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Time-dependent springback of a commercially pure titanium sheet

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Abstract

Time-dependent springback of a commercially pure titanium sheet was investigated experimentally from the viewpoints of strain rate, holding time at the bottom dead center before unloading, and elapsed time after unloading. A draw-bending test showed that the amount of springback decreased linearly with the holding time before unloading when plotted on logarithmic scale and increased with the elapsed time after unloading. To investigate the mechanism of these results, stress relaxation and creep tests were conducted. The variation of the amount of springback with the holding time corresponded well with that of the stress during stress relaxation. On the other hand, the in-plane anisotropy in the evolution of the amount of springback with the elapsed time did not correspond with that of creep strain. The mechanism of the in-plane anisotropy in the elapsed-time dependency was discussed in terms of the stress relaxation and creep behaviors.

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Keywords: Pure titanium; Time-dependent springback; Draw bending; Stress relaxation; Creep

1. Introduction

Commercially pure titanium (CP-Ti) sheets are distinguished in their high specific strength and corrosion resistance, and are generally manufactured using press forming [1-3]. Springback is regarded as one of the significant defects in sheet forming. It was reported that in some metallic sheets the amount of springback changed depending on the holding time at the bottom dead center before unloading, exhibiting holding time-dependent springback even at room temperature [4-5]. Furthermore, it was also reported that some sheets, such as aluminum

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alloy and high tensile-strength sheets, exhibited elapsed time-dependent springback at room temperature, i.e. the amount of springback changed with the elapsed time after unloading [6-7]. It is important to understand the characteristics of time-dependent springback because they affect the final shape of products.

In previous studies [4-7], time-dependent springback was considered to be related with stress relaxation and creep behaviors of materials. Kyuno et al. [5] investigated the effect of stress relaxation on a variation of springback with holding time in a steel sheet and reported that the decrease in stress during stress relaxation caused the decrease of springback. The elapsed time-dependent springback was investigated in aluminum alloy and high strength steel sheets respectively by Wang et al. [6] and Lim et al. [7]. In their works anelasticity and creep driven by residual stress were focused on as the mechanism of the elapsed time-dependent springback. They reported that anelasticity did not make a significant contribution to the long-term springback, whereas creep was more likely to contribute. Because CP-Ti sheets exhibit high strain-rate sensitivity and large stress relaxation and creep behaviors at room temperature [8-10], time-dependent springback would be pronounced. Moreover, CP-Ti sheets show strong in-plane anisotropy in deformation behavior [1-3]; thus, time-dependent springback would also be anisotropic. However, the characteristics of time-dependent springback have scarcely been studied in CP-Ti sheets.

In this study, time-dependent springback of a CP-Ti sheet was investigated. Specifically, a draw-bending test was performed at room temperature to examine time-dependent springback of the sheet from the viewpoints of strain rate, holding time at the bottom dead center before unloading, and elapsed time after unloading. Stress relaxation and creep tests were also conducted to understand the mechanism of the time-dependent springback of the CP-Ti sheet.

2. Experimental procedures

2.1. Material

The material used in this study was a JIS grade2 CP-Ti rolled sheet with a thickness of 1 mm (Kobe steel) [1]. Fig. 1 shows the stress-strain curves obtained from a uniaxial tension test in the rolling direction (RD) and the transverse direction (TD) with the strain rates of 6.67×10^{-4} s^{-1} and 3.33×10^{-2} s^{-1}. Strain was measured using a strain gauge (Kyowa electronic instruments, KFEM). The yield stress was larger in the TD than in the RD. On the other hand, the work hardening was larger in the RD than in the TD. These stress behaviors were independent of the strain rate. Eventually, the stress at a strain of 0.1 was slightly larger in the RD than in the TD although the difference is quite small at the high strain rate. Concerning the effect of strain rate, the stress was apparently higher at the high strain rate (3.33×10^{-2} s^{-1}) than at the low strain rate (6.67×10^{-4} s^{-1}), irrespective of the loading direction.

