BEHAVIOR OF ANNEALED TYPE 316 STAINLESS STEEL UNDER MONOTONIC
AND CYCLIC BIAXIAL LOADING AT ROOM TEMPERATURE*

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1. INTRODUCTION

One major activity within the ORNL High-Temperature Structural Design Program is the development of constitutive equations for structural alloys intended for use in advanced reactor systems. This activity has involved work in several related fields including: experimental studies of deformation behavior under uniaxial and multiaxial stress states; development of mathematical models describing deformation behavior; and confirmatory structural tests on simple structural elements. This paper deals with the continued effort in one of these areas, that of investigating deformation behavior under multiaxial stress states.

In past studies at Oak Ridge National Laboratory (ORNL), the room-temperature behavior of type 304 stainless steel has been extensively investigated in biaxial stress experiments conducted using tension-torsion loading [1,2]. In addition to investigating initial yield behavior, these experiments investigated the effects of both radial ($\sqrt{3} \tau = \sigma$) and nonradial loading on the size, shape, and position of yield loci corresponding to a small offset strain (10 $\mu\epsilon$) definition of yield. The present work represents part of an effort to extend this activity to other structural alloys of interest, in this case type 316 stainless steel.

A further difference between this and previous studies lies in the program of loading imposed subsequent to the determination of initial yield behavior. The principal aim of the earlier work was to generate the data necessary for the development of new or improved theories for describing elastic-plastic behavior. To this end, single specimens were subjected to relatively complex load histories in tension-torsion stress space. In all cases, the tests were run under load control and the histories were defined in terms of stress.

In the present work, the aim is to determine the extent to which the constitutive laws previously recommended for type 304 stainless steel are applicable to type 316 stainless steel. In the tests described here, the stress-limited loading was restricted to two relatively simple histories, as will be described later. Further, since hardening under cyclic conditions is a concern in design, it was planned to investigate the yield behavior of type 316 stainless steel after several cycles of strain-limited loading.

2. EXPERIMENTAL DETAILS

The specimen used in these tests was fabricated from type 316 stainless steel, Republic Steel heat No. 8092297. The material was supplied in solution-annealed condition in the form of 2.5-in.-diam bars. The specimen geometry was similar to that used previously in tests on 304 stainless steel [3]. In this case, however, the parallel working section was 2.75 in. long and the inside and outside diameters were 1.250 and 1.430 in. respectively. After fabrication, the specimen was subjected to the following heat treatment: heat to 1950°F, hold for 30 min, cool at 300°F/min to 1000°F, and continue cooling at a convenient rate to room temperature. All stages of the above heat treatment were performed in flowing argon, and after heat treatment the specimen showed no visible signs of oxidation. Further, careful measurement of the specimen's dimensions made before and after heat treatment showed no evidence of distortion.

The test equipment and procedures used in these yield surface studies have been described in detail previously [3]. Briefly, the tests are conducted on an MTS closed-loop, electrohydraulic test system with provision for tension-torsion loading. The MTS system is controlled by a Digital Equipment Corp. PDP 8/e data-acquisition system (DAS) and an

Electronic Associates, Inc. PDP 8/e computer, as shown schematically in Fig. 1. The primary function of the PDP 8/e computer is to establish, during the first few seconds of individual yield surface probes, the best straight line corresponding to elastic loading and, subsequently, to check for deviation from this straight line resulting from the onset of plastic straining. On detecting a predetermined deviation, $10 \mu\epsilon$ of equivalent plastic strain in the present experiment, the computer is programmed to return the loading to the starting point. The same program allows yield surface probes to be conducted at 16 preset angles in tension-torsion stress space. The other main function of the PDP 8/e computer is to permit specimens to be loaded to predetermined points in stress space prior to conducting yield surface determinations. Although this preloading is performed using load control, the DAS allows strain rate to be controlled within close limits, $\pm 10 \mu\epsilon/\text{min}$, during both elastic and plastic straining.

3. TEST PLAN

It was planned to conduct the investigation in four stages. In stage (1), an initial yield surface was to be determined in a series of repeated experiments. It was hoped that these repeated experiments would give some indication as to the scatter inherent in these yield surface determinations and also insight regarding the use of a $10 \mu\epsilon$ offset definition of yield.

