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Time-Dependent Springback of Various Sheet Metals: An Experimental Study

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In the present study, draw-bending tests were conducted to investigate the effects of holding time at the bottom dead center (holding-time dependency) and elapsed time after releasing from dies (elapsed-time dependency) on springback in steel, Al alloy, Mg alloy, and CP-Ti sheets experimentally. The amount of springback decreased with increasing the holding time, irrespective of the material. The decreasing amounts from the holding time of 5 min to 600 min were 29%, 11%, 8.1%, and 5.7% respectively for the Mg alloy, CP-Ti, Al alloy, and steel sheets. On the contrary to previous studies, it was presumed from simple analyses that the holding-time dependency would presumably be explained in terms of not only stress relaxation but also unloading behavior following stress relaxation. The amount of springback gradually increased with the elapsed time regardless of the material. The amounts of increase from just after releasing from dies were approximately 5.9% for one month in the CP-Ti sheet, 4.1% for 1.5 months in the Al alloy sheet, 1.6% for 1.5 months in the Mg alloy sheet, and 1.1% for 1.5 months in the steel sheet. This magnitude relationship was different from that of creep strains, indicating that the mechanism of the elapsed-time dependency could not be explained only from the creep behavior and there would be other factors that affect the elapsed-time dependency.
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1. Introduction

Springback is one of the significant defects in press forming of sheet metals. It is established that springback occurs due to elastic recovery upon releasing from dies after forming; thus, it is primarily governed by both the flow stress at the beginning of unloading and the deformation behavior during unloading. A lot of studies have been conducted so far to understand springback characteristics and to develop advanced constitutive models to predict springback accurately in various sheet metals.[e.g., 1–3]

Recently it was reported that the amount of springback could be reduced by holding a punch for a certain period during forming. Li *et al.*[4] performed a three-point bending test using a Mg alloy sheet at room temperature and showed that the specimens that had been held at the bottom dead center before unloading exhibited much smaller amount of springback compared to samples without being held. Kyuno *et al.*[5] showed that the amount of springback after spherical stretch forming of steel sheets could be reduced when a punch was stopped at the bottom dead center for 3.0 s before the sheets were released from dies. They presumed that the amount of springback was decreased because of the stress relaxation of the specimens during the holding of punch. Yamashita *et al.*[6] reported that a similar effect could be obtained when a punch was held for a certain period not only at the bottom dead center but also during press forming. They[6] also reported that ductility of material could also be improved by utilizing stress relaxation presumably because the distribution of dislocation density became more uniform after stress relaxation.[7–9] Because arbitrary punch motion can be realized by using servo press machines,[10,11] this phenomenon is recently receiving attention. In this paper, this phenomenon is termed the holding-time dependency of springback.

Moreover, it was also reported that in some metallic sheets the shape of press-formed product kept on changing after unloading, i.e., the amount of springback changed with the elapsed time after releasing from dies. Wagoner *et al.*[12] and Lim *et al.*[13] conducted draw bending tests of Al alloy and advanced high strength steel sheets, respectively, and showed that the amount of springback gradually increased with the elapsed time after unloading in both materials. The elapsed-time dependency was much larger in Al alloy sheets than in steel sheets. They hypothesized that creep driven by the residual stresses could be related to these results. In the present paper, this phenomenon is termed the elapsed-time dependency of springback. Hama *et al.*[14] recently conducted draw-bending tests of a commercially pure Ti (CP-Ti) sheet and examined the holding-time and elapsed-time dependencies of springback. They found that the holding-time dependency would be affected by both stress relaxation and the change of the apparent Young's modulus with plastic strain. They[15] also conducted a crystal plasticity finite-element analysis on elapsed-time dependency of springback in a CP-Ti sheet and showed that the elapsed-time dependency could be explained qualitatively by creep, as reported in the previous studies.[12,13]

Despite the past studies on the time-dependencies of springback, the detailed mechanisms are still not understood sufficiently. One of the reasons is that the previous studies discussed the time-dependent springback separately for each material; thus, comprehensive understanding applicable to various materials is not achieved. For instance, Sato *et al.*[16] conducted creep tests using various metals and found that creep was much more pronounced in hexagonal-close packed (hcp) metals than in face centered cubic (fcc) and body centered cubic (bcc) metals. This result suggests that the elapsed-time dependency of springback should also be different depending on the crystal structure if creep is the primary mechanism. However, the characteristics of time-

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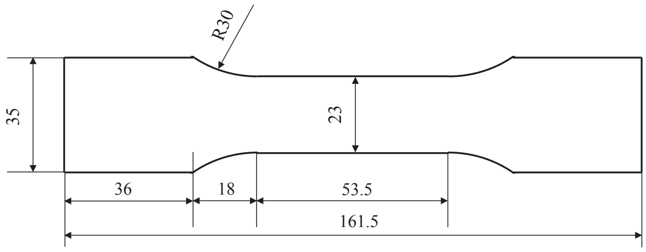

Fig. 1 Geometry of sample used in uniaxial loading tests in mm.

dependent springback have not been compared between different materials.

