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Exploring the Influence of Pre/Post-Aging on Springback in Al-Mg-Si Alloy Tube Bending

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Abstract

Aluminium alloy (Al-alloy) bent tube is one kind of strategic lightweighting components, which attracts application in industrial clusters, such as automobile, aerospace, etc. To meet the demands on high-precision manufacturing, springback gains nowadays increased attention since it causes a series of problems such as increased tolerance limits, variabilities in assembly and service performance. Many Al-alloys exhibit significant naturally aging properties, which is closely related to the control of dimensional accuracy and performance of products. Thus, as one of the most important issues affecting the dimensional accuracy, springback becomes a challenging issue in the precision forming of Al-alloys, and it is of importance to well understand the aging-related springback phenomena. In this research, using rotary draw bending of a typical Al-Mg-Si alloy tube as the case, the influence of natural aging before and after the forming operation on springback is experimentally studied. Firstly, the as-received AA6060-T4 tubes are solution-heat-treated (SHTed) to obtain fully-annealed samples. Then, the tube samples are used for three experimental schemes related to aging and bending. By bending experiments of the samples with pre natural aging (pre-NA) periods from 30 min the 56 days, the influence of pre-NA time on springback is identified. Meanwhile, through bending experiments of the tubes without pre-NA, and followed by measuring the bending angles of the bent samples after different post natural aging (post-NA) time up to 35 days, the time-dependent springback behaviour is studied. Furthermore, through the experimental design of tube bending without pre-NA, and followed by the post artificial aging (post-AA) treatment, the dimension variations of bent tubes during the post-AA process are examined to explore the possible manufacturing approach for tailoring the geometry accuracy and performance of bent parts. Through this work, a fundamental understanding of the influence of pre/post-aging on springback is provided, which can help control the product accuracy of bent Al-alloy tubular products.

Keywords: Springback; Tube Bending; Natural aging; Aluminium alloy; Product accuracy

1. Introduction

Aluminium alloy bent tube as one kind of effective lightweighting are extensively used in almost all industrial clusters, including automobile, highway trains, aerospace, architecture, etc., typically serving as the crucial mass/heat-transferring systems and load-bearing structures [1-2]. Especially for the vehicle manufacturing industry, Al-Mg-Si extrusions are attractive in many applications, due to their good ratio of stiffness and strength to density, corrosion resistance, and weldability, thus meeting the ever-growing demand on the reduction of fuel consumption and emissions [2, 3]. During tube bending, springback is an unavailable problem upon unloading, which refers to the angular and radius changes after removing external load from the bent parts, causing a series of problems such as (needs for) increased tolerance limits, variabilities in secondary processing, assembly and, sometimes, service performance [4, 5]. To satisfy the demands on the manufacturing of high-precision and "zero-defect" product and close-loop-control of properties towards the Industry 4.0 trend,

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accurate control of springback thus become increasingly important, gaining overwhelming attention from both academy and industry.

However, one of the differences from some other metallic materials is that Al-Mg-Si alloys exhibit significant aging behavior, leading to time-dependent variations of strength, work hardening, anisotropy, facture elongation, and so on [6-8]. These variations also create uncertainties to the dimensional accuracy and service performance of aluminium parts from as-received materials to the final service. As shown in Fig. 1, springback-induced geometry accuracy is one of the typical issues related to natural aging, which can be summarized as the following two aspects: (1) Natural aging before forming (Pre-NA): occurs from as-received material to the manufacturing, which is caused by e.g. different storage time of materials before forming; (2) Natural aging after forming (Post-NA): occurs in the uncertain period from the end of forming operation to delivery and further to assembly. Besides the natural aging effect, the room-temperature creep caused the stress relaxation can also contribute to a slight variation of geometric dimension [10]. Therefore, the variation of dimensional accuracy caused by the coupling mechanisms is also called time-dependent springback.

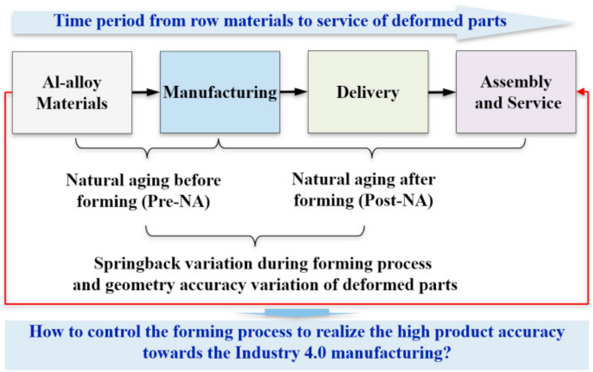

Fig. 1. Schematic of aging-related variation of geometry accuracy in the whole life of aluminium alloy parts.

