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An Experimental Study of Biaxial Yield in Modified 9Cr-1Mo Steel at Room Temperature

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9Cr-1Mo STEEL AT ROOM TEMPERATURE

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SUMMARY

This paper describes two biaxial experiments which investigated yield, hardening, and flow behavior in modified 9Cr-1Mo steel at room temperature. The aim of these experiments was to determine whether the procedures recommended in NE Standard F9-5T for inelastic design analysis are applicable for this material in normalized and tempered condition. The first experiment investigated small-offset yield behavior subsequent to radial preloads ($\sqrt{3} \sigma_{12} = \sigma_{11}$) in tension-torsion stress space. The second experiment investigated yield behavior subsequent to nonradial preloads and also the time-dependent flow occurring during 0.5 hr hold periods at constant stress.

The results of these experiments were qualitatively similar to those obtained earlier for types 304 and 316 stainless steel. Specifically, the von Mises yield criterion was found to provide a reasonable approximation of initial yield behavior. Although the subsequent yield surfaces suffered considerable distortion from their near-circular form after both radial and nonradial preloads, the hardening behavior was to the first order kinematic in nature. The strain-time data obtained during the 0.5 hr hold periods showed characteristics typical of creep curves. As in the case of earlier experiments, the high initial flow rates diminished more rapidly than would be estimated from elevated temperature data.

INTRODUCTION

One activity within the High Temperature Structural Design Program at the Oak Ridge National Laboratory (ORNL) is the development of constitutive equations for structural alloys intended for Advanced Reactor Systems. These equations were first developed using concepts borrowed from classical plasticity and classical creep (ref. 1).

Experiments conducted in support of this work included investigations of yield and hardening behavior under biaxial loading. Early experiments were conducted at 20 °C on a number of alloys in solution annealed condition including types 304 and 316 stainless steel (refs. 2 to 5). The data generated in these experiments were used in conjunction with the results of companion creep test programs to formulate recommended procedures for the inelastic design of nuclear reactor components (ref. 6).

More recently, attention has been directed at another candidate material for this application, modified 9Cr-1Mo steel. The advantage of this material is that up to 600 °C, it combines the relatively high creep strength of the austenitic steels with the superior steam corrosion resistance of the ferritic steels. This combination of properties is obtained by adding niobium and

vanadium to the standard composition and by using the material in normalized and tempered condition.

One difficulty with this approach is that use of materials in normalized and tempered condition represents a departure from past practice in the case of ASME Class 1, nuclear reactor components. Such an approach raises obvious questions regarding the applicability of recommended constitutive models which, as noted above, were developed for austenitic steels in solution annealed condition. One of a number of factors bearing on this question is whether the yield and hardening behavior of modified 9Cr-1Mo steel under biaxial loading is qualitatively similar to that of the austenitic steels. The subject experiments were aimed at addressing this particular question for test conditions as near identical as possible to those investigated earlier.

TEST PLAN

The plan was to use two thin-walled, tubular specimens for the present investigation. The first specimen was to be used to investigate small-offset yield behavior after radial preloads ($\sqrt{3} \sigma_{12} = \sigma_{11}$) in tension-torsion stress space. This experiment was to be conducted in four stages. Stage (1) involved determination of an initial yield surface; Stage (2) involved determination of a yield surface subsequent to a radial preload to a point 1.5 times the radius of the initial yield surface in the tensile sense; Stage (3) repeated Stage (2) for a radial preload in the compressive sense; and Stage (4) involved determining a yield surface after the specimen had been returned to an unstressed and unstrained state. The small-offset definition of yield used in these experiments was 25 microstrain ($\mu\epsilon$).

The second specimen was to be used to investigate yield behavior subsequent to nonradial loadings. This part of the study was to be conducted in five stages. The first two stages were identical to those used in the first experiment. The third stage of the experiment involved rotating the planned preload trajectory through 45° in the clockwise sense, loading along this trajectory a predetermined amount, and then determining the new yield surface. This procedure was to be repeated in stages (4) and (5) for further 45° rotations of the preload trajectory. Another feature of the second experiment was that time-dependent flow was to be measured under constant stress during each stage of preloading.

EXPERIMENTAL DETAILS

The test equipment and procedures used in these yield surface investigations have been described in detail previously (refs. 2 and 3). Briefly, these experiments are conducted under computer control on MTS electrohydraulic test systems with provision for tension-torsion loading. The tubular specimens are instrumented with foil strain gauge rosettes which provide decoupled measures of axial strain and tensorial shear strain. These strain signals are used for control purposes in conjunction with signals from the tension-torsion load cell.

