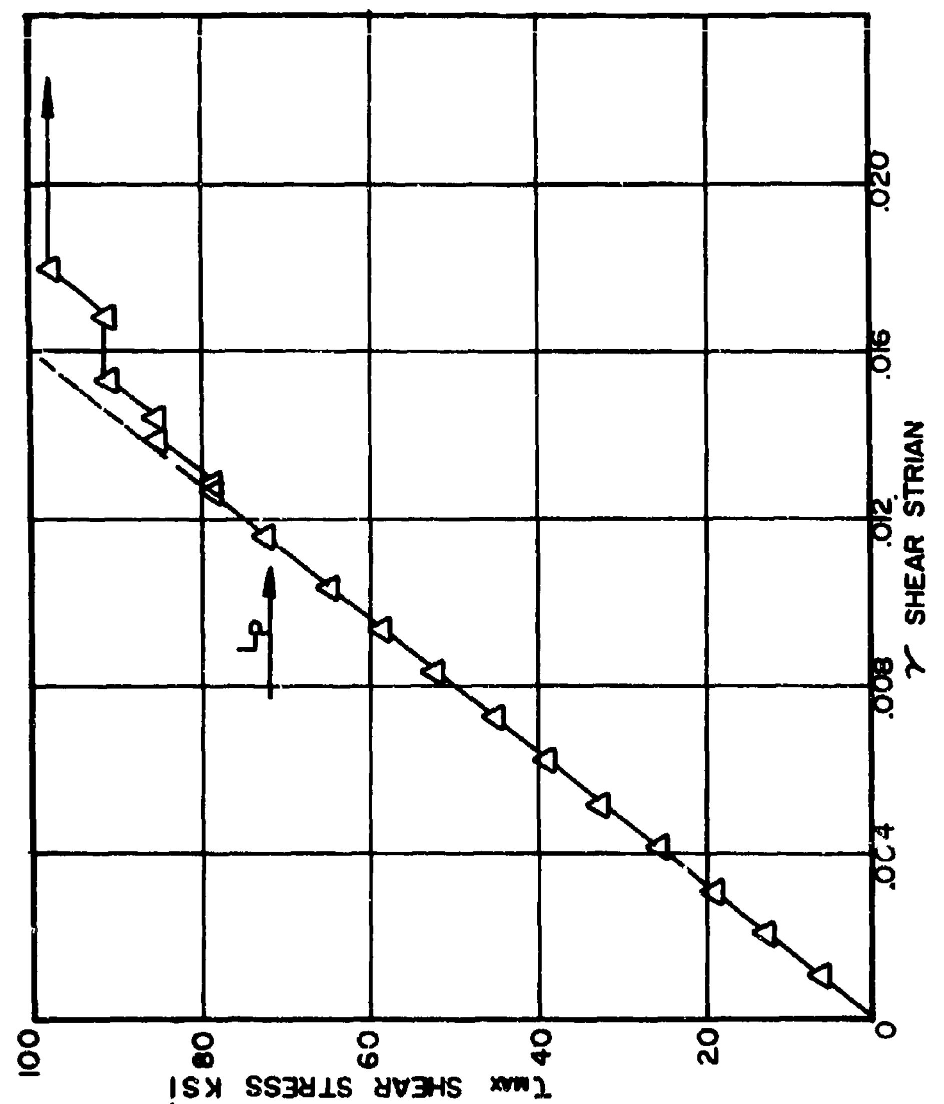

Figure 12. Torsional stress-strain diagram for soli… STA specimen.