In the present study, a draw-bending test is conducted and comparative studies on holding-time and elapsed-time dependencies of springback are performed using various sheet metals that have different crystal structures. The characteristics of stress relaxation, creep, and nonlinear deformation behavior during unloading of these metals are also evaluated to discuss the mechanisms of time-dependent springback in detail.

2. Experimental Method

2.1 Materials

The following commercially available materials were used in this study: a rolled AZ31B Mg alloy sheet (hcp structure), a CP-Ti sheet (hcp structure), a rolled A5052 Al alloy sheet (fcc structure), and a rolled interstitial free (IF) steel sheet (bcc structure). It should be noted that the CP-Ti sheet used was the same as that used in our previous study.[14] The IF steel sheet had a thickness of 0.7 mm, whereas the other three sheets had a thickness of 1.0 mm. Figure 1 shows the geometry of the samples used in uniaxial loading tests. Samples for draw bending tests had a rectangular shape with 220 and 50 mm respectively in the longitudinal and width directions. The samples were prepared along the rolling direction. Experiments were conducted at room temperature.

The stress-strain curves of the sheets obtained from the uniaxial tensile test are shown in Fig. 2. The true stresses were calculated on the basis of the volume constancy condition. When the test was conducted at an initial strain rate of 6.7×10^{-4}/s (Fig. 2(a)), the yield stress was the highest for the CP-Ti sheet, followed in order by the Mg alloy sheet, the IF steel sheet, and the Al alloy sheet. This magnitude relationship of the stress remained unchanged to a strain of approximately 0.1. In the case of an initial strain rate of 3.3×10^{-2}/s, the magnitude relationship of the yield stress was the same as that obtained at an initial strain rate of 6.7×10^{-4}/s. On the contrary, the stress at a strain of approximately 0.1 was higher for the IF steel sheet than for the Mg alloy sheet. The rate sensitivity exponents at a strain of approximately 0.1, m, calculated from Fig. 2 were approximately 0.023, 0.0038, 0.019, and −0.0093 respectively for the CP-Ti sheet, the Mg alloy sheet, the IF steel sheet, and the Al alloy sheet. These values are consistent with literature.[17–21]

2.2 Stress relaxation test

Stress relaxation behavior of the materials, which has been considered as one of the governing factors of the holding-time dependency of springback, was evaluated under monotonic tension at room temperature. Strain gauges (Kyowa electronic instruments, KFEM and KFEL series) were used to measure strains during the test. The strain data were recorded approximately every 50 and 1 ms respectively during loading and stress relaxation.

A sheet was first stretched to a strain of 0.1, and then the crosshead of the testing machine was held to keep the strain for 600 min. This holding time is termed as stress relaxation time in the following. An initial strain rate of the test was set to 6.7×10^{-4}/s. After the strain was kept for a prescribed time, the sheet was unloaded at the same initial strain rate.

Deformation behavior during unloading is also one of the important factors that govern the springback characteristics. Therefore, the nonlinear deformation during unloading after stress relaxation was evaluated by using apparent Young's modulus E_a, which was defined to be the slope of the linear approximation of the stress-strain curve during unloading in the range from the beginning to the end of unloading.[22]

2.3 Creep test

Creep behavior of the materials, which has been considered to be one of the main mechanisms of the elapsed-time dependency of springback, was examined under monotonic tension at room temperature. The creep stress was set to 90% of the 0.2% proof stress, i.e., approximately 85, 123, 165, and 250 MPa respectively for the Al alloy, IF steel, Mg alloy, and CP-Ti sheets, and the test was conducted for 20 min. The sheets were stretched at an initial strain rate of 6.7×10^{-4}/s during loading. To examine the effect of pre-straining during forming on creep behavior, the above-

