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Measurement and Analysis of the Elastic-Plastic Deformation Behavior of an Ultra-thin Austenitic Stainless Steel Sheet Subjected to In-plane Reverse Loading

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Abstract

In order to clarify the deformation behavior of an ultra-thin austenitic stainless steel sheet (SUS301) used for manufacturing electronic parts a new testing devise is designed and built. The test material is 0.2 mm thick and has a 0.2 % proof stress of 1800 MPa. The testing apparatus is equipped with comb-type die couples to measure the stress-strain curves of the sample under tension-compression cyclic loading without buckling for a strain amplitude of ± 0.017. It is found that the stresses are higher in tension than in compression in the rolling direction (RD) for a strain range of $|\varepsilon| \geq 0.002$, while in the transverse direction (TD) the stresses are higher in compression than in tension, and that the test material showed significant difference in the cyclic loading behavior between the RD and TD.

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Keywords: sheet metal forming; tension/compression asymmetry; Baushinger effect; reverse loading; austenitic stainless steel sheet

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1. Introduction

The demand for ultra-thin sheet metals is increasing for electronic parts with the reduction in size and weight of electronic devices and precision instruments. In particular, ultra-thin austenitic stainless steel sheets are widely used as they have several characteristics, such as high ductility, workability and corrosion resistance. However, it is a difficult material to use from the view point of manufacturing, because it causes large springback after forming.

Electronic terminal parts, such as switches and connecters, are usually made of high tensile strength sheet metals with 0.25 to 0.05 mm thickness. Thus, a large springback occurs after unloading. Springback often causes serious problems in determining the optimum process parameters and tool geometry, and is the main impediment to high-efficiency production of electronic parts. In order to establish time- and cost-effective press-forming technologies for electronic parts using ultrathin sheet metals, it is vital to accurately predict the amount of springback using simulation techniques and to determine the optimum forming conditions. Springback is caused by the bending moment retained in press-formed parts before unloading and is also affected by the unloading stress-strain response of the material [1, 2]. Therefore, in order to accurately predict the amount of springback of electronic parts, it is crucial to have a highly accurate material model that is capable of predicting the elastic-plastic behavior of the sheet metal under given forming conditions and to incorporate it into a forming simulation software.

During the processes of electronic parts production, the material undergoes several strain path changes. The raw material is successively cold rolled into flat sheet until the desired thickness is obtained. Blanks are then cut off from the rolled sheet and formed into final part shapes by drawing and/or bending. Furthermore, the formed parts are often subjected to cyclic loading in service. Therefore, in order to obtain in-depth knowledge of the mechanical properties of the electronic parts, it is also vital to observe the stress-strain response of the material subjected to strain path changes, as well as monotonic tensile and compressive loading. It should be noted that the strain path changes during forming processes affect the dislocation substructure of the material and the stress-strain curve is dependent on the amplitude of the applied strain change [3]. Moreover, the directionality of dislocation structures in severely deformed metals and their rearrangement during reloading can result in tension-compression asymmetry (TCA) of the flow stress in the material [4].

Several experimental methods have been proposed to measure the stress-strain responses of thin sheet metals subjected to cyclic loading. Cyclic bending-unbending tests [5-7] and cyclic simple-shear tests [8-10] are popular methods. However, these are not proper experimental methods to accurately measure the in-plane compressive stress-strain curves of thin sheet metals. Dietrich and Turski [11] proposed a unique experimental tooling for applying in-plane compression to a thin sheet specimen without causing buckling. However, the magnitude of strain imposed on the specimen was limited to -0.3%. Inspired by the work of Dietrich and Turski [11], one of the present authors devised an in-plane compression testing method for sheet metals using comb-type die couples and successfully measured in-plane compressive stress-strain curves of cold-rolled low carbon steel sheets and an AA5182-O sheet up to -16% maximum plastic strain [12, 13]. Other testing methods for directly observing the stress-strain curves of sheet metals subjected to tension/compression stress reversals have been proposed by Iwata et al. [14], Yoshida et al. [1], Boger et al. [15] and Cao et al. [16]; see [17] for the details of the testing devices developed in these studied.