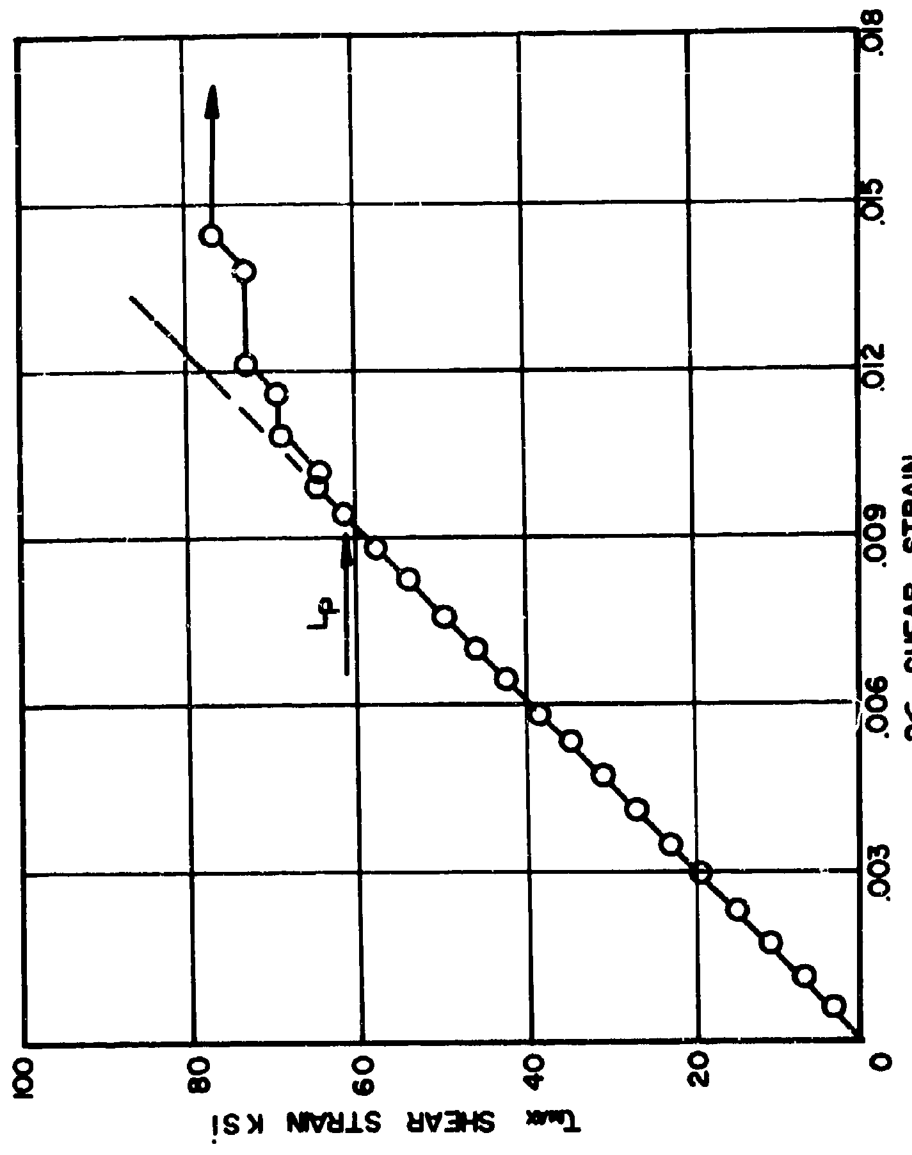

Figure 13. Torsional stress-strain diagram for tubular mill annealed specimen.