Fig. 2 presents the variation of apparent Young's modulus with unloaded strain. Note that apparent Young's modulus was measured by linearly approximating the unloading curve. Apparent Young's modulus was smaller in the RD than in the TD, irrespective of the strain rate. Young's modulus was slightly larger at the low strain rate (6.67×10^{-4} s^{-1}) than at the high strain rate (3.33×10^{-2} s^{-1}) at small strains, while it was almost the same at high strains.

2.2. Draw-bending test

A draw-bending test was performed to investigate the springback properties. A cross-sectional shape of the punch was a rectangle whose dimensions were 40 mm in the width and 50 mm in the depth directions. The punch and die

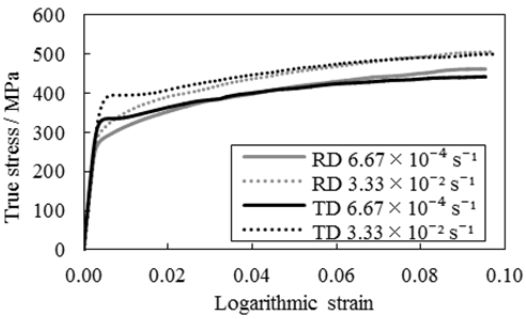

Fig. 1 Stress-strain curves under tension.

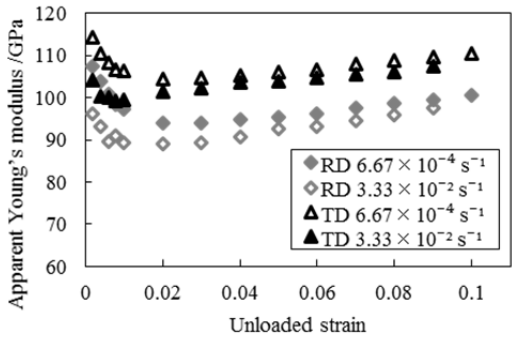

Fig. 2 Variation of apparent Young's modulus with unloaded strain obtained under tension.

shoulder radii were 5 mm and 10 mm, respectively. The blank holding force was maintained using springs with a spring constant of 943 N/mm and was varied from 5 kN to 20 kN. Molybdenum paste was used for lubrication. The sheet was drawn at a constant punch speed of either 10 mm/s or 1000 mm/s until a punch stroke reached 50 mm. At the bottom dead center, the specimens were held for either 5, 50, 600, or 4000 min in order to investigate the effect of holding time on the amount of springback. The test was conducted 3 times for each experimental condition.

The side wall curvature was used to evaluate the amount of springback. A laser displacement sensor (Keyence, LK-080) was used to measure the profile of the product. It should be noted that, owing to the structure of the experimental setup, it took approximately 5 min to remove the sheet from the dies. An average of the curvatures at the side wall was then calculated as an evaluation indicator of springback. The springback was measured for 4000 min after unloading in order to investigate the effect of elapsed time on the amount of springback.

2.3. Stress relaxation and creep tests

In the stress relaxation test, the sample was first stretched to a strain of 0.1 with the strain rate of either 6.67×10^{-4} s^{-1} or 3.33×10^{-2} s^{-1}. It should be noted that these strain rates corresponded respectively to the punch speeds of 10 mm/min and 1000 mm/min in the draw-bending test. Then, the cross head of the testing machine was halted for 600 s and the variation of stress was measured. In the creep test, the sample was first stretched with the strain rate of 6.67×10^{-4} s^{-1} until the stress reached a predetermined value, which was varied from 85% to 95% of the yield stress. Then, the stress was kept to be constant for 1200 s while the variation of strain was measured. These experiments were conducted in both the RD and the TD at room temperature.

3. Results and discussion

3.1. Result of stress relaxation and creep tests

Fig. 3 shows the variation of stress during stress relaxation as a function of time plotted on logarithmic scale. The stress variation before and after the beginning of stress relaxation is also shown. The stress was higher in the RD than in the TD throughout the process, regardless of the strain rate. This magnitude relationship was consistent with the stress during loading at a strain of 0.1. On the other hand, the stress was apparently higher at the high strain rate (3.33×10^{-2} s^{-1}) than at the low strain rate (6.67×10^{-4} s^{-1}) during loading, while this magnitude relationship reversed at the very beginning of relaxation (within 1 s). Eventually at a relaxation time larger than 100 s, the difference in the stress between the two strain rates was very small, irrespective of the loading direction.

