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YIELD STRESS BASED ON NATURAL STRAIN THEORY UNDER CYCLIC TENSION-COMPRESSION LOAD AFTER LARGE SIMPLE SHEAR

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Many researches on the yield behavior under cyclic loads have been conducted for many years. However, almost these studies have been done within the range of relatively small size deformation. Hence, the detailed studies for yield phenomenon under cyclic loads after applying a large pre-deformation have not been sufficiently elucidated. Therefore, in the series of our studies, using test pieces of high purity tough pitch copper, the yield behavior generated under cyclic loads after applying the pre-deformation of large uniaxial tension or large simple shear have been investigated. However, as for the case that the type of pre-deformation differs from the type of deformation in the cyclic load, detailed studies have not been conducted yet. Hence, in the present study, the yield behavior generated under cyclic loads for tension and compression after applying a large pre-deformation of simple shear is examined based on Natural Strain theory. Furthermore, experimental results in the present study are compared with results of previous studies concerning cyclic loads for tension and compression after applying the large uniaxial tension. Consequently, it is revealed that the decreasing tendency of yield stress at the compression side appears more strongly as compared with the experimental result by previous study that the pre-deformity is a uniaxial tension.

Keywords: Finite deformation, Elasto-plastic analysis, Pre-deformation, Anisotropy, Deformation history, Slope of tangent, Proof stress, Ductile materials.

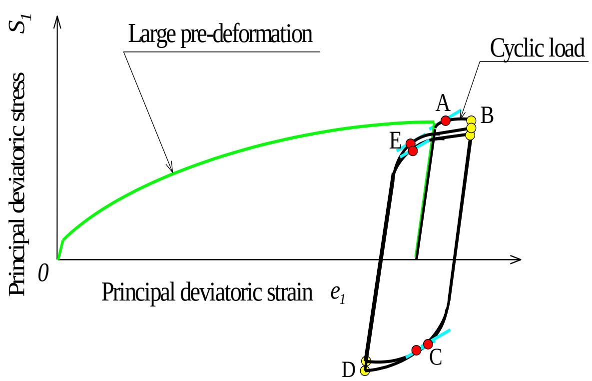
1 INTRODUCTION

The Natural Strain theory used in this study is obtained by integrating an infinitesimal strain rate on an identical line element over the whole process of the deformation path. Consequently, since the shearing strain component is represented by pure angular strain, the rigid body rotation can be clearly removed from the shearing strain component. Moreover, since the additive law of strain on an identical line element can be satisfied, the strain rate can be decomposed into the elastic component and the plastic component. Moreover, the elastic component can also be decomposed into deviatoric part and volumetric part in the same manner as the conventional infinitesimal deformation theory. Therefore, the Natural Strain is an effective strain representation, which can be systematically treated from infinitesimal deformation to the large deformation.

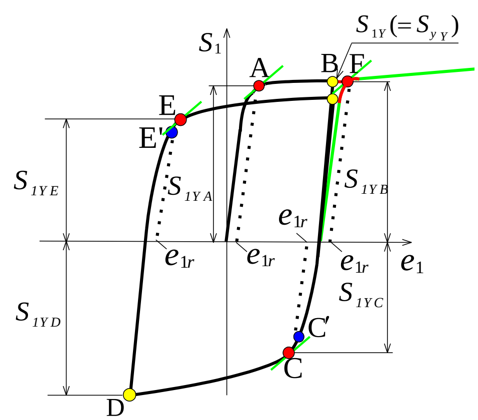
In general, when the structure undergoes cyclic loads due to earthquake etc., a plastic failure arises in the structure even if the number of cycles is small. Therefore, it is an important issue in the structural engineering to find out the actual mechanisms of low-cycle fatigue failure and the yield behavior under cyclic loads. However, although many of researches have been done within the range of an infinitesimal deformation, the detailed studies for yield behavior under cyclic loads after applying a large pre-deformation have not been fully elucidated. Therefore, in a series of studies (Kato 2017, Kato 2018), the yield behavior generated under cyclic loads after applying the pre-deformation of large uniaxial tension or large simple shear have been investigated. In those studies, as the method for determining yield stress in each cycle, the slope of tangent in the principal deviatoric stress -principal deviatoric strain curve has been adopted instead of the estimation method by conventional proof stress. However, concerning the case that the type of pre-deformation differs from the type of deformation in the cyclic load, detailed studies have not been conducted yet. Hence, in this research, the yield behavior generated under cyclic loads for tension and compression after applying a large simple shear is examined.