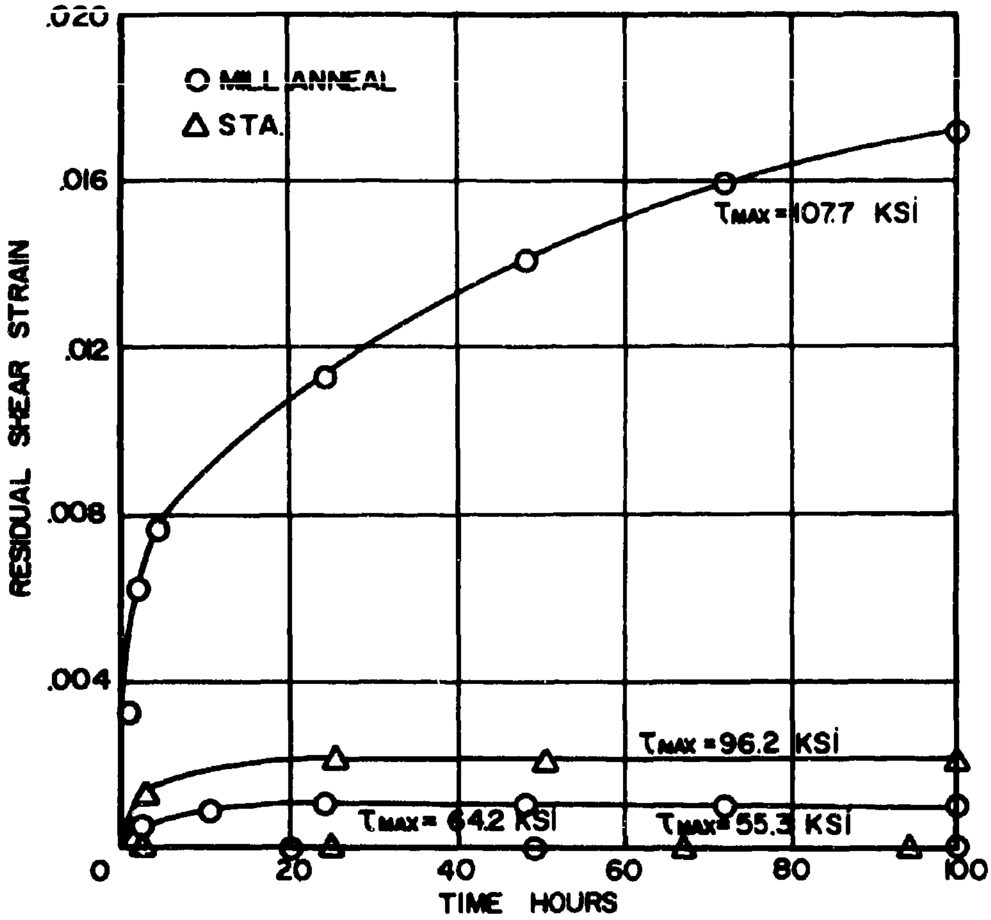

Figure 14. Typical torsional creep curves for the two heat treated conditions.

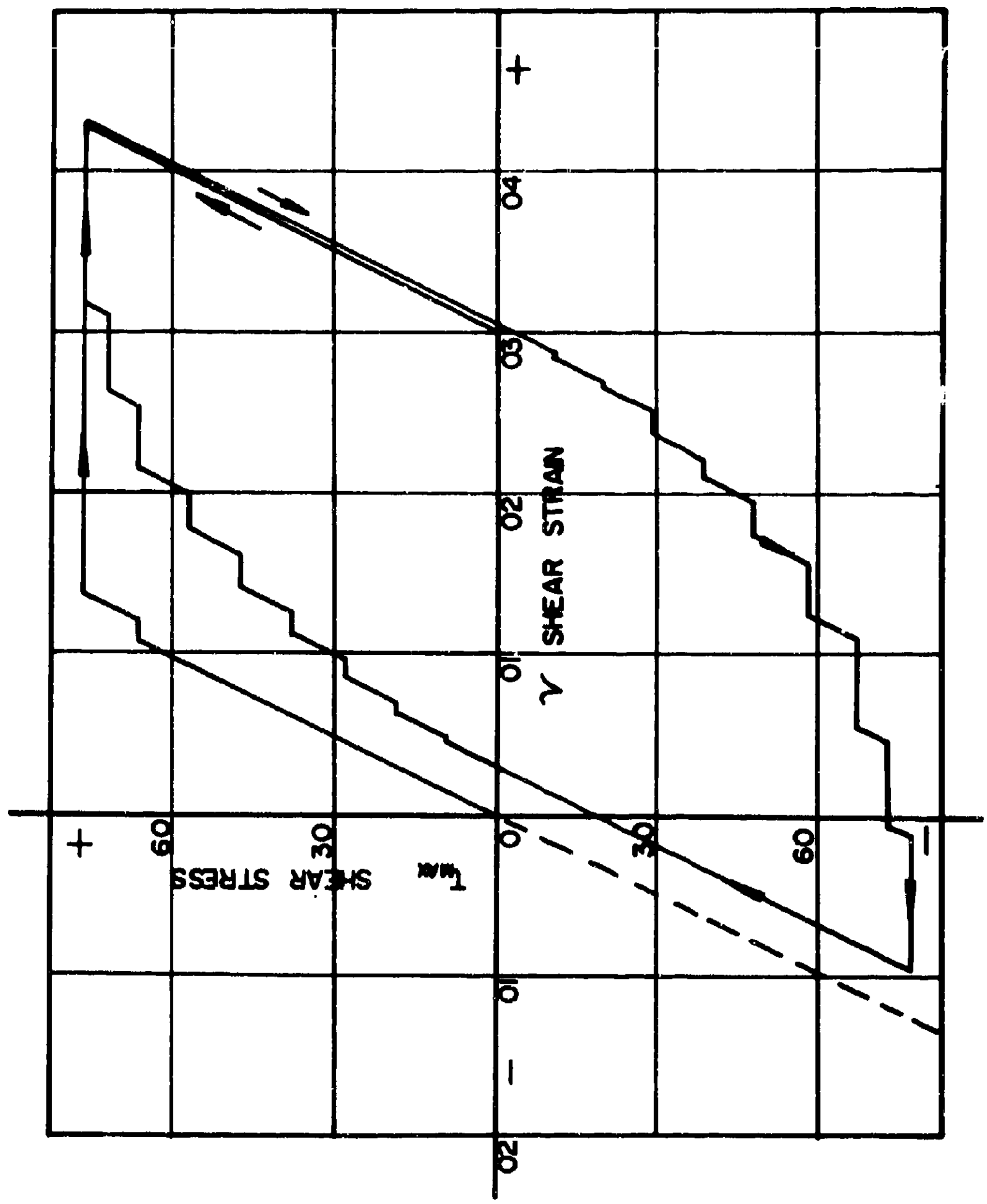

Figure 15. Effect of reversed torsional loading on tubular mill annealed specimen.