As mentioned above, both Pre-NA and Post-NA are time-dependent so that springback angle upon forming and the geometry dimension after forming also vary with the storage time. In addition, aging-related changes in mechanical properties are nonlinear and sensitive to the aging condition [7, 9]. All of these make the springback phenomena for Al-Mg-Si alloy tube bending complicated and the accurate control of springback to be a challenging issue.

This research uses AA6060 extrusion tubes in extensive experiments regarding solution-heat-treatment, natural and artificial aging, rotary draw bending (RDB), and springback measurement, thus to explore the influences of pre/post-aging on springback in tube bending.

2. Experimental design

2.1. Overview of experimental method

In this study, the as-received case material is AA6060-T4 tubes with the outer diameter (OD) of 16 mm and thickness (t) of 2 mm. The ratio of OD-to-thickness is 8 so that the case is categorized as a thick-walled tube (OD/t⩽20). The nominal chemical composition of AA6060 is listed in Table 1. It is a typical Al-Mg-Si alloy, which is primarily used for structures requiring good strength, very good surface finish and good anodizing response, such as profiles for windows, doors, entrance lots, ceilings and furniture and also for thermal applications such as heat sinks.

Table 1. Nominal chemical composition of AA6060 (in wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
0.3~0.6	0.1~0.3	0.1	0.1	0.35~0.6	0.05	0.15	0.1	0.15

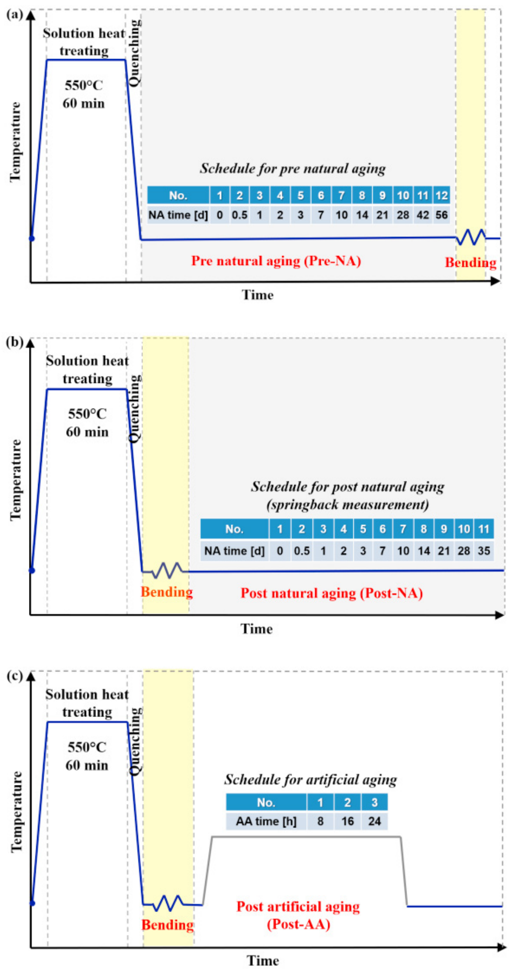

Fig. 2. Overview of experiments: (a) SHT→Pre-NA→Bending scheme; (b) SHT→Bending→Post NA scheme; (c) SHT→Bending→Post-AA scheme.

Aiming at the aging-induced geometry variation, this work designs the process experiments made to control the aging-related variables, thus revealing the influence on springback in AA6060 tube bending. The overview of the experimental methods is shown in Fig. 2. Firstly, the as-received tubes are SHTed and water quenched. Then, the tubes are used for three different experimental schemes; viz., (I) Solution heat treating (SHT) → Pre-NA → Bending; (II) SHT → Bending → Post NA; (III) SHT → Bending → Post-AA.

As shown in Fig. 2 (a), the scheme I is used to explore the influence of natural aging time on springback in tube bending. Scheme II is used to explore the natural aging time after bending on geometry dimension of the bent tube, which is also called time-dependent springback (Fig. 2 (b)). Fig. 2 (c) shows scheme III designed to explore geometry dimension variation of bent tubular parts during the artificial aging process, thus exploring a possible method for improving the formability as well as performance by integrated design of bending and artificial heat treatment. The detailed process schemes for aging, bending experiment and springback measurement are listed in Fig. 2.