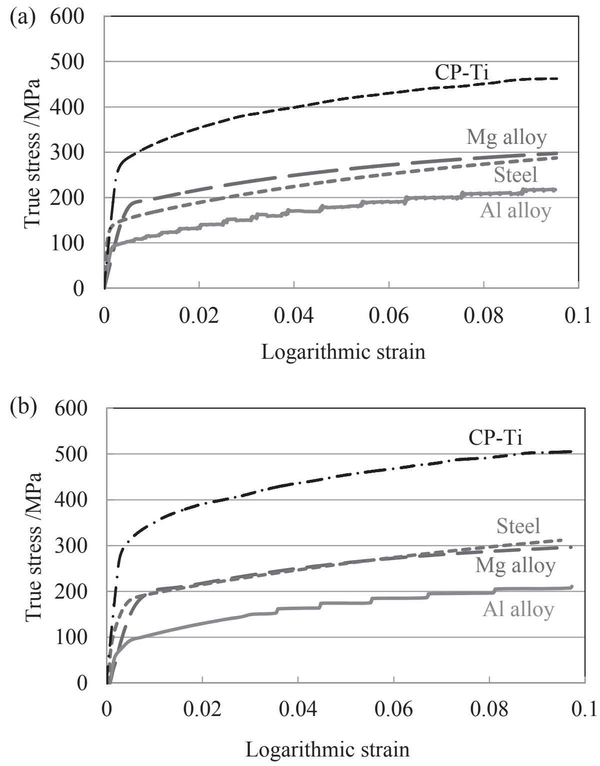

Fig. 2 True stress-true strain curves under uniaxial tension with strain rates of (a) $6.7 \times 10^{-4}\,s^{-1}$ and (b) $3.3 \times 10^{-2}\,s^{-1}$.

mentioned creep test was conducted using virgin and 10% pre-strained sheets. The pre-strain was set to 10% because, as will be explained in the following section, bending and unbending at the die shoulder during draw bending would yield an equivalent plastic strain of approximately 10%, which was estimated using the incremental strain theory.[23)]

2.4 Draw bending test

A draw-bending test was used to evaluate the characteristics of time-dependent springback at room temperature. The experimental procedure followed our previous study.[24)] The punch had a rectangle shape with 50 mm and 40 mm in the depth and width directions, respectively. The punch and die shoulder radii were respectively 5 mm and 10 mm. The clearance between the die and the punch was set to 1.6 mm. To set a same ratio between the initial yield stress and the tensile stress due to friction between the blank holder and the die irrespective of the material, the blank holding force was set to approximately 4, 5, 2, and 2 kN, respectively for the Mg alloy, CP-Ti, Al alloy, and IF steel sheets. The blank holding force was maintained by using four springs with a spring constant of 235.7 N/mm. Molybdenum paste (Moly Paste, Sumico) was used to reduce friction between the die and the blank holder. The punch was penetrated with a constant speed of 10 mm/s to a punch stroke of 50 mm. To study the holding-time dependency of springback, the sheets were held at the bottom dead center for either 5, 60, or 600 min before they were unloaded. It should be noted that it took approximately 5 min to remove sheets from the dies after forming; thus, the shortest holding time was set to 5 min.

Sidewall curvature of the product was used to evaluate amount of springback. The sidewall curvature was measured as follows. The two-dimensional profile of the product was measured along its centerline by using a laser displacement sensor (Keyence, LK-80) at every 0.1 mm intervals. Then a distribution of three-point curvature was calculated along the centerline. Eventually, an average of curvatures at the sidewall part was used as the representative curvature of the product. The curvatures of the products were measured periodically for up to approximately two months after forming.

3. Results and Discussion

3.1 Stress relaxation behavior

Figure 3 shows the variations of the stress during stress relaxation as a function of stress relaxation time. The stress relaxation behavior is apparently different depending on the material. To compare the results between the materials in detail, the stresses at the beginning and the end of stress relaxation, which are denoted respectively as σ_u and σ_e, are shown in Table 1. The stress decrease during stress relaxation is the largest for the CP-Ti sheet, followed in order by the Mg alloy sheet, the steel sheet, and the Al alloy sheet. More quantitatively, the decrease of stress normalized by the stress at the beginning of unloading for the stress relaxation time of 600 min is approximately 27%, 24%, 12%, and 6% respectively for these sheets. The stress decreases for the CP-Ti and Mg alloy sheets are much more pronounced than those for the steel and Al alloy sheets. Although detailed results are not provided here, the stress relaxation test was also conducted at an initial strain rate of 3.3×10^{-2}/s, and it was confirmed that the magnitude relationship between the materials was almost irrespective of the initial strain rate. Interestingly, the magnitude relationship of the stress decrease is clearly different from that of the strain rate sensitivity explained in section 2.1.