In this study, in-plane uniaxial tension/compression responses of a 0.2 mm-thick austenitic stainless steel sheet (SUS301) with a 0.2 % proof stress of 1800 MPa are precisely measured using a comb-type die couples developed by one of the authors [18, 19]. The significant differences in the flow stresses between tension and compression and in those between the rolling direction (RD) and transverse direction (TD) are found for the first time. Moreover, the stress-strain curves under tension followed by compression and compression followed by tension are precisely measured.

2. Experimental method

2.1. Test material

The test material was a 0.2 mm-thick austenitic stainless steel sheet (SUS301). The 0.2 % proof stresses of the test material were 1800 MPa for the RD and 1580 MPa for the TD.

2.2. In-Plane Reverse Loading Test Method

In order to directly measure the stress-strain (ss) curves of the sample subjected to tension/compression stress reversals, in-plane reverse loading tests were performed. Figure 1 shows the testing apparatus used in this study. The testing apparatus is similar to those used in [18, 19], but was newly designed to increase the rigidity of the apparatus so that it can apply higher blank-holding force to the test material than those to lower strength materials as tested in [18, 19]. Figure 1(a) shows an upper view of the upper comb-type die couple, and Fig. 1(b) shows the upper and lower comb-type die couples; the tooth width and length are 0.9 and 3.6 mm, respectively, and the gap between the teeth is 1.0 mm. The die couples are installed in the testing apparatus as shown in Fig. 1(c). Lower die 1 is fixed to the lower plate of the die set and lower die 2 is on a slide rail that enables the die to move smoothly in the horizontal direction. A sheet specimen is set on lower dies 1 and 2 and both ends of the specimen are clamped by chucking plates. Upper dies 1 and 2 are placed on the specimen so that the four positioning pins fixed to the lower dies align with the holes of the upper dies. Accordingly, the movement of the upper dies is synchronized with that of the lower dies. Lower die 2 is actuated in the horizontal direction by a servo-controlled hydraulic cylinder 2, so that continuous in-plane stress reversals are applied to the specimen. Hydraulic cylinder 1 exerts a constant blank-holding force on the specimen through the upper die couples and the cylindrical rollers lying between the upper die couples and the blank-holding platen. The specimen can thus be compressed in the longitudinal direction without buckling. carried out on the as-received test sample using the testing apparatus. The geometry of the specimen is shown in Fig. 2. In order to prevent buckling of the specimen during in-plane compression test, blank-holding pressure was applied to the specimen; it was 24 MPa for the tests for the RD and 26 MPa for the TD.

In order to prevent the specimen from galling the dies, the specimen was lubricated on both sides with Vaseline and Teflon (spray type), resulting in reduction of the coefficient of friction to 0.013. However, it should be noted that the frictional forces between the dies and specimen have little effect on the measured stress, as is described in [18]. This is the significant advantage of this testing device over other reported in-plane compression testing devices [17], in which the predetermined frictional force must be subtracted from the measured force data; such a procedure

