DEFORMATION HARDENING OF TYPE 304 STAINLESS STEEL AT ELEVATED TEMPERATURE

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INTRODUCTION

Recently there has been considerable interest in the development of constitutive equations for material behavior based on the concept of a mechanical equation of state (Hart, 1970, 1976; Kocks, 1975, 1976). In such a procedure, the effects of the prior deformation history of the material are characterized by the values of some internal state variables. In principal, these state variables characterize the dislocation structure which has been introduced by the deformation. In practice it is more convenient to use parameters derived from mechanical tests, such as the flow stress (Kocks, 1975) or a scaling parameter for the stress relaxation curve (Hart, 1970), to describe the state of the material because it is not feasible to quantitatively predict the mechanical behavior from a microscopic description of the dislocation structure existing in the material. It is, nevertheless, of interest to qualitatively relate the mechanical parameters used to describe state with microscopic variables.

One question which arises in connection with state variable descriptions of mechanical behavior is how many variables are required to completely characterize the state. Hart (1970) and Kocks (1975) have argued that for cases of monotonic deformation, a single variable is sufficient to describe the state of the material provided that one is not concerned with the shape of transients that follow changes in load or strain rate and persist for strains of the order of 1%. The state variable used by Kocks is the flow stress at a standard strain rate. Hart uses an equivalent parameter derived from a stress relaxation test. The flow stress has also been shown to correlate well with the dislocation density. This establishes a correlation between the state variable and a variable descriptive of the dislocation structure. Hart (1976) introduced the anelastic strain as an additional state variable in order to improve the ability to handle transients. However, work involving transient behavior following periods of recovery (Alden, 1976) and cyclic deformation histories (Swarcengren, Rhode, and Hicks, 1976; Turner, 1979) have shown that at least one additional parameter is necessary to completely characterize the deformation hardened state of a material. It has been suggested that this additional parameter is related to whether the dislocations in the material are arranged randomly or in cells.

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In the present work, samples of Type 304 stainless steel were hardened by various deformation paths. The mechanical behavior of these predeformed samples was then characterized by their behavior in a tensile test and the dislocation structure was examined by TEM. The behavior of the material during the prior deformation hardening path was also analyzed for indications that the state of the material was changing. The results support the conclusion that more than one state parameter is required to characterize the material.

EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were carried out on polycrystalline samples of commercial Type 304 stainless steel. Two temperatures, 300 and 560°C, were used. The results at both temperatures were qualitatively similar and the conclusions drawn here apply to both test temperatures. Details of the material and experimental procedures have been reported previously (Turner, 1979). Three types of deformation history were employed; cyclic stressing at constant stress amplitude with a zero mean stress and with no mean strain accumulation (balanced cyclic), prestressing followed by cycling at a stress amplitude less than the prestress level (prestressed) and cyclic stressing with a nonzero mean stress (cyclic creep).

Plastic strain amplitudes vs number of cycles of stress for the three types of deformation history are shown in Fig. 1. In the balanced cyclic test, the plastic strain amplitude first decreases, then passes through a minimum and increases. (This behavior is typical of tests at 300°C. At 560°C the cyclic softening beyond the minimum is much less pronounced.) The decrease in the plastic strain amplitude during the first few cycles has been found to be associated with an increase in the flow stress as a result of cyclic work hardening, but the increase in the

Fig. 1. Behavior of the plastic strain amplitude during three types of cyclic tests on Type 304 stainless steel at 300°C. The balanced cyclic test was done with a stress amplitude of 250 MPa and zero mean stress. In the pre-stressed test, the sample was stressed to 300 MPa in tension and then cycled with a stress amplitude of 250 MPa. The cyclic creep test was done with a tensile peak stress of 250 MPa and a compressive peak stress of -200 MPa.

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Fig. 2. Dislocation structures produced in Type 304 stainless steel by cyclic deformation. (a) After 5 cycles of ± 250 MPa at 300°C . (b) After 1000 cycles of ± 250 MPa at 300°C . (c) After 5000 cycles between $+300$ and -240 MPa at 500°C .

amplitude beyond the minimum does not reflect a change in the flow stress (Turner, 1979). It is found that the increasing plastic strain amplitude is associated with a conversion of the dislocation structure from a nearly random structure, Fig. 2(a), to the well defined cell structure shown in Fig. 2(b). In the pre-stressed test, the plastic strain amplitude immediately following the prestressing to a high stress is small because the material is hardened. As a result of cycling, the plastic strain amplitude increases, indicating that cyclic softening is occurring. The resulting microstructure after many cycles consists of regions of cells similar to those formed by balanced cycling, but some regions of the material are found to contain random tangle dislocation structures. It is believed that this represents incomplete conversion of the structure to the cells typical of cyclic deformation.