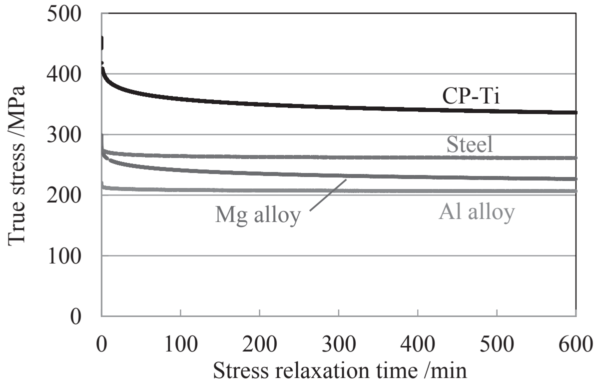

Fig. 3 Variations of true stress during stress relaxation.

Table 1 Variation of true stresses during stress relaxation. σ_u and σ_e respectively denote stresses at the beginning and end of stress relaxation. $\Delta\sigma$ denotes decrease in stress during relaxation.

	σ_u /MPa	σ_e /MPa	$\Delta\sigma/\sigma_u$
CP-Ti	460.0	336.1	0.27
Mg alloy	299.1	226.7	0.24
Steel	295.6	261.4	0.12
Al alloy	220.5	206.6	0.06

Figure 4 depicts the relationship between the apparent Young's modulus during unloading and the stress relaxation time. The horizontal axis is in a logarithmic scale. The apparent Young's modulus increases slightly with the stress relaxation time. More quantitatively, the increases in the apparent Young's modulus for the stress relaxation time of 600 min are approximately 2.9%, 5.0%, 2.6%, and 1.6% respectively for the CP-Ti, Mg alloy, steel, and Al alloy sheets. This result exhibits that the unloading behavior is affected by stress relaxation. Although detailed results are not provided here, the measurement was conducted also at an initial strain rate of 3.3×10^{-2}/s, but the results were almost independent of the strain rate.

3.2 Creep behavior

Figure 5(a) shows the evolution of the creep stain as a function of time for the virgin samples. The Cp-Ti sheet exhibits the largest creep strain, followed in order by the Mg alloy sheet, the steel sheet, and the Al alloy sheet. Interestingly, the creep strains for the CP-Ti and Mg alloy sheets are more pronounced than for the steel and Al alloy sheets as in the case of stress relaxation. The tendency that the CP-Ti sheet exhibits larger creep strain than the Mg alloy sheet and the magnitude relationship between the four materials are consistent with the results reported by Sato *et al.*[16)] where annealed materials were used. These results

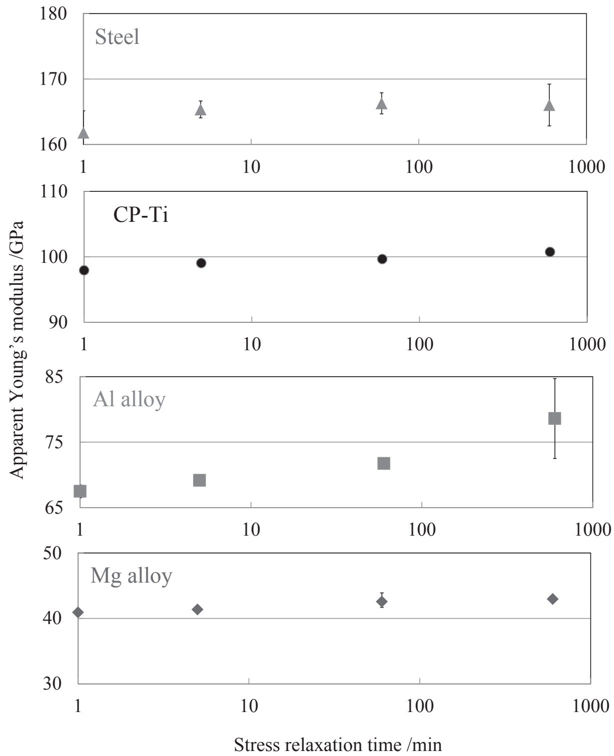

Fig. 4 Relationship between apparent Young's modulus and stress relaxation time.