2 PRE-DEFORMATION AND CYCLIC LOAD

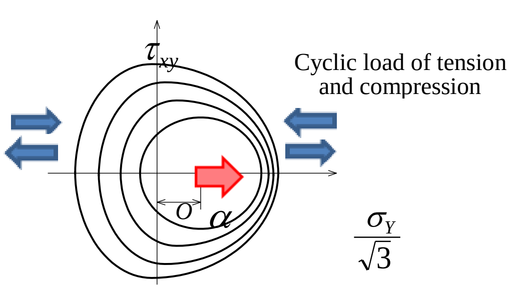
Figure 1 (a) and (b) shows the cyclic load of tension and compression after large pre-deformation. As shown in Figure 1(a), different size of large pre-deformation is firstly applied to the test piece. During this process, the anisotropy has been formed in the material. As a consequence, the value of yield stress at the pre-deformation side is different from the opposite side for Bauschinger effect, see S_{1YB} and S_{1YC} in Figure 1(b). Figure 1(c) and (d) represent the schematic diagram of the anisotropy of yield surface in a stress space, which occurs immediately after pre-deformation. In these figures, Figure 1(c) shows the yield surface concerning the pre-deformation of uniaxial tension, and the principal axis of anisotropy is formed in the tension and the compression side.



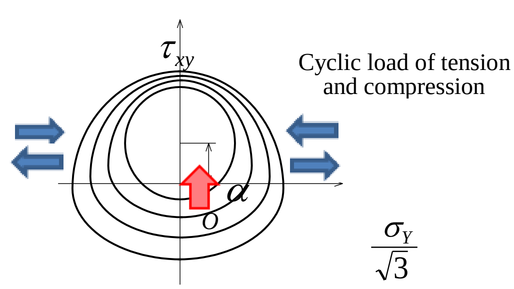
(a) Cyclic load after large pre-deformation.



(b) Stress-strain curve in the first cycle.



(c) Pre-deformation of uniaxial tension.



(d) Pre-deformation of simple shear.

Figure 1. Relation between the anisotoropy in yield surface after large pre-deformation and the cyclic load.

Hence, the direction of the principal axis of anisotropy is the same as the direction of cyclic load for tension and compression. On the other hand, Figure 1(d) shows the yield surface concerning the pre-deformation of simple shear in this research, and the principal axis of anisotropy is formed in the shear deformation side. Hence, under this condition, the direction of the principal axis of anisotropy is different from the direction of cyclic load for tension and compression.

3 ESTIMATION METHOD OF YIELD STRESS UNDER CYCLIC LOAD

Figure 1(b) shows the first cycle for a deviatoric stress and deviatoric strain diagram when the tensile load and the compressive load are subjected alternately to the test pieces after applying a pre-deformation of a large simple shear. The reloading process when the tension applies again after unloading process of tension from a point B is represented by a green curve. Since the value of stress at a point B is preliminary determined, the yield stress during the reloading process is already determined. And, in this figure, it is represented by a point F. In the neighborhood of a yield point F, the deviatoric stress and deviatoric strain curve becomes a shallow curve, and in a series of our studies (Kato and Kazama 2013, Kato 2014), it is formulated as follows.

$$S_1 = a\left(1 - exp(be_1)\right) + ce_1 + d \tag{1}$$

However, *a*, *b*, *c* and *d* in Eq. (1) are coefficients determined by using the *Levenberg-Marquardt Method*, which is one of the non-linear least-squares methods. Furthermore, the slope of tangent is also obtained by differentiating Eq. (1), and it is represented by Eq. (2).

$$\frac{dS_1}{de_1} = -a\,b\,\exp\left(be_1\right) + c \tag{2}$$

Hence, the slope of the tangent at yield point F can be derived by using Eq. (2). Therefore, the slope of tangent at yielding can be specified in advance and it is indicated by the straight blue line.

