Effect of heat treatment conditions on stamping deformation and springback of 6061 aluminum alloy sheets

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Abstract

The stamping deformation and springback of the 6061 aluminum alloy sheets under different heat treatment conditions were investigated by three-point bending tests. A validated reliable finite element (FE) model was used to further reveal the springback mechanism. It was found that the heat treatment conditions have great influence on the stamping deformation and springback of 6061 aluminum alloy sheets. The most severe local deformation occurred at the punch position of the T6–8h alloy sheet, showing minimum bending radius and thickness. However, the bending radius and thickness of the homogenization treated (HT) alloy sheet were maximum, resulting from more materials participate in bending deformation. The HT and solution treated (ST) alloys exhibited higher stamping performance than that of the natural aged (NA) and T6 alloys. The material strength of the T6 alloys can be improved by aging time, motivating greater springback and neutral layer offset. The springback and neutral layer offset of the T6–8h alloy sheet were the highest, while the HT alloy sheet was the lowest. Furthermore, the effect of material parameters on stamping deformation and springback of sheet was studied by combining with theoretical analysis and experimental results. The research showed that the bending radius and thickness of the sheet in the fillet region increase with the increase of strain-hardening exponent and elongation and with the decrease of yield ratio. After unloading, springback angle and radius increase with the increase of yield strength and strength factor and with the decrease of strain-hardening exponent. These achievements may serve as a guideline for enhancing stamping performance and reducing springback of the aluminum alloy sheet in bending process.

1. Introduction

The global automotive industry is facing challenges in several key fields, including energy, emissions, safety, and affordability. Lightweighting is one of the important strategies used to take these challenges [1]. As an alternate to steel, iron and other metals for automotive lightweighting, aluminum alloy has emerged due to its high specific strength, high stiffness, low density, good energy absorption and strong corrosion resistance. 6xxx aluminum alloy is a developing lightweight material and heat-treatable strengthened alloy, which is widely applied in the automotive manufacturing industry [2, 3]. In manufacturing, automotive body parts are mainly characterized by bending deformation, so the formability of the material is very important for stamped workpiece [4]. Good stamping formability is very adaptable to the processing method of the part. However, the plastic bendability of the aluminum alloy is very poor at room temperature, but the mechanical properties of the heat-treated aluminum alloy will be significantly improved [5–7]. After bending, springback is an inevitable and universal phenomenon for the part because of the elastic recovery when the loading is removed, affecting the shape and dimensional accuracy of the formed parts seriously [8]. Therefore, it is of great significance to investigate the stamping performance and springback mechanism of aluminum alloy sheets under heat treatment conditions.
Hong L et al [9] investigated the effects of different tempers on precipitation hardening of 6xxx aluminium alloys. The results indicated the short-time pre-aging at 170 °C benefits sheets to obtain lower strength under delivery condition and consequently to enhance stamping formability of sheets. Dorward R C [10] investigated the forming behavior of Al–Cu–Mg–Mn alloy 2024 sheet under the O temper (fully annealed) and W temper (solution heat treated and quenched) conditions. It was found that tensile forming indicators of the sheet under the O temper are significantly higher than those under the W temper. Shi Y et al [11] studied the bendability of AA5754 aluminum alloy in fully recrystallized temper (O temper). Both experimental and numerical results showed that a strong Cube crystallographic texture in the sheet provides improved bendability compared with a low Cube texture sheet. Snilsberg K E et al [12] research showed that, for extruded aluminum alloys profiles, the bendability when the bending axis is perpendicular to the extrusion direction is better than the direction of the bending axis parallel to the extrusion direction. Lloyd D J et al [13] assessed the bending performance of two aluminium based automotive alloys, the heat treatable skin alloy, AA 6111 and the non-heat treatable structural alloy AA 5754 by the cantilever bend test. The results showed that the performance of AA 5754 alloy is superior to AA 6111. GU R et al [14, 15] analyzed the springback mechanism and laws of the tube bending by the numerical-analytic method. The research can provide a significant guide to accurate prediction and control of springback. Kim H S and Koç M [16] found that the dimensional accuracy of springback could be improved by U-shape warm forming of AA 5754–O aluminum alloy under higher blank holder force (BHF), which could be interpreted as the uniform distribution of stress in the thickness direction when BHF was high. Grèze R and Laurent H [17, 18] investigated the springback of AA5754–O aluminum alloy by a split-ring test in warm forming conditions. It was found that the springback amount decreased by 67% at 200 °C compared with room temperature. Jeshvagani R A et al [19] investigated springback and mechanical properties of 7075 aluminum alloy in creep forming process. The results indicated that springback increased with decreasing time and temperature, and the appropriate forming cycle was 150 °C/24 h. Weinnmann K J et al [20] investigated the effect of the Bauschinger effect on the flexural resilience of the sheet under repeated pure bending conditions. The results showed that the effect of the Bauschinger effect on the springback of the sheet is inversely proportional to the strain. moon Y H et al [21] investigated the effect of die temperature combination on springback of 1050 aluminum alloy sheet. It is proved by the U-shape experiment that the springback amount of the formed parts can be reduced by 20% by using the heated four-die and cooled four-die combination mode compared with the four-die combination mode at room temperature. Gau J T and Kinzel G L [22] investigated the effect of the cladding singer effect on steel sheet and aluminum alloy sheet during simple bending. The results showed that the Bauschinger effect has a significant effect on the springback of the alloy sheet, while the bauschinger effect can be neglected for the steel sheet. Keum Y T and Han B Y [23] measured the springback amount of 1050 and 5052 aluminum alloys when bent at various forming temperatures. The results showed that the springback amount of the deformed sheet during warm forming is reduced, especially above 150 °C.