During yield surface probes, the best straight lines corresponding to elastic loading are first determined for both the axial and torsional components of loading. As loading increases, checks are made for any deviations

from linear stress-strain response resulting from the onset of inelastic straining. On detecting a deviation of 25 $\mu\epsilon$ equivalent plastic strain, loading is returned to zero. Equivalent strain, $\bar{\epsilon}$, is calculated in these experiments using the expression

$$\bar{\epsilon} = \left(\epsilon_{12}^2 + 3/4 \epsilon_{11}^2 \right)^{1/2}$$

where ϵ_{12} is the tensorial shear strain and ϵ_{11} is the axial strain. The same program allows yield surface probes to be conducted at 16 preset angles in tension-torsion stress space. A second use of the computer control is to facilitate the loading specimens over predetermined paths in stress space prior to investigating subsequent yield behavior.

The material investigated was 9Cr-1Mo steel, CarTech Heat 30383, supplied in normalized and tempered condition in the form of 95 mm o.d. bar. After finish-machining, the tubular specimens were subjected to the following heat-treatment:

Normalize - heat to 1038 °C, hold for 1 hr, and air cool to room temperature.

Temper - heat to 760 °C, hold for 1 hr, and air cool to room temperature.

Postweld held-treatment (PWHT) - heat to 732 °C, hold for 42 hr, and air cool to room temperature.

The final stage of heat-treatment was selected as being typical for breeder reactor service. The specimens were under vacuum during all stages of heat-treatment and subsequent inspection showed no evidence of distortion or visible signs of oxidation. A metallographic investigation showed that the microstructure consisted of tempered martensite in the form of equiaxed grains with size in the range 8 to 9 ASTM units.

TEST RESULTS

The stress-strain response determined in test No. 1 are shown in figure 1 along with the approximate centers of the yield surfaces. The initial yield surface is shown in figure 2 and those determined after preloading to $\sigma_{12} = \sigma_{11}/\sqrt{3} = \pm 189$ MPa are shown in figure 3. As indicated in these figures, two experimental runs were made in determining these and all subsequent yield surfaces. This procedure was followed to get some indication of the repeatability of the data. Yield surface 4, determined after returning the specimen to an unstressed and unstrained state, is shown figure 5 along with the earlier data.

The stress-strain histories followed in Test No. 2 are shown in figure 5. These histories include the inelastic deformation occurring during the 0.5 hr hold-periods at constant stress. Comparisons are drawn in figure 6 between yield surfaces determined in Test No. 2 with those determined under similar conditions in Test No. 1. The five yield loci determined in Test No. 2 are shown in figure 7 and the flow curves determined in this experiment are summarized in figure 8.

DISCUSSION

Considering first the initial yield behavior, it is apparent in figure 2 that the von Mises yield criterion provides a reasonable representation of small-offset yield in 9Cr-1Mo steel. The radius of the circle in modified stress space is about 178 MPa. As expected, this value is considerably greater than radii determined earlier for types 304 and 316 stainless steel which were about 60 and 90 MPa, respectively. The variability of the data shown in figure 2 is typical for initial yield surface experiments conducted at ORNL. The data scatter was judged to be within reasonable limits bearing in mind the relatively small definition of yield used in these experiments.

The yield surfaces determined after preloading to $\sigma_{12} = \sigma_{11}/\sqrt{3} = \pm 189$ MPa exhibit distortion which is typical for radial preloading (refs. 2 to 5). As shown in figure 3, this distortion consists of a contraction of the yield surface in the probing direction with a flattening on the side nearest the origin. Using the diameter of the initial yield surface as a reference, the major and minor axes of the subsequent yield surfaces are reduced by factors of about 0.98 to 0.75. As can be inferred from figure 1, this distortion results from the stress-strain response of the material being much more rounded after initial yield has been exceeded.

Yield surface (4), determined after the specimen had been returned to a state of zero stress and zero strain, is compared in figure 4 to the other yield loci determined in Test No. 1. It is apparent in this figure that although the final preload restored the symmetry of the yield surface, it did not eliminate the contraction in the radial loading direction. Again using the diameter of the initial yield surface as a reference, the major and minor axes of yield surface (4) differ by factors of 1.05 and 0.78 from the initial circular form. Similar contractions were found to exist in the earlier tests conducted on Type 316 stainless steel (ref. 4).

Attention is directed next at the results obtained in Test No. 2. As noted above, the test conditions investigated during the initial stages of this experiment duplicated those of Test No. 1. This approach was followed with the aim of obtaining some indication of possible specimen-to-specimen variability in the data. The results obtained in the two tests are compared in figure 6. Here it can be seen that the radii of the initial yield surfaces differ by less than 5 percent. Also, the two yield surfaces determined after loading to $\sigma_{12} = \sigma_{11}/3 = 189$ MPa can be seen to be similar in size, shape and position in stress space. Thus, provided sufficient care is taken in specimen preparation, it appears that specimen-to-specimen variability is not an important factor in these experiments.