Fig. 4 shows the variation of creep strain. The creep strain increased with time, irrespective of the condition. On the other hand, its evolution was different between the RD and the TD. In the TD, the creep strain increased slowly at the very beginning (0 to 30 s), then increased rapidly during the early stage (30 to 400 s) and tended to saturate after that, presenting a sigmoidal curve. In contrast, a sigmoidal curve was not observed in the RD. Eventually, the creep strain at 1200 s was larger in the TD than in the RD.

The creep strain became large with the stress. It should be noted that creep strain hardly occurred when the stress was smaller than 85% and 80% of the yield stress respectively in the RD and in the TD, consistent with a previous study [11-12]. The aforementioned results suggested that the threshold stress for creep strain showed anisotropy.

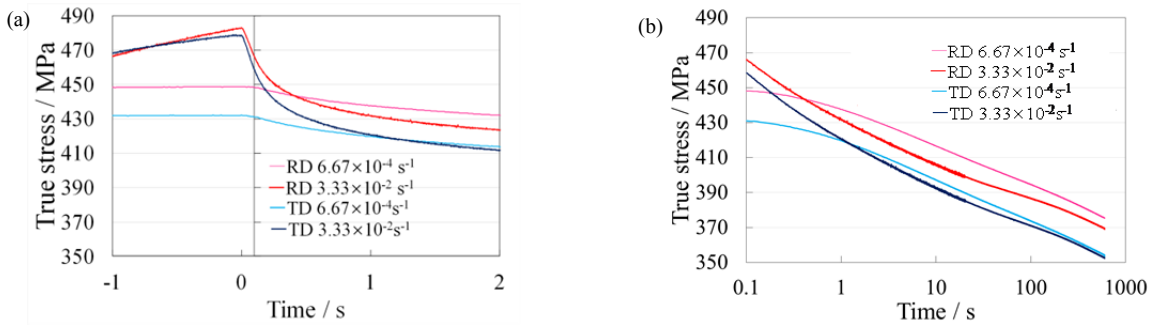

Fig. 3 Variations of stress (a) before and after beginning of stress relaxation and (b) during stress relaxation.

3.2. Result of draw-bending test

3.2.1 Effect of anisotropy and strain rate on initial curvature

The effect of in-plane anisotropy and strain rate on initial curvature, i.e. the result obtained with the holding time of 5 min and the elapsed time of 0 min, is investigated. Fig. 5 shows the relationship between the initial curvature and the blank holding force. It should be noted that the curvature tended to decrease slightly as the blank holding force increased, but the change was very small, irrespective of the forming condition. First, the effect of in-plane anisotropy is examined. The curvature was obviously larger in the RD than in the TD, irrespective of the forming speed. Because the deformation during the holding of punch was similar to that during stress relaxation, the reason of this anisotropy would be explained considering stress relaxation as follows. The stress at a relaxation time of 300 s (5 min) was higher in the RD than in the TD (Fig. 3). Furthermore, as shown in Fig. 2, apparent Young's modulus was smaller in the RD than in the TD. Both characteristics would yield the amount of springback larger in the RD than in the TD; thus, the large difference in the curvature was observed between the RD and the TD.

Next, the effect of the forming speed is discussed. The amount of springback was larger at the high forming speed (1000 mm/min) than at the low forming speed (10 mm/min), but the difference was very small, irrespective of the loading direction. As mentioned earlier, the stress at a relaxation time of 300 s was slightly higher at the low strain rate (6.67×10^{-4} s^{-1}) than at the high strain rate (3.33×10^{-2} s^{-1}), but the difference was very small. On the other hand, as shown in Fig. 2, apparent Young's modulus was slightly larger at the low strain rate (6.67×10^{-4} s^{-1}) than at the high strain rate (3.33×10^{-2} s^{-1}) at small strains, while it was almost the same at high strains. Clearly, both differences between the two strain rates were comparatively small, and moreover, the trends observed in the stress and apparent Young's modulus would yield an opposite effect each other on the amount of springback; thus, the difference in the curvature depending on the forming speed was also small.