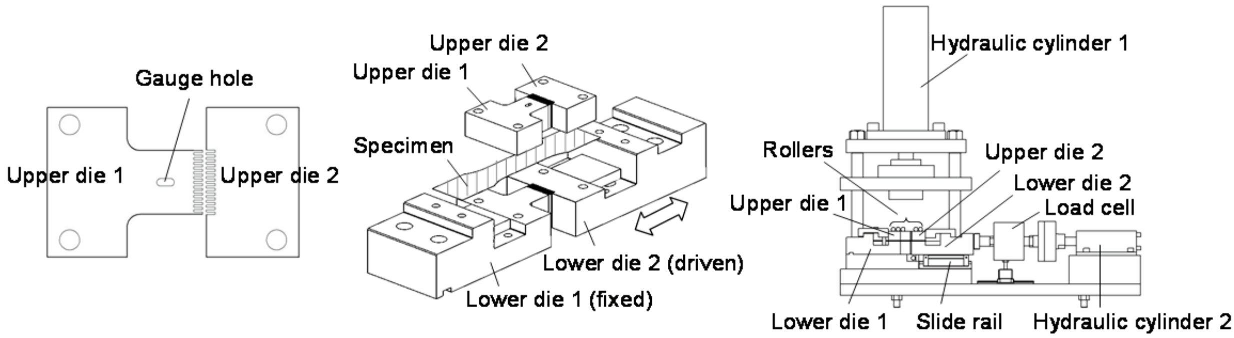


Fig. 1. In-plane stress reversal testing machine. (a) Upper dies, (b) Comb-type dies and (c) Overview of the testing apparatus.

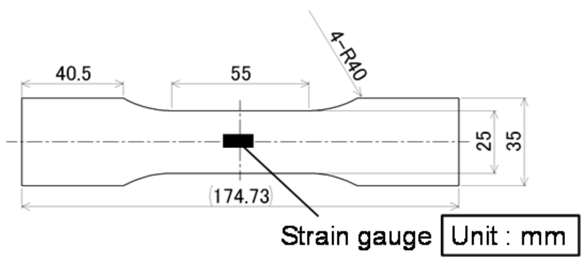


Fig. 2. Specimen for in-plane stress reversal test

may cause unavoidable uncertainty in the accuracy of the measured stress data.

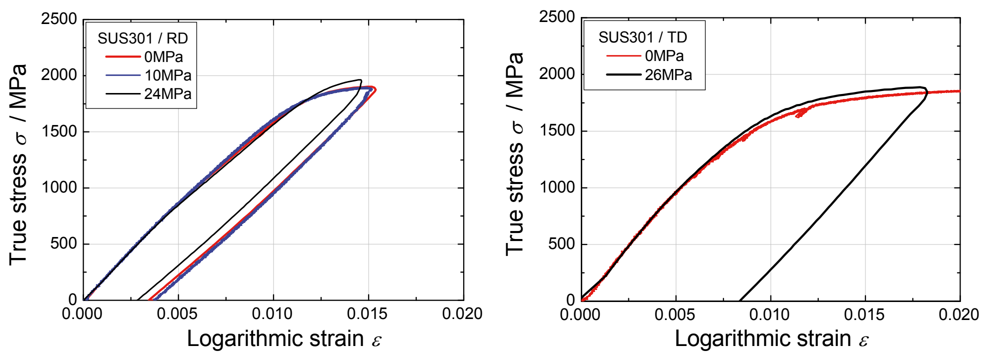
The amount of the longitudinal strain was measured using a strain gauge (Kyowa Dengyou Co., KFG-02-120-C1-16). The strain gauge has a capability of measuring strain up to 5%. The lead wires of the strain gauge were passed through a hole opened in the upper die 1, as shown in Fig. 1(a). The strain gauge was glued onto the specimen at the position where the hole in upper die 1 was located, so that the strain gauge was free from the contact pressure to upper die 1. The tension/compression forces applied to the specimen were measured using a load cell connected to the right side of lower die 2, as shown in Fig. 1(c).