As for the yield stress in a cycle, firstly, the yield stress obtained after applying the tensile strain with specified constant strain amplitude is represented by a point B just before unloading of tension. Secondly, the yield stress in compression side is obtained by representing the shallow curve by using the Eq. (1). And, the stress, which has the same value as the slope at a point F, i.e., the stress at point C in this figure, is assumed to be a yield stress. Thirdly, the yield stress obtained after applying the compressive strain with specified constant strain amplitude is represented by a point D. Finally, the yield stress in tension side, which is derived by applying a tensile load again after unloading of compression, is obtained by representing the shallow curve by using Eq. (1) once again. Similarly, the stress, which has the same value as the slope of tangent measured at the point F, i.e., the stress at point E in this figure, is assumed to be a yield stress.

On the other hand, the yield stress by proof stress is determined by using the value of the residual strain e_{1r} that is obtained by unloading from a point F. Hence, as shown in point C’ and E’, the proof stress is estimated smaller as compared with the estimated yield stress in this study.

4 EXPERIMENTAL METHOD

In the experiments, the cylindrical specimens made from high purity tough pitch copper are used, i.e., purity 99.99 % and outer diameter 22 [mm], inner diameter 16 [mm], gauge length 30 [mm].

Next, as for the experimental condition, this experiment is composed of two stages. Namely, experiments applying the pre-deformation of the large uniaxial tension to the specimens are firstly conducted. Subsequently, the cyclic loading tests for tension and compression are conducted.

(1) Experimental condition of pre-deformation of large simple shear. Three different types of shear deformation, namely, values of slip k = 0.37, 0.53, 0.98 [-], i.e., values of the principal stretch λ = 1.2, 1.3, 1.6 [-], are applied to the test pieces.

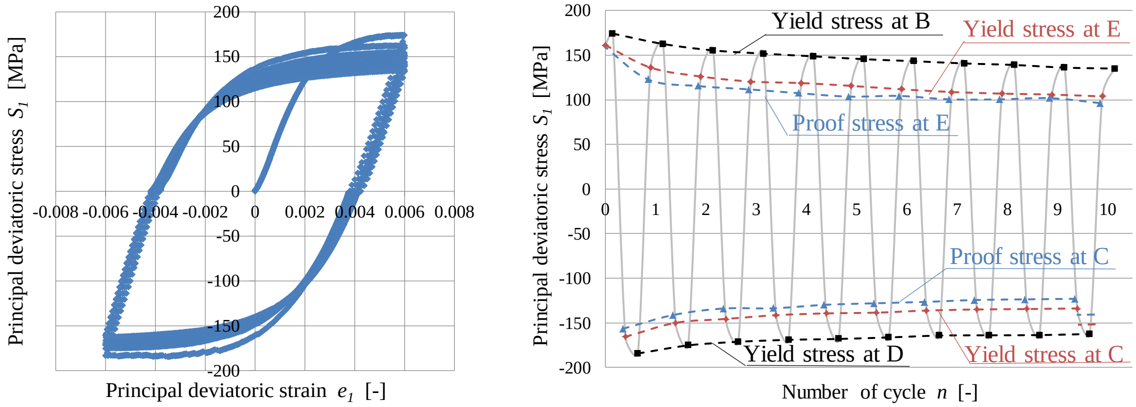
(2) Experimental condition of cyclic loading tests for tension and compression. After attaching the strain gauges to the test pieces, the experiments of the cyclic loading tests for tension and compression are conducted with the constant strain amplitude, namely, $\triangle e_1 = \pm 0.006$ [-]. In these experiments the numbers of cycles n are all ten times. Then, the values of yield stress at points B, C, D and E in Figure 1 are determined, and the changes of yield stress with an increase of the number of cycle n are investigated. Moreover, as for the values of the principal stretch λ =1.2 and λ =1.3 [-], the low-strain amplitude, i.e., $\triangle e_1 = \pm 0.003$ [-], is also examined in this research.