The five yield loci determined in Test No. 2 are compared in figure 7. Here, it can be seen that both radial and nonradial preloads produced the same type of distortion. As noted earlier, this distortion consists of a contraction of the yield surface in the loading direction with a flattening on the side nearest the origin. One implication of this result is that constitutive models involving purely kinematic translations of the initial yield surface provide a relatively crude approximation of subsequent yield behavior in 9Cr-1Mo steel. This result is consistent with the results of a number of previous investigations conducted on a range of engineering materials (refs. 5 to 9).

As indicated in figures 1 and 5, time-dependent flow occurred in both experiments after preloading beyond initial yield. The results of flow strain measurements made during Test No. 2 are shown in figure 8. As indicated in this figure, flow strains as high as 0.2 percent were incurred during 0.5 hr hold-periods at constant stress. Another feature of the data is that the flow rates diminish rapidly with time. During preload (1), for example, the flow rates dropped by almost three orders of magnitude from the initial value of 20 percent/hr. Similar behavior has been observed previously in experiments conducted on types 304 and 316 stainless steel (refs. 5 and 12). This indicates that in detailed inelastic analysis, consideration should be given to time-dependent material response, even at room temperature.

CONCLUSIONS

The following conclusions were drawn from this study of yield, hardening and flow behavior in modified 9Cr-1Mo steel at room temperature.

1. The von Mises yield criterion provides a reasonable approximation of initial yield behavior.
2. The yield loci determined in the two tests for the same loading conditions were in good agreement. This was taken to indicate that specimen-to-specimen variability is not an important factor in tests conducted at ORNL.
3. The hardening behavior of the material is to the first order "kinematic" in nature. The distortions observed in the yield surfaces indicate, however, that detailed predictions of yield behavior are not possible using a simple kinematic plasticity model.
4. Significant flow strains were incurred during 0.5 hr hold-periods at constant stress. This indicates that time-dependent material response is an important factor, even at room temperature.
5. The yield, hardening, and flow behavior of modified 9 Cr-1Mo steel at room temperature are qualitatively similar to those of the austenitic steels.

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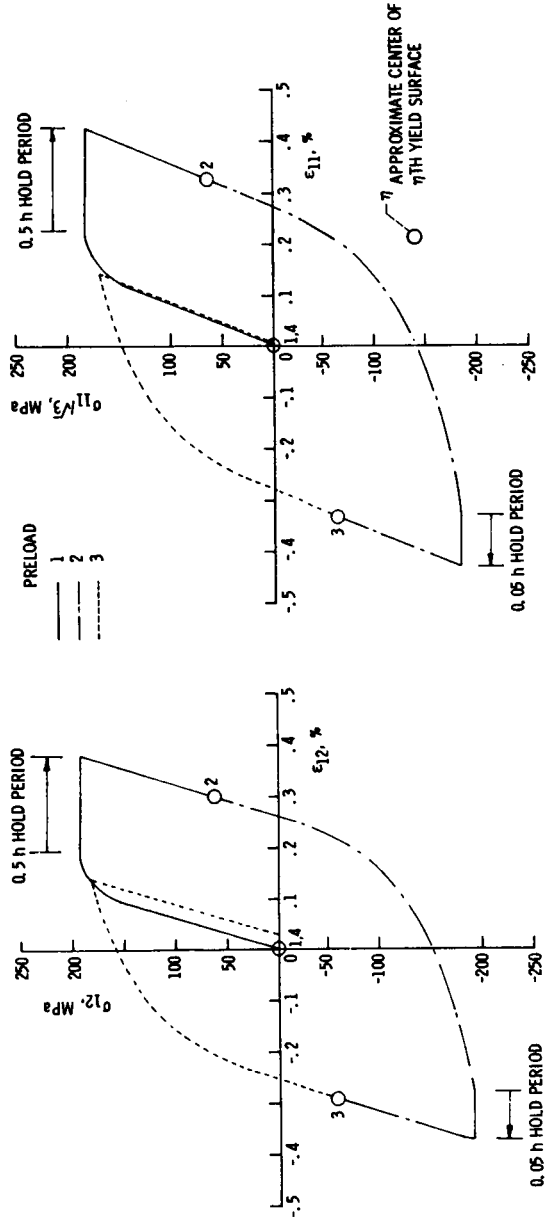


Figure 1. - Stress-strain history for Test No. 1.