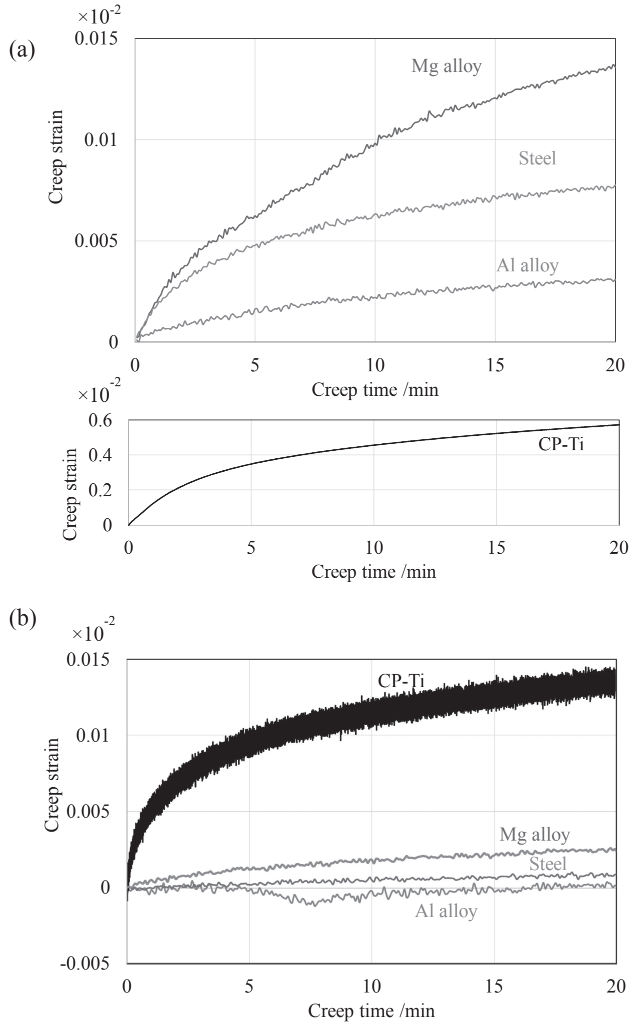

Fig. 5 Relationship between creep strain and creep time. (a) Virgin sample and (b) pre-strained sample.

suggest that the difference in accumulated amounts of dislocation density between the annealed and rolled sheets, which would affect creep behavior,[16)] might not affect the magnitude relationship for the present experimental conditions.

Sato *et al.*[16)] classified the creep behavior in terms of crystal structures: creep strain is likely to be larger in hcp metals than in fcc and bcc metals. Matsunaga *et al.*[25)] discussed the mechanism that hcp metals show large creep strain as follows. Because the number of active slip systems in hcp metals is small at room temperature, entanglement of dislocation is difficult to occur and dislocation can move freely in grains; thus, creep strain can easily occur. Moreover, they also presumed from their experiments that twinning activity would yield smaller creep strain at room temperature.[26)] Because the active twinning systems under uniaxial tension is different between Mg alloy sheets[27–29)] and CP-Ti sheets,[30–32)] this difference could also affect the difference in the creep behavior between the Cp-Ti sheet and the Mg alloy sheet.

Figure 5(b) depicts the results for the pre-strained samples. The magnitude relationship is the same as that of the virgin sheet. On the other hand, the CP-Ti sheet still shows quite large creep strain. The Mg alloy sheet also exhibits relatively large strain, while the creep strains are quite small for the Al alloy and steel sheets Apparently, the effect of pre-straining on the magnitude of the creep strain is significant, suggesting that the results of the pre-strained sheets should be considered when the effect of creep strain on the time-dependent springback is discussed.

Sato *et al.*[16)] showed that creep strain in an as-rolled CP-Ti sheet was much smaller than that of an annealed sheet because of high dislocation densities in an as-rolled sheet. This hypothesis would hold also in the present results.

3.3 Holding-time dependency

Figure 6 shows the relationship between the sidewall curvature after springback and the holding time at the bottom dead center. The horizontal axis is in a logarithmic scale. The curvature decreases with increasing the holding time almost linearly, irrespective of the material. Comparing the decreasing amount from the holding time of 5 min to 600 min between the materials, the Mg alloy sheet shows the largest decrease (29%), followed in order by the CP-Ti sheet (11%), the Al alloy sheet (8.1%), and the steel sheet (5.7%). Apparently, the holding-time dependency is more pronounced for the Mg alloy sheet than for the other three sheets and, moreover, it is also large for the CP-Ti sheet. Although detailed results are not provided here, similar experiments were conducted with the punch speed of 1000 mm/min, which was 100 times faster than the present case, and it was found that the effect of holding time on the curvature was almost independent of the forming speed. These results are consistent with the literature.[4,5)]