In the cyclic creep experiment, the unbalanced stress cycle causes a rapid net elongation of the sample as shown in Fig. 3. The rate of extension, expressed either as strain per cycle or strain rate, continually decreases with increasing strain with no indication that it is approaching any steady state rate. The decrease in strain rate with cycles or time clearly indicates that a change in state of the material is occurring since the material continually increases its resistance to cyclic creep. However, Fig. 1 shows that the plastic strain amplitude in the cyclic creep test reaches a constant value after only a few cycles. Whatever change in state is occurring during the cyclic creep does not produce any change in the plastic strain amplitude. The microstructure of a sample subjected to cyclic creep for 5000 cycles is shown in Fig. 2c. The tight cell structure that is typical of a material subjected to the balanced cyclic test is not found in the cyclic creep sample. Instead a loose cell structure is found. This structure is similar to that found in a balanced cyclic test sample after approximately 100

Fig. 3. Mean strain accumulation in a cyclic creep test on Type 304 stainless steel at 300°C with a tensile peak stress of 250 MPa and a compressive peak stress of -220 MPa.

cycles. This indicates that the net strain that occurs during the cyclic creep test, interferes with the formation of the kind of tight cells shown in Fig. 2(b). Furthermore, the absence of cells and the lack of any softening in the cyclic response is consistent with the identification of the increase in the plastic strain amplitude with the conversion to a cellular microstructure.

Samples that had experienced the three types of deformation history described above, were tested in a constant elongation rate tensile test. The results are shown in Fig. 4 on plots of work-hardening rate, $\theta = d\sigma/d\epsilon_p$, vs flow stress, σ , where ϵ_p is the plastic strain. In a single state parameter description of deformation, the θ vs σ curve is unique because both the flow stress and the work hardening rate are functions only of the single state variable and the temperature and the applied strain rate which are held constant for all tests. The dashed line in Fig. 4 is the behavior of an annealed sample in a tensile test. For a material which is describable by a single state variable the θ vs σ curves for samples subjected to various prior deformation histories would drop steeply, on a curve determined largely by anelastic behavior, and join the annealed material curve at the current flow stress. Such behavior is shown by the curve for the sample from the balanced cyclic test. For the other two cyclic prior histories used, the θ vs σ curves for the tensile test never join the curve for the annealed sample. In both cases, the curves are above the curve for the annealed material. This means that for these samples, the workhardening rate is always greater at a given flow stress than it would be if the prior cyclic history had not been experienced.

A few additional points are worth noting from the results of the post cyclic tensile tests. The initial flow stress for the balanced cyclic test samples (determined by a back extrapolation of the stress strain curve) was approximately 5% greater than the stress amplitude of the cycle. This is consistent with the statement made previously that the decrease in plastic strain amplitude during the first few cycles of the test resulted from cyclic work hardening. The initial flow stress for the cyclic creep sample is found to be essentially the same as the maximum tensile stress of the cycle. This is again consistent with the plastic strain

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Fig. 4. Tensile behavior of Type 304 stainless steel following various cyclic deformation histories at 300°C compared to the behavior of an annealed sample. The cyclic deformation in the balanced cyclic history was 1000 cycles at a stress amplitude of 250 MPa. The sample from the prestressed test was stressed to 300 MPa and then cycled for 5000 cycles at a stress amplitude of 260 MPa. The cyclic creep test was carried on for 5000 cycles with a tensile peak stress of 260 MPa and a compressive peak stress of -160 MPa.

amplitude behavior, but it is interesting because it means that ~10% net strain occurred during the cyclic creep with no hardening effect. The initial flow stress for the prestressed samples is very difficult to define because the yield transition is quite smooth. Essentially the entire stress range between the cyclic stress amplitude and the prestress is part of a transient. During this transient, the slope of the stress strain curve is abnormally high. θ does not approach values typical of the normal plastic behavior until the flow stress exceeds the prestress value. This indicates that the cyclic softening that occurs in a prestressed sample does not represent a complete reversal of the monotonic work hardening.

CONCLUSIONS

1. The θ - σ curve for monotonic deformation is not unique. Cyclic deformation hardening which involves one or more overloads above the cyclic stress amplitude or cycling that produces net elongation can change the shape of a subsequent tensile stress-strain curve. This means that at least one parameter in addition to the current flow stress is needed to describe monotonic deformation after an arbitrary prior history. In terms of microstructure, this additional parameter does not appear to be related to the cellularity of the dislocation structure because both the samples from the prestressed test which contain a cellular structure, and the samples from the cyclic creep test which have a noncellular microstructure have different tensile behavior from that of an annealed material. Also the sample which was subjected to balanced cyclic deformation had a cellular microstructure but deformed in tension like a monotonically hardened sample.

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2. The plastic strain amplitude during a cyclic test depends on at least one state parameter other than the current flow stress because the plastic strain amplitude is found to change during a test while the applied stress amplitude and the flow stress remain constant. The additional parameter needed to describe the plastic strain amplitude is probably different from the additional parameter needed to describe post cyclic tensile behavior because there is a poor correlation between changes in the plastic strain amplitude and changes in the tensile behavior. The plastic strain amplitude is well correlated with the cellularity of the microstructure. A possible parameter for this state variable is the Bauschinger strain which occurs when the applied stress is reversed from the positive flow stress to the negative flow stress.

3. The decrease in the strain rate in a cyclic creep test indicates a change in the state of the material. This state change is not accompanied by a change in the plastic strain amplitude of the cycle, an increase in cellularity of the microstructure, or a change in the flow stress. Therefore, it appears to be unrelated to the state variable discussed in Conclusion 2. It may be identical to the change in state which causes the post cyclic tensile behavior to be changed as discussed in Conclusion 1.

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