3. Experimental results

3.1. Results of monotonic tension and compression tests

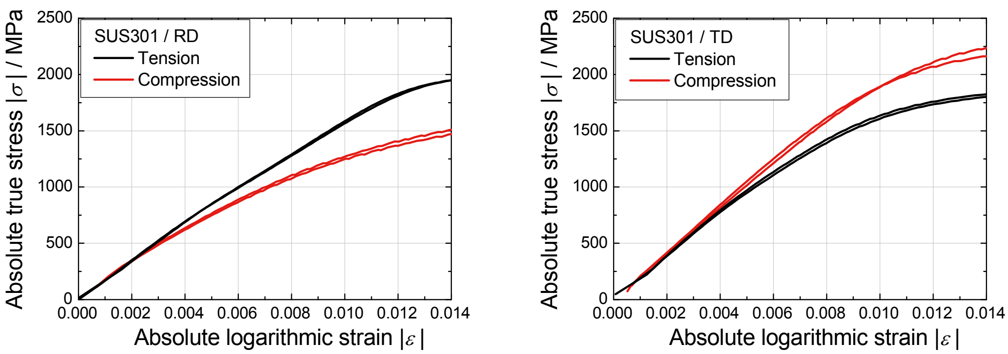
Figure 3 shows the tensile ss curves measured using the testing apparatus shown in Fig. 1, with and without a blank-holding pressure (p_{BH}). In the RD the difference in the flow stresses with $p_{BH} = 0$ and 10 MPa are negligibly small while those with $p_{BH} = 24$ MPa in the RD and 26 MPa in the TD are slightly higher than those with $p_{BH} = 0$. This is due to the friction effect between the specimen and the dies, as quantitatively analyzed in [18]. In the following figures the increase of flow stress due to friction was not subtracted from the measured flow stress data.

Figure 4 compares the tensile and compressive stress-strain curves for the RD (a) and TD (b); both tests were performed with $p_{BH} = 24$ MPa in the RD and 26 MPa in the TD. The test material exhibited significant TCA both in the RD and TD. In the RD the stresses are higher in tension than in compression for a strain range of $0.002 \le |\varepsilon|$; it is 22 % higher in tension than in compression at $|\varepsilon| = 0.014$. This phenomenon is possibly caused by the Bauschinger effect of the sample. This is because the sample was elongated in the RD during the cold rolling



(a) (b)

Fig. 3 True stress-logarithmic strain curves measured in the tension followed by unloading experiment in (a) RD and (b) TD.



(a) (b)

Fig. 4 True stress-logarithmic strain curves measured in the monotonic tension/compression tests for (a) RD and (b) TD process in material production; therefore, the flow stress of the sample subjected to the in-plane compression in this test became lower than that under tension because of the reverse loading following the cold rolling process. In the TD the stresses are higher in compression than in tension for a strain range of $0.002 \le |\varepsilon|$; it is 24 % higher than the tensile one at $|\varepsilon| = 0.014$. The TCA observed in the TD is probably caused by the directionality of dislocation structures of severely deformed metals and their rearrangement during reloading [3, 4]. The TCA as shown in Fig. 4 was also observed in the tension/compression tests on a 0.25 mm-thick phosphor bronze sheet [18] and a 0.3 mm-thick SUS304 stainless steel sheet [19]. Therefore, the TCA is possibly a phenomenon common to heavily cold rolled sheet metals..

Figure 5 shows the ss curves in the tests of (a) TC (initial tension followed by unloading, compression, and subsequent unloading) and (b) CT (initial compression followed by unloading, tension, and subsequent unloading). The test material shows significant difference in the TC and CT behavior between RD and TD. In the TC tests the initial tensile flow stress is almost identical to each other in RD and TD while the subsequent compressive flow stress is 25 % higher in TD than in RD at ε=-0.015. In the CT tests the initial compressive flow stress is 30 % higher in TD than in RD at ε=-0.02 while the subsequent tensile flow stress is almost identical to each other at ε= 0.01.

Figure 6 shows the variation in instantaneous slope, $d\sigma/d\varepsilon$, of the stress-strain curves shown in Fig. 5(a) during (a) initial tension, (b) unloading followed by compression, and (c) subsequent unloading. It is noted that the general trends in the variation in $d\sigma/d\varepsilon$ are almost identical to each other between RD and TD during unloading followed by compression (Fig. 6(b)), while the magnitudes of $d\sigma/d\varepsilon$ is consistently higher in RD than in TD (Fig. 6(c)).