Kyuno *et al.*[5)] hypothesized that the holding-time dependency was primarily governed by the stress relaxation

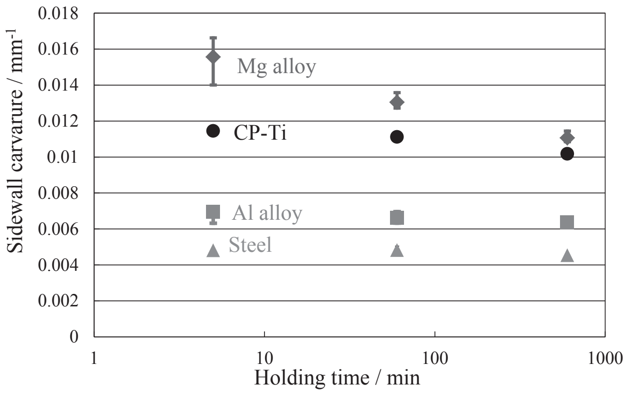

Fig. 6 Relationship between sidewall curvature and holding time.

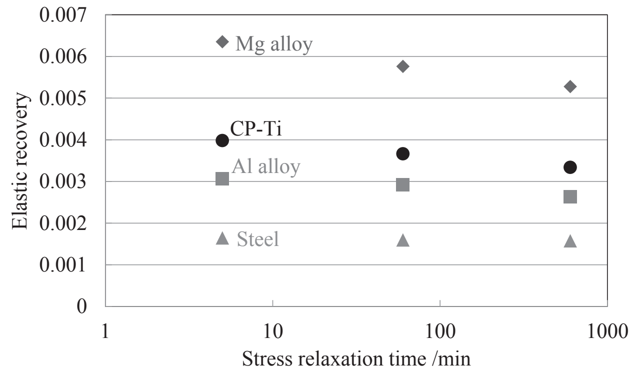

Fig. 7 Relationship between elastic recovery and stress relaxation time.

behavior. If this hypothesis holds, it is further presumed that materials that exhibit pronounced stress relaxation behavior would yield large holding-time dependency. However, as observed in Fig. 3 and Table 1, the stress reduction during stress relaxation is the largest for the CP-Ti sheet, followed in order by the Mg alloy sheet, the steel sheet, and the Al alloy sheet, inconsistent with the magnitude relationship observed in the holding-time dependency. These results suggest that there would be other factors that govern the holding-time dependency.

Generally speaking, the amount of elastic recovery during unloading is governed by not only the stress at the beginning of unloading but also the stress-strain curve during unloading. In the present study the unloading curve is evaluated by using apparent Young's modulus, as shown in Fig. 4, and apparent Young's modulus increases with the stress relaxation time. Because it is established that the effect of the change in apparent Young's modulus on the amount of springback is not negligible,[33] it is presumed that the change in apparent Young's modulus should also be taken into consideration when the holding-time dependency of springback is discussed. For this purpose, to conduct finite-element simulations of the present draw bending process would be effective to comprehensively evaluate both effects of stress relaxation and apparent Young's modulus. However, currently it is difficult to run reliable simulations from the following reasons. First, material models that can describe accurately anisotropic as well as tension-compression asymmetric deformation behaviors of the materials used are hardly available. Moreover, modelling of deformation behavior under reverse loading is also difficult especially for the Mg alloy and CP-Ti sheets where the activities of twinning and detwinning are pronounced. Second, because the stress relaxation characteristics of the materials are not understood yet, it is also difficult to take these characteristics into account appropriately in finite-element simulations. From the same reasons, the bending moment which governs the amount of sidewall curvature after springback cannot be evaluated properly.

Alternatively, in the present study, the amount of elastic recovery ε_u is roughly estimated as $\varepsilon_u = \sigma_u/E_u$, where E_u denotes the apparent Young's modulus during unloading. σ_u and E_u are determined respectively from Figs. 3 and 4. Figure 7 shows the relationship between the elastic recovery and the stress relaxation time. The elastic recovery decreases as the stress relaxation time increases, irrespective of the material. The Mg alloy sheet exhibits the largest decrease, which is approximately 17% from the stress relaxation time of 5 min to 600 min, followed in order by the CP-Ti sheet (16%), the Al alloy sheet (14%), and the steel sheet (4.2%). Interestingly, the magnitude relationship of the decrease in elastic recovery is the same as that observed in the holding-time dependency. This result suggests that the holding-time dependency would roughly be explained by stress relaxation and unloading curve following stress relaxation. However, it is needless to say that further detailed discussion is necessary to draw a definitive conclusion. More accurate evaluation will be conducted in our future work.