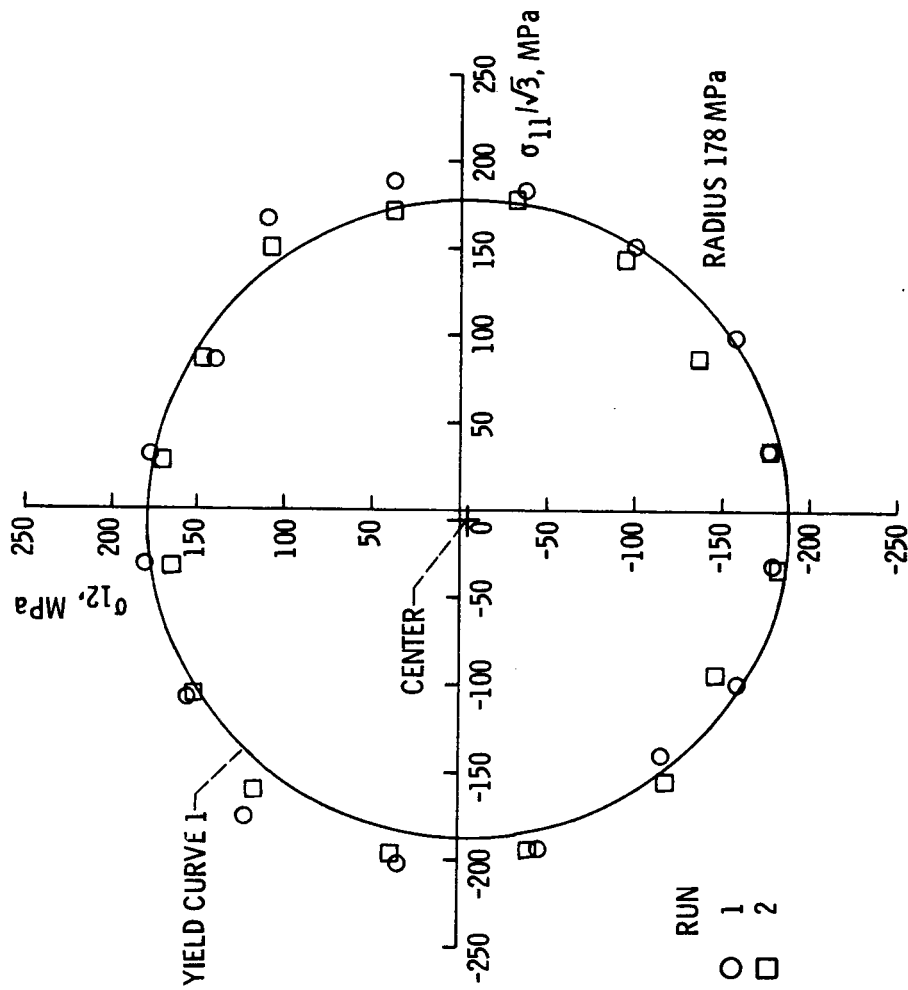


Figure 2. - Initial yield surface for Test No. 1.