2.2. Solution heat treatment

In order to explore the effect of pre/post aging on the dimensional accuracy of deformed parts, the as-received AA6060-T4 tubes are first solution heat treated. The Nabertherm N41/H chamber furnace is used for SHT experiments. The as-received tubes are cut into segments with a length of 400 mm and then taken into the furnace at 550 °C for 60 minutes. The heating rate is 50 °C per minute. At the end of solution heat treatment, the tube segment samples are quenched in cold water immediately after solution heat treatment. The SHTed tube segments are used for the different purposes mentioned above.

2.3. Rotary draw bending experiment

Rotary draw bending (RDB) is applied for tube forming experiments. RDB is the most commonly used method for the manufacture of bent tubular parts. As shown in Fig. 3, the whole tube is subjected to multi-tool constraints, viz., bend die, clamp die, and pressure die. The mandrel die and wiper die are not applied in RDB experiments due to the large OD-to-thickness ratio. The tube can be drawn around the bending center to form a bent tubular part with a certain bending radius and bending angle. Then, the tube is unloaded as the tools are released. The StarTechnology STAR EVO BEND 800 CNC bending machine, employing bending dies with a radius of *R*=40 mm (*R/D*=2.5), is used. The bending velocity is 25°/s, and the push velocity of the pressure die is kept proportional to the tangent velocity of the center line (as shown in Fig. 3).

Fig. 4 shows an image of the bent tubes under different aging conditions. For the geometry dimension measurement of the bent tubes, as shown in Fig. 3 (d), a Leitz-PMM-C-600 coordinate measurement machine (CMM) is used for inspection of the springback angle.

As shown in Fig. 3 (b), springback refers to the changes in both angles and radius, as given in Eq. (1) and (2).

$$\Delta\theta = \theta_b - \theta_a \tag{1}$$

$$\Delta R = |R_b - R_a| \tag{2}$$

where $\Delta\theta$ and ΔR are the springback angle and springback radius, respectively, and the subscript 'a' denotes the actual angle/radius after springback, and 'b' denotes the targeted bending angles/radius. In most industrial applications, only the angular springback is considered, so that this work only utilizes the springback angle for analysis. To characterize springback under different bending angles, a springback ratio coefficient is defined as follow:

$$\eta = \Delta\theta / \theta_b = (\theta_b - \theta_a)/\theta_b \tag{3}$$

where η is the springback ratio coefficient. It represents the relative elastic recovery after unloading, which may change with the bending angle.

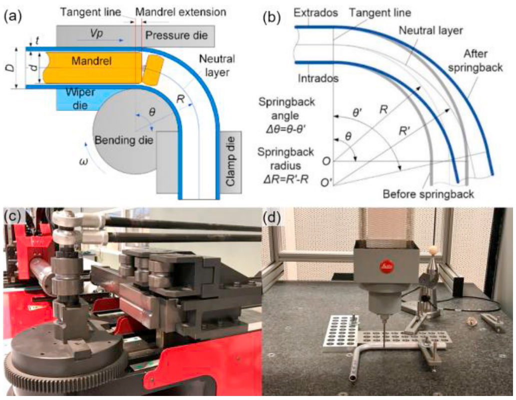

Fig. 3. Rotary draw bending of tube and springback measurement: (a) tube bending principle; (b) schematic of unloading springback; (c) bending machine and tooling; (d) CMM for springback measurement.

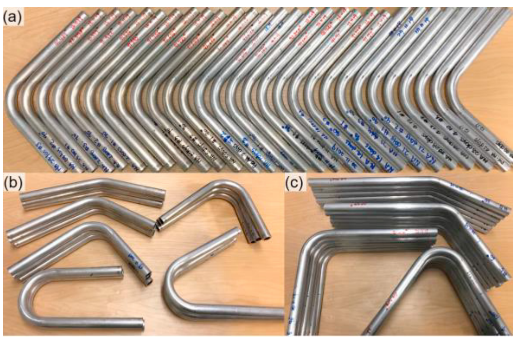

Fig. 4. Experimental bent tubes: (a) with different pre-NA time; (b) bent tube after SHT without aging; (c) as-received tubes with T4 temper.