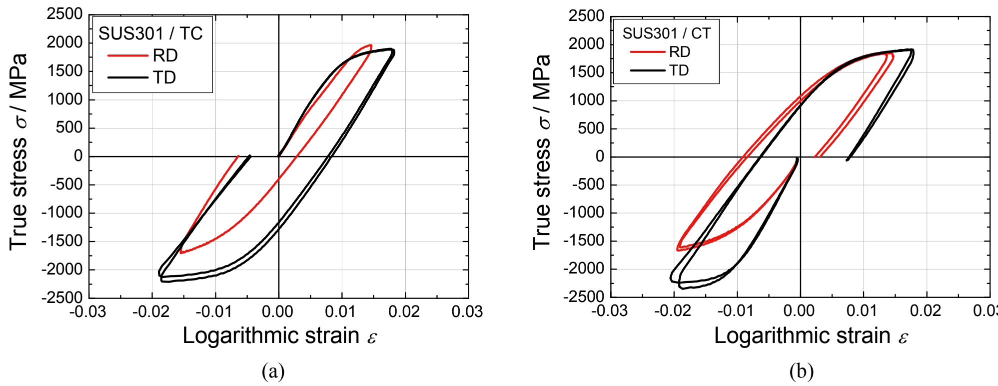


Fig. 5 True stress-logarithmic strain curves measured in the stress reversal tests: (a) TC test and (b) CT test.

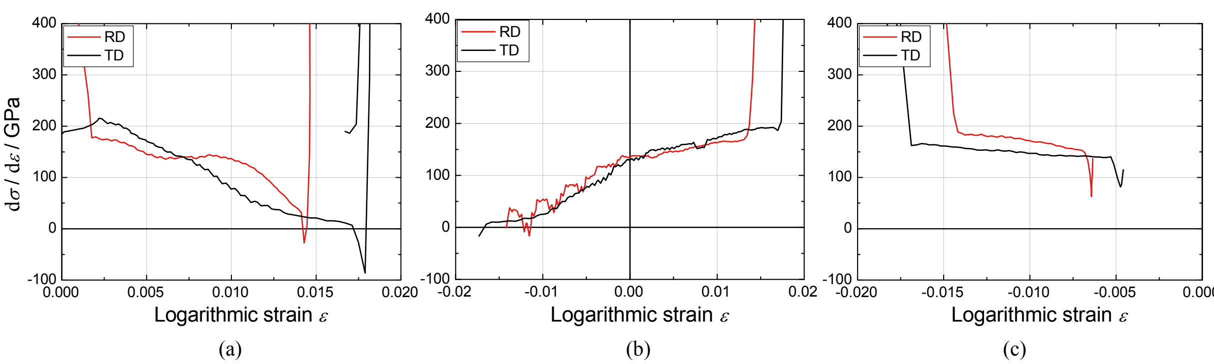


Fig. 6 Variation in the instantaneous slope of the stress-strain curves shown in Fig. 5(a) during (a) initial tension, (b) unloading followed by compression, and (c) unloading.

4. Conclusions

The in-plane tension/compression stress-strain curves of a 0.2 mm-thick austenitic stainless steel sheet (SUS301) with a 0.2 % proof stress of 1800 MPa were successfully measured within a strain amplitude of ± 0.017. A testing apparatus equipped with comb-type die couples was designed and built to apply in-plane tension/compression reverse loading to the test material without buckling. Following experimental observations were obtained.

(1) The stress-strain curves of the test material were successfully measured without buckling of the specimens for a strain amplitude of ± 0.017.

(2) In the RD the stresses are higher in tension than in compression for a strain range of $0.002 \le |\varepsilon|$; it is 22 % higher in tension than in compression at $|\varepsilon| = 0.014$. In the TD the stresses are higher in compression than in tension for a strain range of $0.002 \le |\varepsilon|$; it is 24 % higher than the tensile one at $|\varepsilon| = 0.014$.

(3) The test material shows significant difference in the TC and CT behavior between the RD and TD.

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