5 EXPERIMENTAL RESULTS

Figures 2 and 3 show some examples of experimental results obtained under cyclic loading tests for tension and compression after applying the pre-deformation of large simple shear with respect to the constant strain amplitude (the strain amplitude $\triangle e_1 = \pm 0.006$ [-]). In these figures, (a) is the deviatoric stress and deviatoric strain diagrams and (b) shows the variation of yield stress with an increase of the number of cycles. In Figure 2 (b) and 3(b), black plots show the stress at B and D (i.e., $S_{1\mathrm{YB}}$ and $S_{1\mathrm{YD}}$ in Figure 1(b)) and red plots show the stress at C and E (i.e., $S_{1\mathrm{YC}}$ and $S_{1\mathrm{YE}}$ in Figure 1 (b)), respectively. As obviously from these figures, the yield stress at C and D on the compression side and yield stress at E and B on the tension side have a decreasing tendency as number of cycles increase, and as is clear from a comparison of Figures 2 and 3, these tendencies are remarkable as the value of pre-deformation large. On the other hand, results by conventional proof stress, namely, yield stresses at point C' and E' in Figure 1(b), are represented by blue curves in these figures. Hence, the estimated yield stresses at point C and E, namely, red curves, is larger as compared with the results by proof stress.

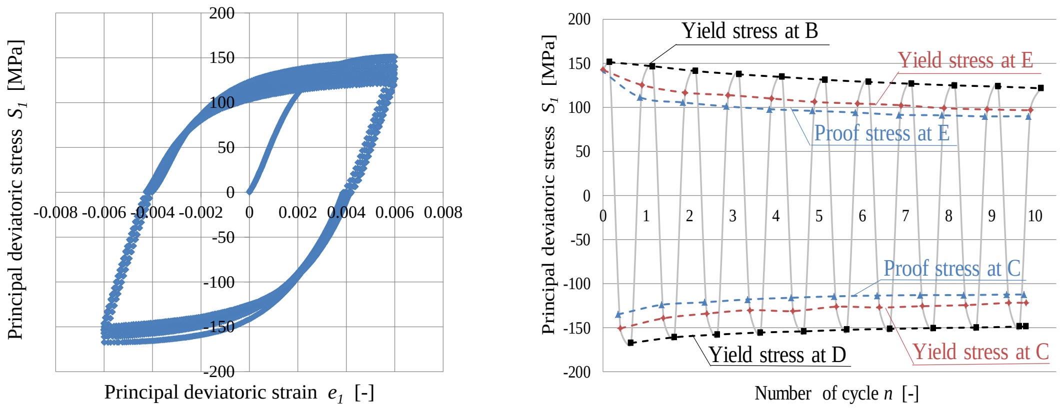
Figure 4 represents the experimental result in the case of low-strain amplitude ($\triangle e_1 = \pm 0.003$ [-]). It is seen that the decreasing tendency of yield stress is small as compared with the results of Figure 3, where the value of pre-deformation is the same.

On the other hand, Figure 5 shows the the previous result in the case of pre-deformation of uniaxial tension (principal stretch λ = 1.3 [-] and strain amplitude $\triangle e_1 = \pm 0.006$ [-]). From the comparison of the result of Figure 3, it is seen that the decreasing tendency of the yield stress at point D on the compression side is smaller than the yield stress at point B on the tension side. Moreover, it can be confirmed form this figure that the shape of stress-strain curve obtained during the process of tension after compression, which is surrounded red ellipse in Figure 5, is different. This is due to a difference in the direction that the principal axis of anisotropy of yield surface is formed (see Figure 1(c) and (d)).