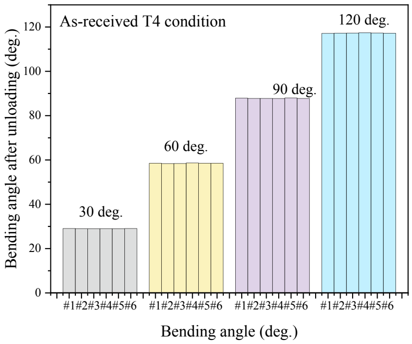

Fig. 5. Repeated experiments for verification of data stability.

Springback is sensitive to tooling and bending process parameters. As shown in Fig. 5, repeated experiments with six times under 30~120° bending angles are conducted to evaluate the process stability, indicating a very good repeatability with the average error less than 0.09°, except for several irregular points with a maximum difference up to 0.20°. This error is much less than the springback angles, though, meaning that the experimental error is considered negligible. For all the bending experiments, to ensure the reliability, three repeated experiments under the same operation condition are conducted.

3. Results and discussion

3.1. Springback characteristics of as-received and SHTed tubes

As shown in Fig. 6, the springback characteristics between as-received T4 temper tubes and SHTed tubes bent at angles 30~120° are compared. It can be seen that the springback angles of tubes with T4 condition are about twice as large as that of SHTed tubes. The difference is more pronounced at the smaller bending angles. Increasing the bending angle, the springback angle of both types of samples trends to increase linearly. However, the slope in the curve made by the T4 samples is greater than that of the SHTed samples. The significant difference of springback is caused by the material stress-strain curve difference between T4 and SHTed samples.

Normally, the yield strength-to-elastic modulus ratio is taken as a parameter to roughly estimate the springback amount. Elastic modulus is obviously insensitive to temper condition, while the yield strength and the work hardening effect will change after natural aging, leading to the higher strength-modulus ratio, and more pronounced springback.

From Eq. (3), the springback ratio (η) is calculated with the result given in Fig. 6 (b). It is very interesting that the changing trends of springback ratio for two types of samples are quite different. Increasing the bending angle, the springback ratio of T4 tubes is decreased by about 32% from 3.37% at θ=30° to 2.30% at θ=120°. However, the springback ratio of SHTed tubes is increased by about 18% from 1.07% at θ=30° to 1.26% at θ=120° and then increased to 1.40% at θ=180°. The reason for this phenomenon might be attributed to the difference in the level of residual stress after unloading for different bending cases. Tube bending is a process with pronounced non-uniform deformation with tension dominated extrados and compression dominated intrados. For the T4 tubes, the strength is higher, it is easy to accumulate relatively lager residual stress after unloading, resulting in the larger loss of springback. However, for the SHTed samples, the strength is much lower, the residual stress level is relatively lower. However, this needs further exploration in combination with finite element simulation and mechanics analysis.

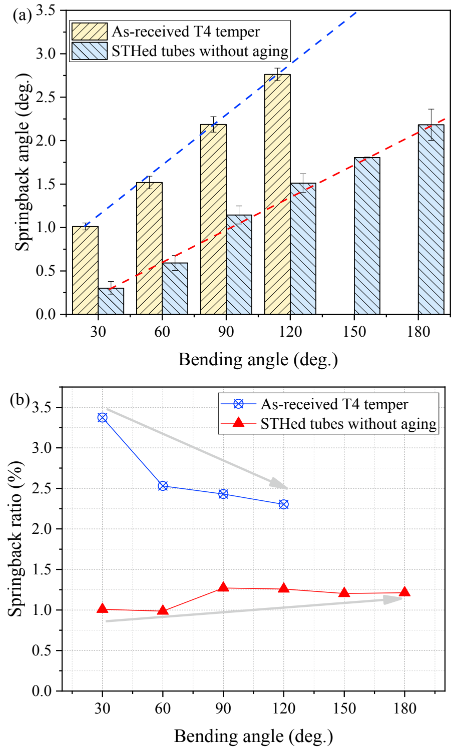

Fig. 6. Influence of bending angle on springback: (a) springback angle; (b) springback ratio.

3.2. Influence of pre-natural aging on springback

According to the experimental scheme shown in Fig. 2 (a), the bending angle of 90° is taken for analyzing the pre-NA related influence on springback. Fig. 7 (a) shows the springback angle in rotary draw bending of the tubes with different natural aging periods from 30 minutes up to 56 days. The springback ratio is also calculated to evaluate the percentages of springback with regard to the bending angle, as shown in Fig. 7 (b). It can be found that springback presents a significantly increasing trend with natural aging time. The most significant variation of springback angle occurs within the first week, in which the springback angle is dramatically increased by 49% from 1.44° to 1.70°. In the following six weeks, the rate becomes gradually slower with natural aging time, yet there is still a pronounced increase of springback angle.