As mentioned above, the springback characteristics may be explained reasonably from the results of stress relaxation and the apparent Young's modulus. Note that the effect of strain rate on the springback characteristics would not be explained reasonably using the stress during loading because it was obviously larger at the high strain rate than at the low strain rate. The above discussion suggests that it may be important to take the stress relaxation into account to discuss the springback characteristics when the holding at the bottom dead center is involved.

3.2.2 Effect of holding time at bottom dead center

Fig. 6 shows the variation of curvature with the holding time at the bottom dead center. The results obtained with the blank holding force of 5 kN in the RD are presented. The curvature decreased linearly with the holding time when plotted on logarithmic scale. The curvature decreased by 17 % from the holding time of 5 min to that of 4000 min. The difference in the forming speed did not affect significantly the change in curvature. This result may be owing to the fact that the internal stresses of the specimen decreased during holding because of stress relaxation. This presumption is supported by the results that the linearity in the curvature variation as well as the negligible effect of the forming speed on the curvature corresponded well with the variation of the stress during stress

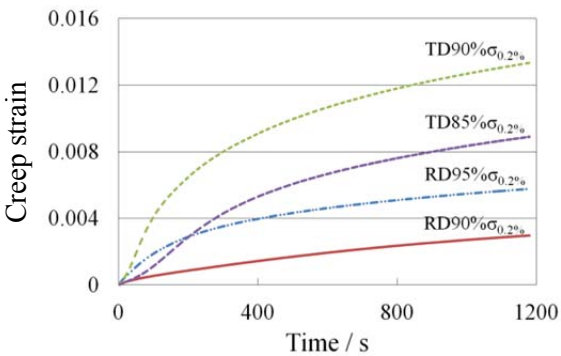

Fig. 4 Evolution of creep strain under different stresses.

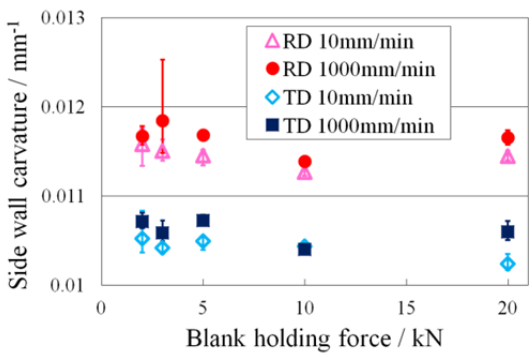

Fig. 5 Relationship between side wall curvature and blank holding force.

relaxation (Fig. 3). Therefore, it is presumed that the effect of holding time at the bottom dead center would be primarily explained from the decrease in stress during stress relaxation. Our previous study showed that nonlinear stress-strain curve exhibited during unloading in a magnesium (Mg) alloy sheet was because of the activity of basal slip that had the smallest critical resolved shear stress (CRSS) [13]. Because the CRSS is also different depending on the slip system in CP-Ti [3], it is hypothesized that a similar microscopic deformation occurred during stress relaxation although a sheet is not completely unloaded during stress relaxation.

3.2.3 Effect of elapsed time after unloading

Fig. 7 shows the variation of curvature with the elapsed time after unloading. The results obtained with the forming speed of 10 mm/min and the blank holding force of 5 kN are depicted. In the RD, the curvature increased 3 to 6% during the elapsed time of 4000 min. The elapsed-time dependency was smaller as compared to the holding-time dependency; the increase in curvature with the elapsed time was between 1/6 and 1/3 of the decrease in curvature with the holding time. The aforementioned time-dependency of springback of the CP-Ti sheet is qualitatively similar to those of a Mg alloy sheet reported in a literature [4], in which the time-dependent springback was explained in terms of twinning activity and resultant creep behavior. Because the amount of creep strain (Fig. 4) is large enough to yield the curvature change with the elapsed time (Fig. 7), it is presumed that creep behavior may be one of the factors of the elapsed time-dependency also in the CP-Ti sheet. Moreover, it was reported that both slip and twinning would be active during creep in Ti and its alloys [14-16], suggesting that twinning activity would also play an important role in the time-dependent springback in the CP-Ti sheet as in a Mg alloy sheet [4].