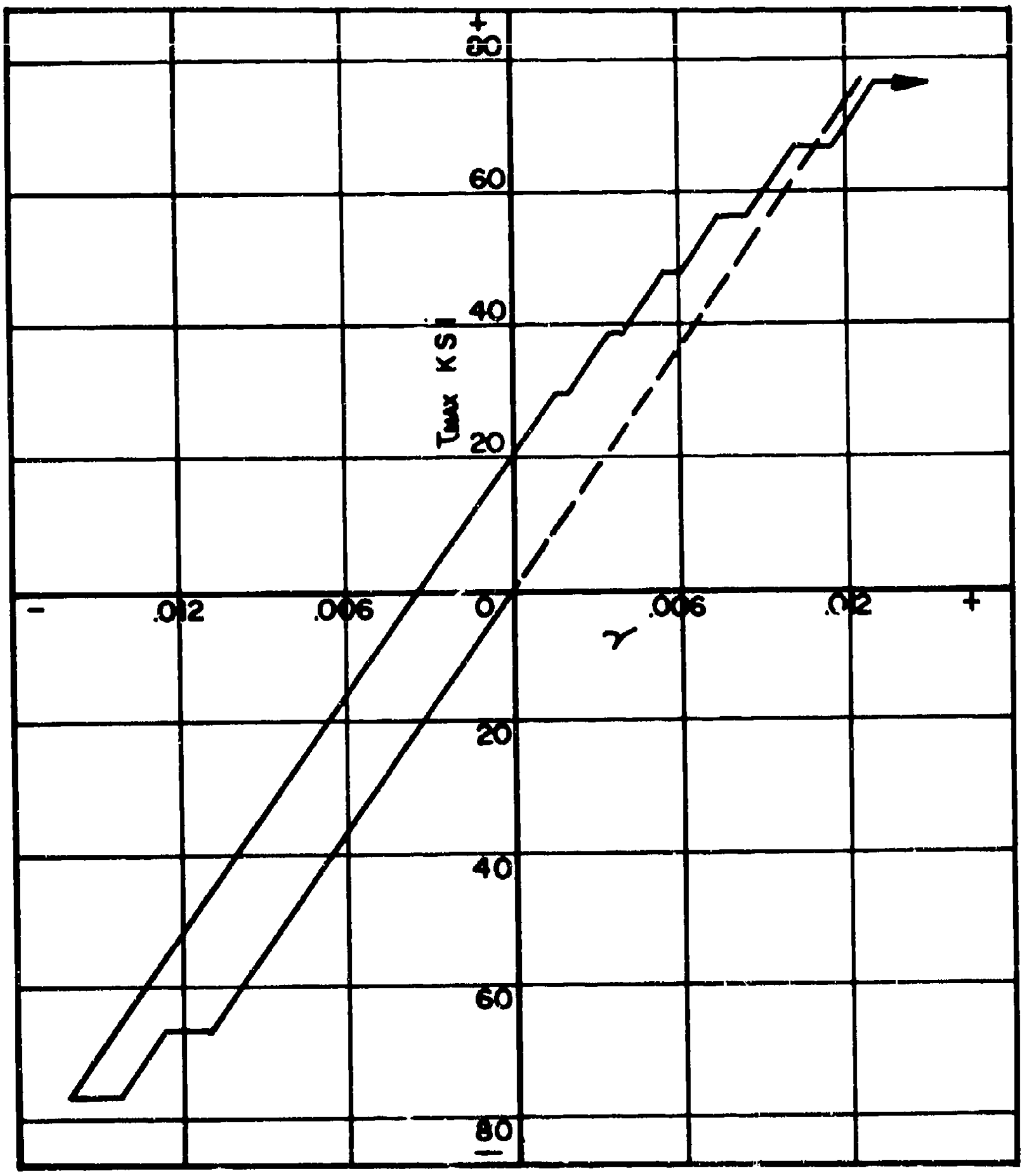

Figure 16. Effect of intermediate anneal plus reversed torsional loading on tubular mill annealed specimen (same specimen as in Figure 15).

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