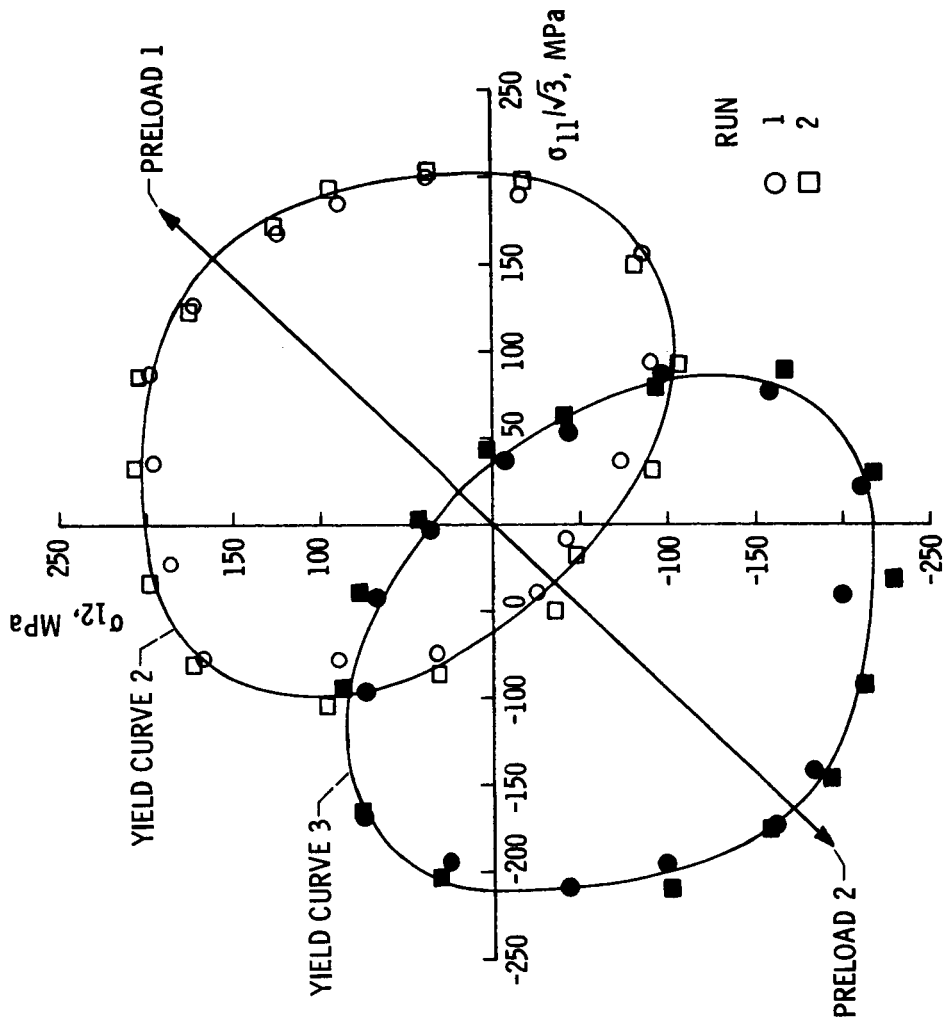


Figure 3. - Yield Loci determined in Test No. 1 after preloading to $\sigma_{12} = \sigma_{11}/\sqrt{3} = \pm 189$ MPa.

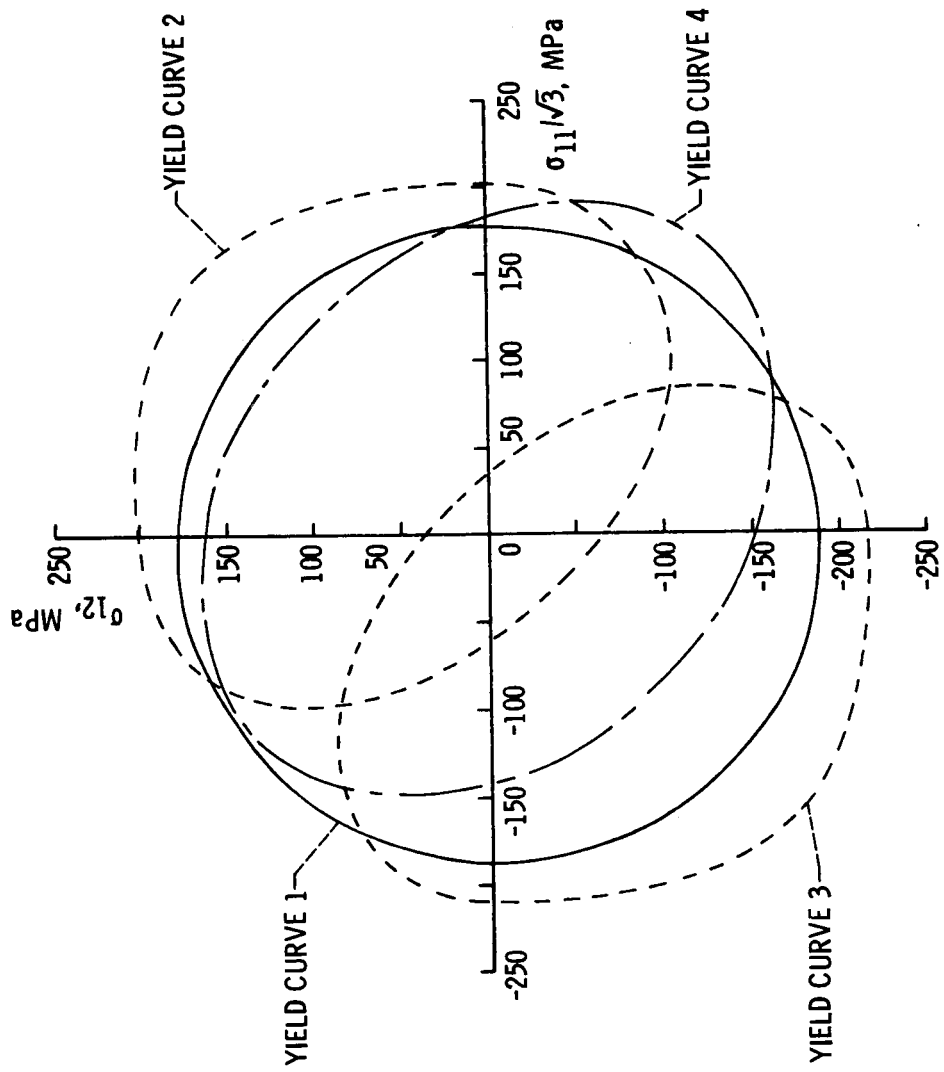
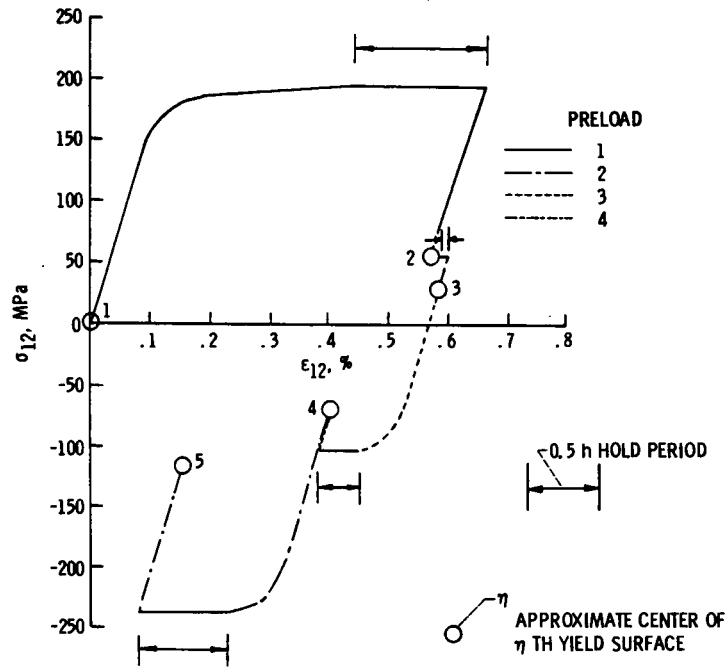
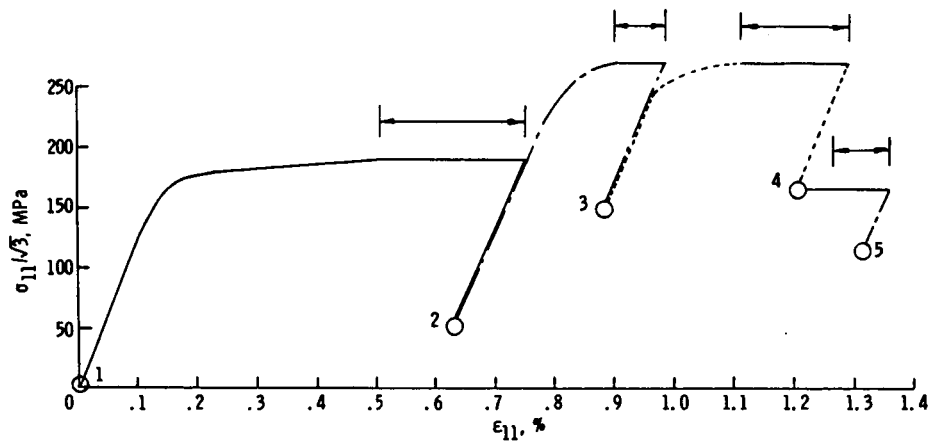