In stage (2), the specimen was first to be prestressed radially in the tensile sense 50% beyond initial yield (loaded in tension-torsion stress space over a radial path from the origin where the radius of the path is that of the initial yield surface factored by 1.5), unloaded to the estimated center of the new yield surface, and the new yield surface determined. This procedure was to be repeated for radial loading 50% beyond initial yield in the compressive sense. Finally, in the second stage, the specimen was to be subjected to a stress-strain history such as to return it to an unstressed and unstrained state. A yield surface was then to be determined for this condition.

In stage (3) of the experiment, the above procedure was to be repeated for prestress values 100% beyond initial yield. It should be noted that conditions in all of the above tests were to be defined in terms of stress and that strain was to be used for controlling the rate of loading only.

This was not the case in stage (4) of the experiment. Here it was planned to cycle between fixed equivalent strain values and to determine yield loci at five cycle intervals for both tensile and compressive loading. The value of equivalent strain range was to be selected by trial to give significant cyclic hardening. As in the case of the stress-limited tests, the stress path followed in tension-torsion stress space was to be radial.

4. TEST RESULTS

The initial yield surface determined in stage (1) of the experiment is shown in Fig. 2. It will be noted that individual probes to establish the surface were repeated five times. This value was selected as being a reasonable compromise in that it allowed a clear indication of the scatter to be obtained without excessive time being necessary for this stage of the study.

The axial and torsional stress-strain responses determined in stage (2) of the experiment are shown in Fig. 3. Also shown in this figure is an indication of the time-dependent

plastic strain which occurred during hold periods at maximum stress conditions. The procedure adopted on reaching target stress values in this and previous studies was to hold at constant stress conditions for a predetermined period before unloading to the estimated center of the new yield surface. In these experiments, the hold period was 15 min, whereas in most of the earlier work, stress conditions were held constant until all time-dependent deformation had ceased. The yield surfaces determined in this stage of the experiment, namely, yield surfaces (2), (3), and (4), are shown in Figs. 4 and 9. It should be noted that individual probes were repeated twice in defining these and all subsequent yield surfaces.

The stress-strain responses obtained in stage (3) of the experiment are not shown in order to keep the number of figures presented within reasonable limits. This also applies to yield surfaces (5) and (6) determined after loading 100% beyond initial yield in the tensile and compressive senses respectively. However, yield surface (7), determined after returning the specimen to an unstressed and unstrained state, is shown with other data in Fig. 9.

In stage (4) of the experiment, it proved necessary to strain cycle over two equivalent strain ranges. The first value investigated, 0.9%, was chosen as being a value likely to give significant cyclic hardening, while at the same time not being much larger than values likely to be encountered in service. Behavior was investigated over five cycles of this loading. The stress-strain responses are again not shown for reason of conciseness. The yield surfaces determined during the first cycle in tension and compression, yield surfaces (8) and (9), are shown in Fig. 5. Also shown in this figure are the yield surfaces determined on the fifth cycle, yield surfaces (10) and (11). Examination of the stress-strain histories showed that no cyclic hardening had occurred during the five loading cycles. It was decided, therefore, to increase the equivalent strain range to about 2% and to repeat the experiment. The axial and torsional stress-strain responses for cycles [1] through [5] at 2% are shown in Fig. 6, while those for cycles [6] through [10] are shown in Fig. 7. The yield surfaces determined for tensile loading on cycles [1], [5], and [10] are shown in Fig. 8 as yield surfaces (13), (14), and (16), while those determined for compressive loading are shown in the same figure as yield surfaces (12), (15), and (17). As in previous stages of the experiment, a yield surface was determined after returning the specimen to an unstressed and unstrained state. This final yield surface is shown in Fig. 9 as yield surface (18).

5. DISCUSSION

Considering first the initial yield behavior, it is apparent from Fig. 2 that the von Mises yield criterion is a reasonable idealization of the initial yield of type 316 stainless steel. A circle representing the von Mises criterion in this modified stress space with radius about 89 MPa was found to characterize the initial yield locus quite closely.