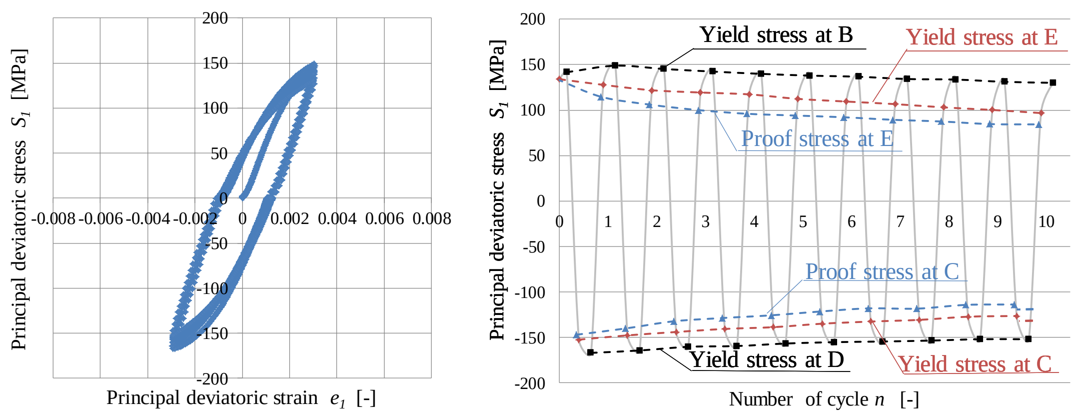
(a) Deviatoric stress and deviatoric strain. (b) Variation in yield stress with the number of cycles.

Figure 2. Yield stress in cyclic load for tension and compression after simple shear (λ=1.6, $\varDelta e_1$ = 0.006).



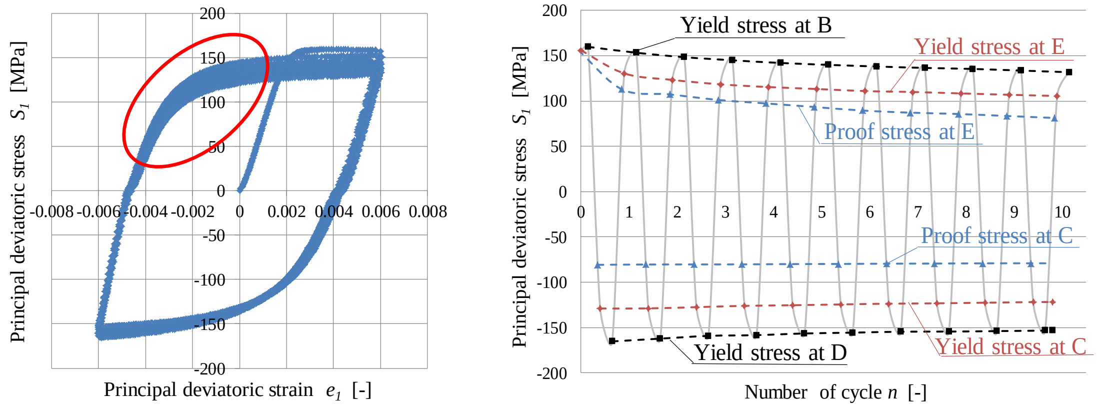
(a) Deviatoric stress and deviatoric strain. (b) Variation in yield stress with the number of cycles.

Figure 3. Yield stress in cyclic load for tension and compression after simple shear (λ=1.3, $\varDelta e_1$ = 0.006).



(a) Deviatoric stress and deviatoric strain. (b) Variation in yield stress with the number of cycles.

Figure 4. Yield stress in cyclic load for tension and compression after simple shear (λ=1.3, $\varDelta e_1$ = 0.003).



(a) Deviatoric stress and deviatoric strain. (b) Variation in yield stress with the number of cycles.

Figure 5. Yield stress in cyclic load for tension and compression after uniaxial tension (λ=1.3, Δe_1 = 0.006).

6 CONCLUSIONS

In this study, using the test pieces, which was already applied the large simple shear, the yield stress under cyclic loads for tension and compression was estimated. As a result, the following conclusions are obtained.

(1) The yield stresses have a decreasing tendency with the number of cycle increase. However, the decreasing tendency reduces as the number of cycles increases, and they approach to the constant value.

(2) As a value of the pre-deformation of simple shear is larger, the decrease tendency of the yield stress at the tension side and compression side during the early stage of cycle load is more emphasized.

(3) The yield stress by proof stress is small as compared with the yield stress estimated in this study at both the tension side and the compression side.

(4) The decreasing tendency of the yield stress on the compression side in this experiment appears slightly strong as compared with results in the case of pre-deformation of uniaxial tension.

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