Figure 4. - Comparison of yield loci determined in Test No. 1.

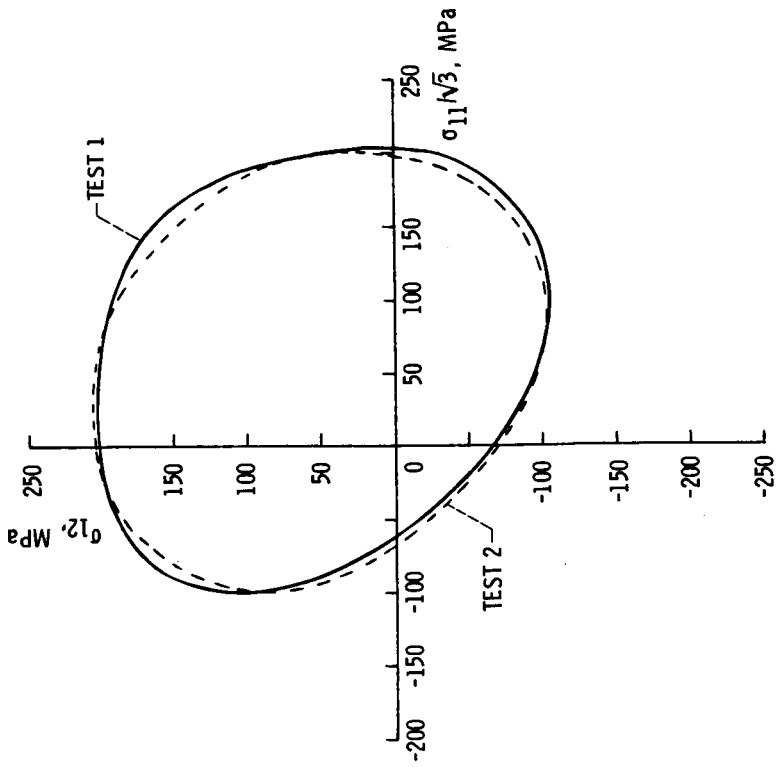


(a) Shear stress vs tensorial shear strain.