The stress-strain behavior of the material during prestressing 50% beyond initial yield, Fig. 3, may be characterized by relatively abrupt yielding followed by nearly linear strain hardening. Subsequent yielding in the reversed direction, however, is seen to be far more rounded. It is, of course, this "rounding" of the stress-strain response that is responsible for the Bauschinger effect and the large amount of translation that yield surfaces defined by small offsets undergo* (Fig. 4). As can be deduced from Fig. 3, the larger the offset

*In the context of the plasticity model formulated by Krieg [4], the small offset yield surfaces examined here may probably be identified with the "inner" yield surface or "loading" surface which may move about as well as isotropically grow in stress space. In this regard, see also Robinson [5].

employed in the definition of yield, the more nearly will the yield surface be fixed in position in stress space. This observation is completely in accord with conclusions drawn in a survey article on experimental yield surface investigations by Michno and Findley [6].

Another significant feature shown in Fig. 3 is the amount of time-dependent inelastic strain which accumulated during the 15-min hold periods at the constant stress. The inelastic strain rate immediately upon reaching the given stress is seen to be quite high (the initial equivalent strain rate was estimated to be of the order of 1000 $\mu\epsilon/\text{min}$). An inelastic shear strain of about 0.25% was accumulated during this period for loading in the tensile sense. Even larger flow strains were observed during loading 100% beyond initial yield. In that case, the shear strain increased by almost 0.5% during a 15-min hold under tensile loading. Time-dependent yielding at room temperature is well known to investigators conducting yield surface explorations, and, as discussed by Philips [7], the shape and position of yield surfaces based on small offsets may be strongly affected by the length of the hold period. The stress-strain path followed in returning the specimen to an unstressed and unstrained state is also shown in Fig. 3. In the case shown, no difficulty was experienced in achieving this state. This was not the case during stage (3) of the experiment; several attempts were necessary to achieve a final stress-strain state at or very close to the origin of loading.

The yield loci determined after loading 50% beyond initial yield, yield surfaces (2) and (3) in Fig. 4, can be seen to be much reduced in size from the initial surface and also to be distorted from the initial near-circular form. Using the diameter of the initial yield surface as a reference, the major and minor axes of yield surface (2) are reduced from the reference diameter by factors of about 0.9 and 0.6, respectively. This "softening" is evidently due to the reduced elastic range resulting from prestressing. As pointed out above, subsequent yielding in the reversed direction, following the initial prestress, is characterized by a much more rounded stress-strain curve having a lesser elastic range than that corresponding to the virgin state (Fig. 3). This softening or reduction in mean size of the yield surface would undoubtedly be much less when employing a larger offset definition of yield. Comparison between these and earlier yield surfaces for 304 stainless steel determined under similar loading showed that the distortion, predominantly a pronounced flattening in the direction of radial loading, was very similar for both materials. The data scatter evident in Fig. 4 is typical for all yield loci determined subsequent to the initial yield surface. Comparisons were also drawn between yield surfaces (2) and (3) and those determined after loading 100% beyond initial yield, surfaces (5) and (6). It was found that the latter yield loci were very similar in size and shape to those shown in Fig. 4. The most significant effect of increasing the magnitude of preloading was to shift the position of the yield surfaces further away from the origin of loading.

Yield surfaces (8) through (11), determined after cycling over an equivalent strain range of 0.9%, are shown in Fig. 5. It can be seen that the four yield surfaces are almost identical in size and shape, lending further confidence in the experimental techniques used in this study. It should be noted that direct comparison between these and earlier yield surfaces is not possible because of differences in the rate of loading during individual probes. The average value used in defining yield surfaces (1) through (7) was about 320 $\mu\epsilon/\text{min}$, while that used in defining the yield loci shown in Fig. 5 was about 515 $\mu\epsilon/\text{min}$. Although this increase in strain rate might have affected the size of the yield surfaces, it

did not cause any significant change in the shape of the yield surfaces which exhibit the characteristic distortion discussed earlier.

The stress-strain response of the material during cycling over an equivalent strain range of 2% is shown in Figs. 6 and 7. The hysteresis loops shown give some indication as to the modest amount of cyclic hardening which occurred during the ten cycles of this loading. Also, some idea can be obtained from these figures as to how closely the nominal equivalent strain range was achieved on particular cycles. An experimental difficulty indicated in Fig. 7 is that an axial strain gage failed on the tenth cycle. However, because the torsional strain gages were unaffected by this failure, it was possible to use these gages to unload the specimen in a controlled manner. The failed gage was replaced with the specimen *insitu*, and after recalibration of the axial strain measurement system the test was resumed. After definition of yield surface (17), the specimen was loaded so as to return it to an unstressed and unstrained state. It will be noted in Fig. 7 that this was only partially successful in that small positive strains remained in the specimen on unloading.