Compared with the SHTed sample, the springback angle of tubes with three weeks aging is increased by 59%, and the springback angle of tubes after six weeks is increased by 75%. After six weeks, the rate of increased springback angle seems to be very slow with the accumulation of natural aging time.

Compared with springback of the as-received T4 tempered tube, it can be found that the springback of T4 tempered tube is 91% higher than the SHTed tube without aging. Even after natural aging with six weeks, there is still about 0.2° less than the springback of the T4 tempered tubes. Therefore, the natural aging time before forming operation creates a remarkable variation of dimensional accuracy for bent tubes, and the aging effect can go on for more than two months. This should be carefully considered in the design of manufacturing of Al-alloy bent tubular parts.

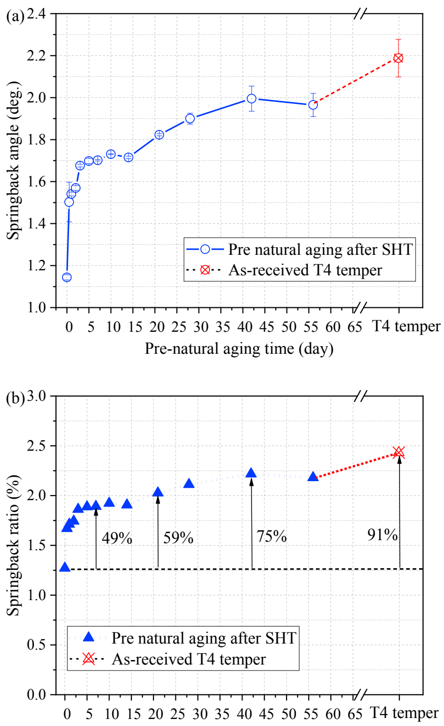

Fig. 7. Influence of pre-NA on springback: (a) springback angle; (b) springback ratio.

3.3. Influence of post natural aging on springback

Based on the experimental scheme shown in Fig. 2 (b), the change of springback angle of SHTed tubes with 90° bending angle after different post-NA time is examined, as shown in Fig. 8. After post-NA for 35 days, three samples present a minor decrease of springback angle. The maximum reduction of springback angle is 0.31°. Similarly, three kinds of bending angles with 30°, 90° and 120° are selected to explore time-dependent springback behaviour, as shown in Fig. 9, indicating a minor variation in springback angle. However, the trends for 30°, 90°, and 120° are different. Especially for the bending angle of 30°， the changes are very small and might be considered within the experimental error. For the bending angles of 90° and 120°, however, it is obvious that the variation is caused by the Post-NA, and not any potential experimental error. The springback angle for the bending angle of 90° seems to decrease with post-NA time. For the bending angle of 150°, however, it shows that the springback angle initially increases and then decreases with storage time. As shown in Fig. 5, the maximum difference of springback angle for an identical bending condition can be up to 0.2°. Therefore, even though the dimensional variability can be found, it is difficult to obtain a consistent conclusion describing time-dependent springback for AA6060 alloy tube bending.

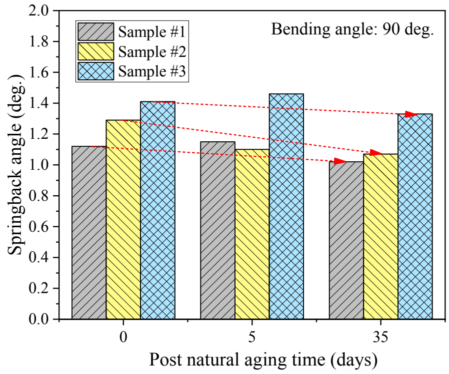

Fig. 8. Influence of post-NA on springback under 90° bending.

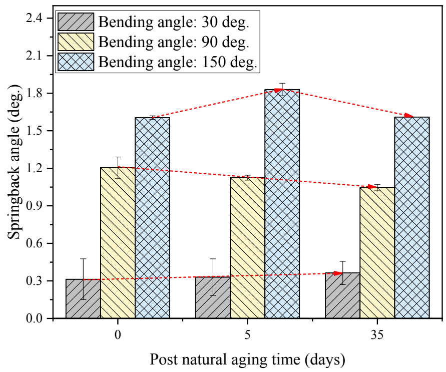

Fig. 9. Influence of different post-NA time on springback.