The effect of the in-plane anisotropy is discussed using the results with the holding time of 5 min, as an example. The magnitude of the elapsed time-dependent springback was slightly larger in the RD than in the TD. As explained in 3.2, the creep strain was larger in the TD than in the RD (Fig. 4). Following the literatures [14-16], the anisotropy in creep behavior would be due to the difference in slip and twinning activities. Clearly, the magnitude relationship in the creep strain was inconsistent with that of the elapsed time-dependent springback. One of the factors that yield the aforementioned inconsistency would be the anisotropy in the residual stress after unloading which is the driving force of creep [6-7]. Because the magnitude of stress at the beginning of unloading would be larger in the RD than in the TD because of stress relaxation (Fig. 3), the magnitude of residual stress after unloading would also be greater in the RD than in the TD. Therefore, the creep strain after unloading could be larger in the RD than in the TD as the creep strain would increase with the stress (Fig. 4). Additionally, the effect of pre-strain on creep may also be one of the possible factors. It was reported that in some metals the creep behavior was affected by pre-straining [9]. Hence, the creep behavior that occurred in the deformed products may be different from that of the virgin material.

4. Conclusion

A draw-bending test was performed to examine time-dependent springback of a CP-Ti sheet in terms of strain rate, holding time at the bottom dead center, and elapsed time after unloading. Stress relaxation and creep tests were also conducted to understand the mechanism of time-dependent springback. The following conclusions were drawn.

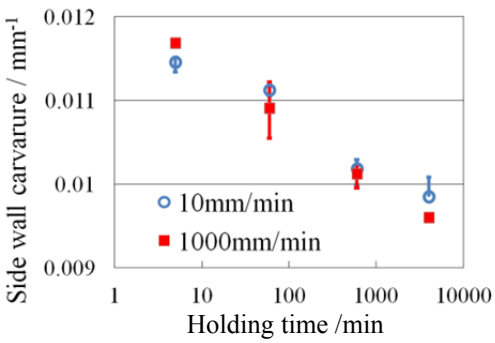

Fig. 6 Variation of springback with holding time at bottom dead center.

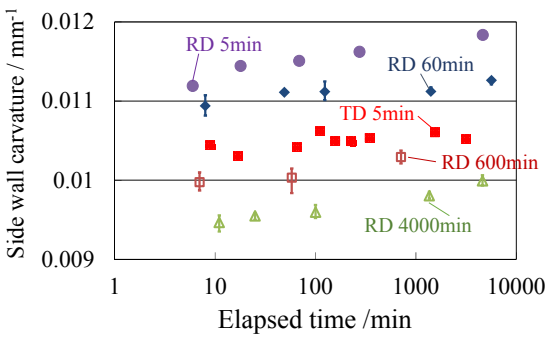

Fig. 7 Variation of springback with elapsed time after unloading for samples subjected to different holding times.

(1) By considering the variation of stress during stress relaxation and apparent Young's modulus, the effects of in-plane anisotropy and strain rate on the initial springback can be explained qualitatively well.
(2) The amount of springback decreases with the holding time at the bottom dead center and increases with the elapsed time after unloading. The decrease in curvature with the holding time is 3 to 6 times larger than the increase in curvature with the elapsed time.
(3) The decrease in curvature with the holding time corresponds qualitatively well with the variation of stress during stress relaxation.
(4) The increase in curvature with the elapsed time is larger in the RD than in the TD, which does not correspond with the result of creep test. A difference in residual stress after unloading between the RD and the TD would be one of the factors that yield larger elapsed time-dependency in the RD than in the TD.

Acknowledgments

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