Yield loci determined while cycling over a 2% equivalent strain range are compared in Fig. 8. It can be seen that limited hardening occurred in the direction of radial loading and also in the normal direction. Further, it will be noted that the yield loci suffer similar distortion to that discussed earlier for yield surfaces (2) and (3). Comparisons were also drawn between yield loci determined after the two series of strain cycling (cf. Figs. 5 and 8). The first cycle of loading over an equivalent strain range of 2% caused some initial softening, yield surfaces (12) and (13) being smaller in the direction perpendicular to that of radial loading than yield surfaces (8) through (11). Subsequent cycles caused hardening, yield loci determined on the fifth and tenth cycles being larger than those determined in the earlier series of cyclic loading, most markedly in the direction of radial loading.

As previously noted, the specimen was loaded so as to return it to an unstressed and unstrained state at various stages of the experiment. In Fig. 9, the initial yield surface is compared to yield surfaces (4) and (7) determined after the first and second series of stress-limited loadings and to yield surface (18) determined after the cyclic experiments. It can be seen that yield loci (4), (7), and (18) are smaller than the initial yield surface in the direction of radial loading but larger in the normal direction. Further, on comparing yield loci (4), (7), and (18), it can be seen that both monotonic and cyclic loading caused some hardening to occur throughout the test. According to any plasticity model in which the sole measures of the "inelastic state" are stress, temperature, and plastic strain (or a quantity proportional to plastic strain as in linear kinematic hardening), each of the yield surfaces of Fig. 9 would have been identical, since in each case the specimen would be in the same inelastic state. This is obviously not true here, indicating that these variables, in themselves, are not adequate state measures. The introduction of an additional scalar state variable, as in the classical isotropic hardening plasticity, allowing uniform expansion of the yield surface is also clearly insufficient to predict the distortions which occur with deformation history. This is not to say, however, that the relatively simple theories cited above may not be useful as idealizations of the extremely complex behavior of type 316 stainless steel and other structural alloys.

6. CONCLUSIONS

The following conclusions were drawn from this study of the elastic-plastic behavior of type 316 stainless steel at room temperature.

1. The von Mises yield criterion provides a reasonable approximation of initial yield behavior.
2. Although subsequent yield surfaces suffered considerable distortion from the initial near-circular form, the hardening behavior of the material under the small offset definition of yield employed is to the first-order "kinematic" in nature.
3. The apparent softening observed in subsequent yield surfaces resulted from the use of a small offset definition of yield coupled with a tendency for stress-strain response to become more rounded with subsequent plastic straining.
4. The significant time-dependent deformations noted during hold periods at constant stress indicate that careful attention should be given to loading rate and the duration of hold periods in studies of elastic-plastic behavior at room temperature.
5. The prior stress-limited loading effectively eliminated capability for cyclic hardening at 0.9% equivalent strain range. The modest cyclic hardening observed for loading over 2.0% equivalent strain range caused the area of the fifth and tenth cycle yield surfaces to be somewhat larger than that of the first cycle.

7. REFERENCES

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Fig. 1. Block diagram of biaxial testing system.

Fig. 2. Initial yield surface.

Fig. 4. Yield loci after loading 50% beyond initial yield.

Fig. 5. Yield loci after equivalent strain cycling over 0.9% range; comparison after 1st and 5th cycles.

(a) Shear stress vs tensorial shear strain

(b) Modified axial stress vs axial strain

Fig. 6. Stress-strain response : cycling over equivalent strain range of 2%; cycles 1 through 5.

(a) Shear stress vs tensorial shear strain

(b) Modified axial stress vs axial strain

Fig. 7. Stress-strain response to cycling over equivalent strain range of 2%; cycles 6 through 10.

Fig. 8. Yield loci after equivalent strain cycling over 2% range; comparison after 1st, 5th, and 10th cycles.

Fig. 9. Comparison of initial and subsequent yield loci under conditions of zero stress and zero strain.