3.4 Elapsed-time dependency

Figure 8 shows the evolution of sidewall curvature as a function of elapsed time after releasing from dies. The

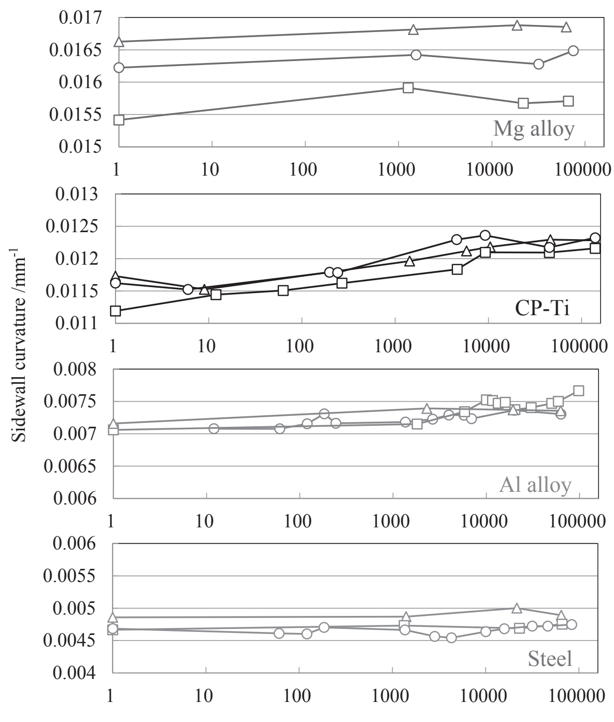

Fig. 8 Relationship between sidewall curvature and elapsed time after releasing from dies. Results for holding time of 5 min are shown.

horizontal axis is in a logarithmic scale. It should be noted that the results of three samples are separately depicted for each material in Fig. 8, which are represented by ○, □, and △. The results measured for the samples with the holding time of 5 min are shown. The curvatures gradually increase with the elapsed time regardless of the material. The amounts of increase from just after releasing from dies are approximately 5.9% for one month in the CP-Ti sheet, 4.1% for 1.5 months in the Al alloy sheet, 1.6% for 1.5 months in the Mg alloy sheet, and 1.1% for 1.5 months in the steel sheet. Apparently, the magnitude relationship of the elapsed-time dependency is different from that of the holding-time dependency. Moreover, the elapsed-time dependency is much less than the holding-time dependency irrespective of the material. Although detailed results are not shown here, these results were almost independent of the holding time at the bottom dead center. Moreover, the results obtained with the forming speed of 1000 min/mm were also consistent with the abovementioned results.

Wang *et al.*[12] hypothesized that the creep behavior of the material could affect the elapsed-time dependency. This presumption was supported by our previous study on crystal plasticity finite-element simulations of elapsed-time dependent springback in a CP-Ti sheet.[15] It was shown in the previous study that crystalline slip systems were active even after releasing from dies, which were driven by residual stresses. It should be noted that the slip activities after releasing from dies were not exactly under constant stresses because the residual stresses were gradually decreasing owing to gradual change in the shape of products. However, because the decrease of residual stresses was very gradual, it is reasonable to say that the deformation behavior after releasing from dies is close to creep. On the basis of the abovementioned discussion, it is presumed that the curvature change in the steel sheet would increase if the thickness is the same as those of other three sheets (1.0 mm). This is because, as Wang *et al.*[12] discussed, residual stresses would increase with the ratio between a thickness and a die radius.

In contrast, as explained in Fig. 5, the magnitude relationship of creep strain differs significantly from that of the aforementioned elapsed-time dependency. Specifically, the creep strain for the pre-strained Mg alloy sheet was relatively large, but this trend did not hold for the elapsed-time dependency. In contrast, for the Al alloy sheet, the elapsed-time dependency was pronounced, while the creep strain for the pre-strained sheet was negligibly small. In fact, based on a simple calculation, the change in strain due to the curvature change for 1.5 month in the Al alloy sheet (approximately 4.1%) is estimated to be approximately 0.0002, which is larger than the creep strain for the pre-strained sheet estimated from Fig. 5(b), indicating that the curvature change cannot be covered only by the creep strain. These results suggest that it may be difficult to explain the mechanism of the elapsed-time dependency only from the creep behavior and that there would be other factors that affect the elapsed-time dependency.