The time-dependent springback phenomenon has been experimentally observed in many alloys, such as high-strength steels, titanium, magnesium as well as aluminium alloys [11-14]. The mechanisms underlying time-dependent springback are stress relaxation and creep behaviour driven by the residual stress in the deformed materials [10, 14]. Wang et al. experimentally proved that time-dependent springback can be a significant portion of total springback in draw bead bending of aluminium sheets, indicating that the largest observed percentages after 15 months are 18% for 6022-T4, 14% for 6111-T4, 13% for 2008-T4 and 11% for 5182-O [10]. Besides the alloy type and temper condition, time-dependent springback is also sensitive to the forming parameters, such as the ratio of bending radius to sheet thickness, bending type, temperature, etc., which can decide the level of residual stress after unloading.

However, a definite trend for time-dependent springback behaviour cannot be found in the present work. This might be caused by two reasons: 1) the lower strength of SHTed AA6060 alloy tube without aging makes the springback angle and the residual stress level in the bent tubes smaller, failing to produce pronounced time-dependent springback; 2) along with the accumulation of storage time, the yield strength of the bent tube is increased, and then the ratio of residual stress to instantaneous yield stress is decreased, which makes the driving force of time-dependent springback more insufficient, leading to such a minor variation of springback. Based on this understanding, the time-dependent springback influence on deformed parts will be pronounced for the Al-alloys with the higher strength and the less natural aging capacity.

3.4. Influence of post artificial aging on springback

The influence of post artificial aging on springback is explored according to the experimental scheme shown in Fig. 2 (c). It can be found from Fig. 10 that the post-AA does not cause obvious change to the springback angle. Taking the bending angles of 90° and 150°, the post-AA seem to have the opposite effects: the springback angle with bending angle of 90° is increased after artificial aging; however, the springback angle is decreased for the bent tube with 150°. The differences are 0.12° and 0.20° for bending angles of 90° and 150°, respectively, which are very near to the average and maximum experimental errors. Therefore, it can be concluded that the influence of post artificial aging on springback is minor for the cases investigated.

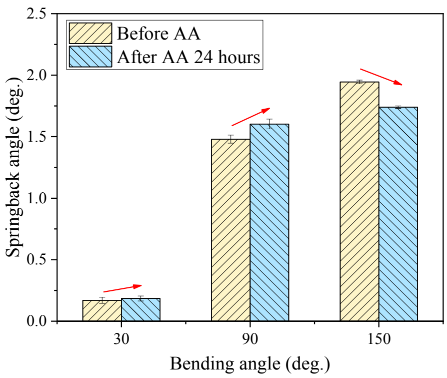

Fig. 10. Influence of post-AA on springback.

The main advantage of the "SHT→Bending→Post-AA" method is the improved formability of Al-alloy in a fully solutionized condition. Bending of solutionized tubes provides a small bending radius with less wall thinning and, sometimes, ovalization. Furthermore, the post artificial aging treatment gives the bent tubes higher strength. Therefore, the "SHT → Bending→Post-AA" method may provide a good approach to improve the bendability, forming quality as well as the performance of aluminium bent tubular parts. However, how to accurately control the whole process, thus ensuring tight dimensional accuracy is still a challenging issue. This work limited to springback but the wall thickness and ovalization as well as bending limits further studies are encouraged.

4. Conclusions

This work aims to provide a fundamental understanding of aging-related springback behaviour for Al-Mg-Si alloys. Using rotary draw bending of AA6060 tubes as the case, the influences of Pre-NA, Post-NA, and Post-AA on springback are revealed and discussed. The main conclusions are as follows:

(1) Springback angle of the T4 tempered tube is more than twice that achieved for the fully-annealed tube during bending. The springback ratio is decreased by 32% with the increase of bending angle for T4 tubes, yet the ratio for the fully-annealed tubes presents an opposite trend.

(2) The pre-natural aging exhibits significant influence on springback and the influence can last a very long time, typically more than 2 months. The springback angle is increased by about 75% after the aging time with 56 days. The first week of aging contributes the most to the total increased springback, and the rate is gradually reduced with time.

(3) Both time-dependent springback and post-AA caused dimensional variation is observed, but the characteristics of their influences can hardly be quantitively captured due to the process uncertainties in the present rotary draw bending of AA6060 tubes.

(4) The "SHT → Bending → Post-AA" scheme may provide a promising approach to improve the bendability, forming quality and performance of bent tubular parts for the heat-treatable aluminium alloys.

Acknowledgements

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