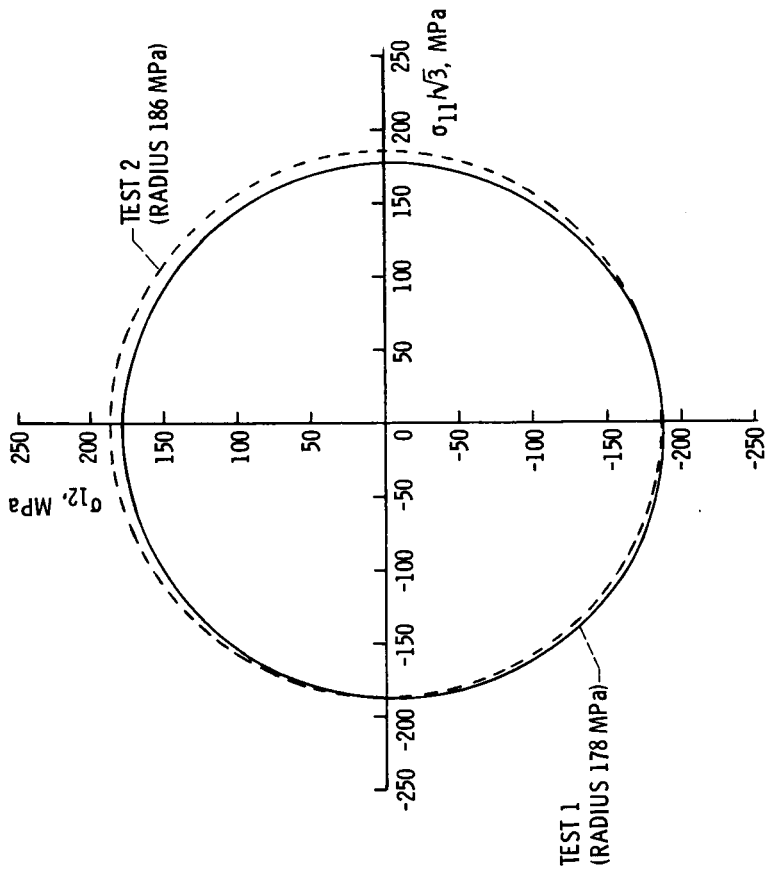


(b) Modified axial stress vs axial strain.

Figure 5. - Stress-strain history for Test No. 2.



(a) Initial yield surfaces.



(b) Yield surfaces determined subsequent to preloading to

$$\sigma_{12} = \sigma_{11}\sqrt{3} = 189 \text{ MPa.}$$

Figure 6. - Comparison of yield surfaces determined in Tests 1 and 2.