It is likely that other possible factors of the elapsed-time dependency depend on the material, as in the case of creep behavior.[34–38] For the Al alloy sheet, Wang *et al.*[12] used both heat-treatable and non-heat-treatable sheets for the elapsed-time dependent springback test to examine the effect of aging. They reported that significant differences were not observed between the two sheets, indicating that aging would not be a significant factor on the elapsed-time dependency.

On the other hand, for hcp metal sheets, twinning activity would be one of the possible mechanisms. Li *et al.*[4] observed a small amount of twinning activity after springback in Mg alloy sheets and presumed that it may somewhat affect the elapsed-time dependency of Mg alloy sheets. On the other hand, Hama *et al.*[15] showed from crystal plasticity simulations of elapsed-time dependency in a CP-Ti sheet that activity of twinning was negligible after releasing from dies, suggesting that elapsed-time dependent springback would result from slip activities. Apparently, opposite trends were observed between Mg alloy and CP-Ti sheets. The larger twinning activity after springback in a Mg alloy sheet than in a CP-Ti sheet is presumably due to the relatively small CRSS for twinning in the Mg alloy sheet. Interestingly, the CP-Ti sheet with less pronounced twinning activity exhibits larger elapsed-time dependency than the Mg alloy sheet with more pronounced twinning activity, consistent with the presumption that twinning activity would yield smaller creep strain at room temperature,[25] as discussed earlier. These results suggest that twinning activity would also yield smaller elapsed-time dependency as in the case of creep behavior. However, it should also be noted that the effect of twinning activity on the elapsed-time dependency cannot be discussed only from the results of creep behavior under uniaxial tension because twinning activities are largely different between tension and compression and are also affected by strain-path changes. Further study on other deformation mechanisms will be conducted in our future work.

4. Conclusion

In the present study, the effects of holding time at the bottom dead center and elapsed time after releasing from dies on springback after draw bending were investigated experimentally in steel, Al alloy, Mg alloy, and CP-Ti sheets. The former and latter are respectively denoted as holding-time and elapsed-time dependencies. As possible mechanisms of these dependencies, stress relaxation and creep behaviors of these metals were examined. The relationship between the apparent Young's modulus and the stress relaxation time was also measured. The results obtained in this study are summarized as follows.

(1) The decrease in normalized stress during stress relaxation for 600 min is approximately 27%, 24%, 12%, and 6% respectively for the CP-Ti sheet, the Mg alloy sheet, the steel sheet, and the Al alloy sheet.
(2) The apparent Young's modulus increases slightly with the stress relaxation time irrespective of the material. The increases in the apparent Young's modulus for the stress relaxation time of 600 min are approximately 2.9%, 5.0%, 2.6%, and 1.6% respectively for the CP-Ti, Mg alloy, steel, and Al alloy sheets.
(3) For the virgin samples, the CP-Ti sheet exhibits the largest creep strain, followed in order by the Mg alloy sheet, the steel sheet, and the Al alloy sheet. For the pre-

strained samples, the CP-Ti sheet shows notably large creep strain and the Mg alloy sheet also exhibits relatively large creep strain, whereas the creep strains are quite small for the Al alloy and steel sheets, showing that the effect of pre-straining on the magnitude of the creep strain is significant.

(4) The amount of springback decreases with increasing the holding time, irrespective of the material. The decreasing amounts from the holding time of 5 min to 600 min are 29%, 11%, 8.1%, and 5.7% respectively for the Mg alloy, CP-Ti, Al alloy, and steel sheets. It is presumed from simple analyses that the holding-time dependency would be explained not only by stress relaxation but also by unloading behavior following stress relaxation.

(5) The amount of springback gradually increases with the elapsed time regardless of the material. The amounts of increase from just after releasing from dies are approximately 5.9% for one month in the CP-Ti sheet, 4.1% for 1.5 months in the Al alloy sheet, 1.6% for 1.5 months in the Mg alloy sheet, and 1.1% for 1.5 months in the steel sheet. Because the magnitude relationship of creep strain between the materials differs significantly from that of the elapsed-time dependency, it may be difficult to explain the mechanism of the elapsed-time dependency only from the creep behavior and that there would be other factors that affect the elapsed-time dependency.

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