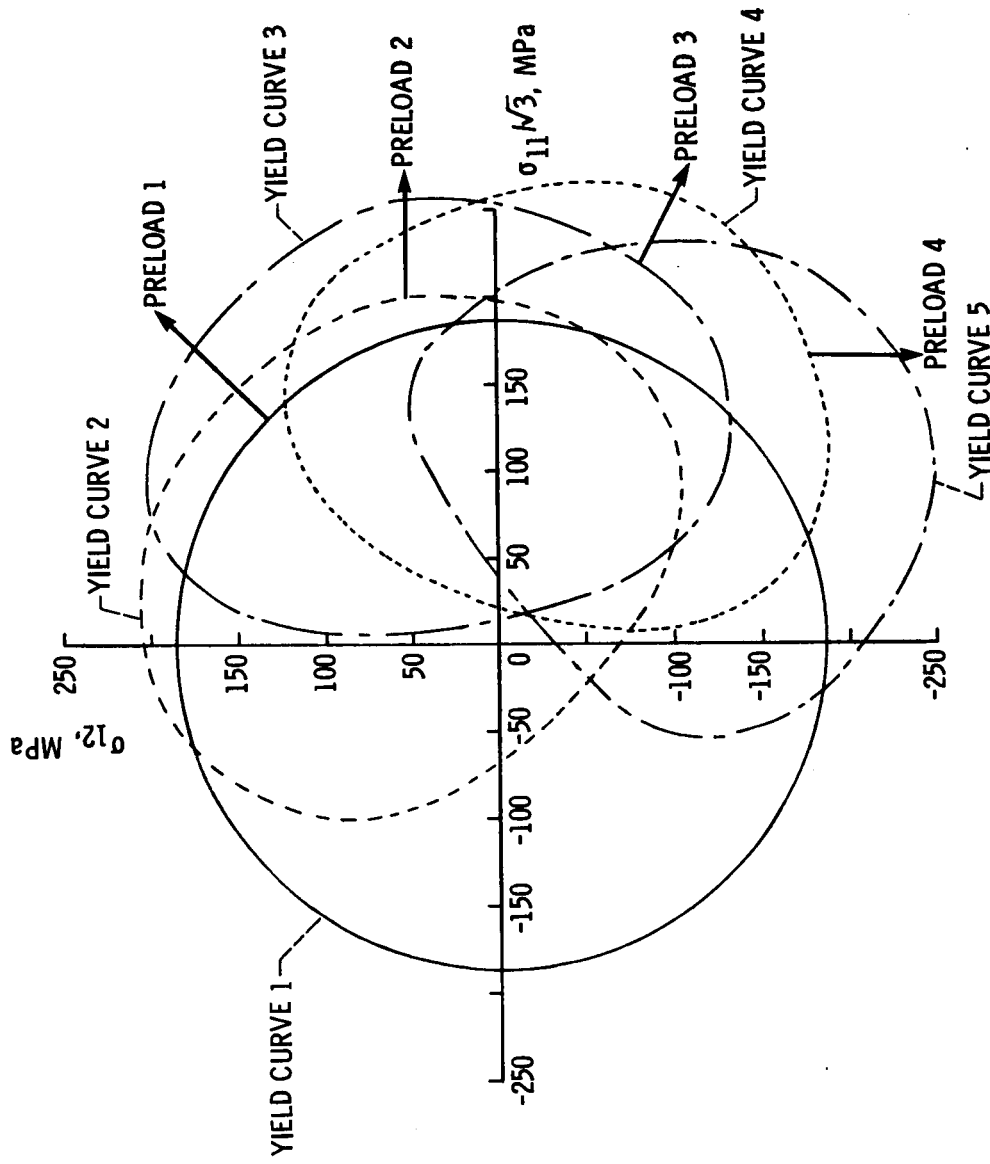
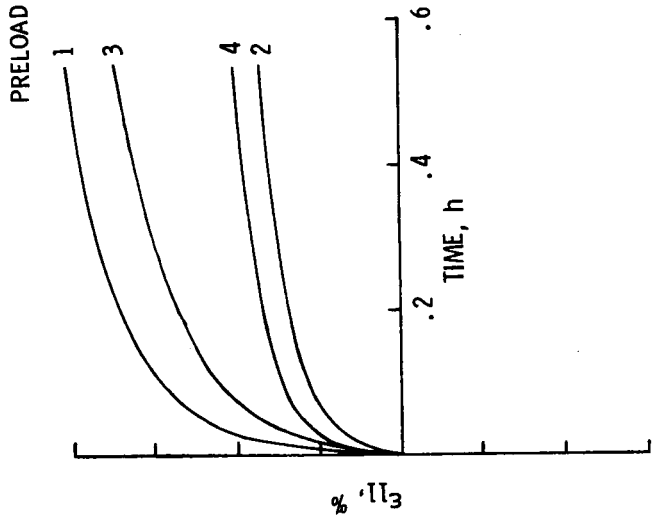
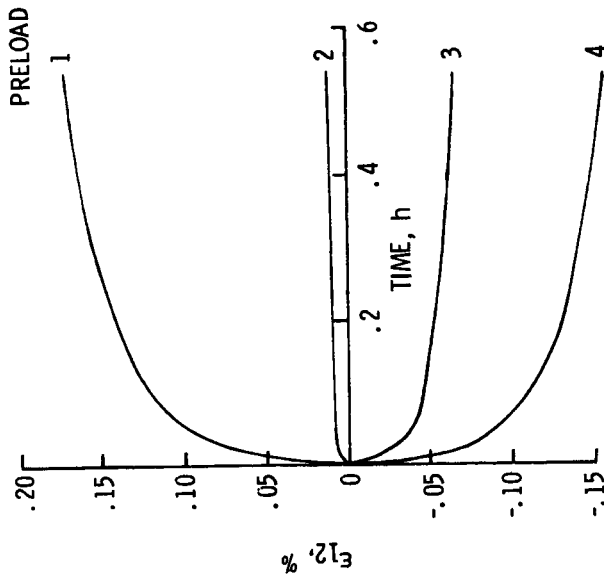


Figure 7. - Comparison of yield loci determined in Test No. 2.



(a) Tensorial shear strain vs time.



(b) Axial strain vs time.

Figure 8. - Flow curves determined in Test No. 2 subsequent to radial and non-radial preloads.

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