From the above review, it can be seen that heat treatment conditions, especially about the temper, can significantly change the mechanical properties of aluminum alloy, thus resulting in the change of stamping performance of the sheet. However, the research on the stamping deformation and springback of 6061 aluminum alloy sheet under T6 temper is relatively limited. In this paper, the effect of heat treatment conditions on stamping deformation and springback of 6061 aluminum alloy sheets was systematically studied by three-point bending tests. In addition, the mechanism of the springback of sheets was analyzed by combining with FE numerical simulation.

### 2. Experiment

#### 2.1. Materials preparation
A commercial rolled 6061 aluminum alloy sheet with a thickness of 2 mm was used in this study. The chemical composition is given in table 1.

#### 2.2. Heat treatment test
The heat treatment tests were carried out on a SX2–2.5–10 N box-type resistance furnace. The ST alloy was prepared by treating the initial NA alloy at 535 °C for 1 h to make sure that the Mg, Si phase entirely dissolved into the aluminum matrix, and then followed by water quenching to obtain the constituent in solution.
reduce the influence of parking time as much as possible, for the T6 temper, the ST alloy was quickly put into a DZF-6123 air circulation oven at 180 °C for 4 h and 8 h, respectively. The HT alloy was achieved by treating the initial NA alloy at 565 °C for 12 h. The NA and HT alloy specimens were sectioned parallel to the rolling direction. The specimens for optical microscope observation were prepared by mechanical grinding and polishing, electropolishing and subsequent anodic coating. A hybrid solution (volume ratio 1:9 perchloric-anhydrous ethanol) was used for electropolishing at 25 V for about 8 s. The anodic coating was performed using a volume ratio 1:40 fluoroboric-water at 18 V for 3 min. The microstructural investigation was carried out on a Leica DMi8 inverted microscopy. In figure 1(a), the grain of the NA alloy shows a fine strip shape due to rolling. However, the grain size of the HT alloy is larger, and the orientation of grain is distributed at random, as shown in figure 1(b). Each test was conducted for five times to ensure the reproducibility of experiments. The same method was also applied to the subsequent experiments.

2.3. Tensile test
At room temperature, the quasi-static tensile tests were performed on an INSTRON 5982 electronic universal testing machine with a tensile speed of 2 mm min\(^{-1}\), corresponding to a strain rate of 0.0002564 s\(^{-1}\). The tensile loading was oriented perpendicular to the rolling direction of specimens cut by a wire cutter. According to ASTM E8M-04 guidelines [24], the specific sizes of standard specimen are shown in figure 2. During the experiments, the engineering stress versus strain data was automatically recorded by computer. The relevant mechanical properties of alloys can be obtained from the data. Three stable experimental values were taken as references.

2.4. Three-point bending test
The three-point bending tests were performed on an INSTRON 5982 electronic universal testing machine with a punch speed of 10 mm min\(^{-1}\) and a punch radius of 7.5 mm under displacement control, as shown in figure 3. ASTM E290-14 specifications [25] were followed for preparing and testing the bending specimens. The sizes of specimen prepared perpendicular to the rolling direction were 160 mm \(\times\) 20 mm \(\times\) 2 mm. The 2D schematic view of experimental process is depicted in figure 4. At the beginning, the specimen was placed on the two same
cylindrical supports with a radius of 7.5 mm. The punch was slightly in contact with the upper surface of the specimen. The displacement between two supports was fixed to be 120 mm due to the good ductility of aluminum alloy at room temperature. During the stamping, the specimen was symmetrically located in the middle of the supports. The unloading process was conducted once the punch stroke reached to 30 mm. The bending force versus displacement data was automatically acquired by computer during the bending tests. Before unloading, the profile of bending specimen was captured by the 3D scanner and then imported into the Creo Parametric software. The parameters, interior angle $\theta_i$ and bending radius $R_i$, were determined by the software. After unloading, the interior angle $\theta_f$, bending thickness $t_f$ and bending radius $R_f$ were measured by a TZTEK vision measuring system. Moreover, the thickness was measured three times, and the average value was taken. The springback angle $\Delta \theta$ and springback radius $\Delta R$ can be obtained by $\Delta \theta = \theta_f - \theta_i$ and $\Delta R = R_f - R_i$, respectively. The bending deformation and stamping performance of the sheet can be characterized by the $R_i$ and $t_f$. With the increase of $R_i$ and $t_f$, the stamping performance of the sheet is enhanced. After bending, the offset of neutral layer due to asymmetrical deformation of the sheet between the outer and inner bending regions, which can be expressed by neutral layer coefficient ($k$-value). When the $k$-value is lower than 0.5, it indicates that the neutral layer shifts to the inner compression zone. When $k$-value exceeds 0.5, the neutral layer shifts to the outer tension zone. With the increase of $k$-value, the migration of neutral layer increases. According to a theory of stamping process manual [26], the $k$-value can be given by the following equation:

$$k = 0.5 \beta^2 - (1 - \beta) \frac{R_i}{t_0}$$

where $k$ is the coefficient of neutral layer, $\beta$ is the coefficient of incrassation, $R_i$ is the bending interior radius before unloading, and $t_0$ is the initial thickness. Here, $\beta = \left(t_0 - t_f\right)/t_0$ and $t_f$ is the thickness of specimen after bending.
3. Results

3.1. Tensile properties

The engineering stress versus strain curves of tensile specimens are plotted in figure 5. The significant feature is that there is no obvious yield platform in curves, which can be divided into three stages: elastic deformation stage, hardening stage and failure stage.

The tensile mechanical properties of 6061 aluminum alloys under different heat treatment conditions are listed in table 2. It can be obviously seen that heat treatment conditions have great influence on the mechanical properties of material. The material strength of the HT and ST alloys is lower than that of the NA alloy. The material strength of the HT alloy is minimum, and its the yield strength $\sigma_{0.2}$ and tensile strength $\sigma_b$ are 35.01 MPa and 150.74 MPa, respectively. However, the elongation $\delta$ of the HT alloy is maximum, reaching 26.58%, which is about twice than that of the NA alloy. With the increase of aging time, the strength of the T6 alloys increases, but the elongation decreases. Compared with the ST alloy, the yield strength and tensile strength of the T6–8 h alloy increased by 425.1% and 154.8%, respectively, while the elongation decreased by 50.82%. The yield ratio $\sigma_{0.2}/\sigma_b$ refers to the ratio of the yield strength and tensile strength of the material. From the table, the yield ratio is inversely proportional to the elongation of the material. The yield ratio of the NA and T6 alloys is about 3 times as much as the HT and ST alloys.

Table 2. Tensile mechanical properties of 6061 aluminum alloys.

| Materials | $\sigma_{0.2}$/MPa | $\sigma_b$/MPa | $\sigma_{0.2}/\sigma_b$ | $\delta/$ (%) | $n$ | $K$/MPa |
|-----------|-----------------|---------------|-----------------|-------------|-----|---------|
| HT        | 35.01           | 150.74        | 0.232           | 26.58       | 0.742 | 310.77  |
| ST        | 56.56           | 200.91        | 0.282           | 21.37       | 0.713 | 396.30  |
| NA        | 195.62          | 275.71        | 0.710           | 12.13       | 0.556 | 430.88  |
| T6–4 h    | 218.09          | 300.41        | 0.726           | 11.39       | 0.407 | 465.55  |
| T6–8 h    | 240.45          | 311.06        | 0.773           | 10.86       | 0.356 | 478.21  |

3.2. Stamping deformation behavior

The final stamped specimens under different material conditions are shown in figure 6. It can be seen from figure 5 that heat treatment conditions exert a significant impact on the bending deformation behavior of sheets. Obviously, the bending deformation of specimens mainly occurs at a position to contact with the punch, while the two straight edges are essentially undeformed. The bending deformation region of the NA and T6 alloy sheets is larger, and the shape is similar to the V-shape, while the HT and ST alloy sheets exhibit the U-shape.

Table 3 presents the parameters of different material states after bending. With the increase of aging time, the interior angles increase. The interior angles of the NA and T6–4 h alloy sheets are slightly lower than those of the T6–8 h alloy sheet. The interior angles of the T6–8 h alloy sheet are maximum, and the interior angles before and after unloading are 122.2° and 142.5°, respectively. However, for the HT alloy sheet, the interior angles before and after unloading are 109.0° and 119.1°, decreased by 8.64% and 13.00% compared with the NA alloy sheet,
respectively. Moreover, the bending radii and thickness are inversely proportional to interior angles. The bending radii and thickness of the HT alloy sheet are maximum, while the T6–8 h alloy sheet is minimum. Additionally, for the T6 alloy sheets, the bending radii and thickness decrease with the increase of aging time.

The bending force versus displacement curves for the different material states are plotted in figure 7. The variation of curves is greatly affected by the material states. The variation trend of the NA alloy is similar to the T6 alloy with the increase of displacement. With the increase of aging time, the bending force of the T6 alloy sheets increases. The bending force of the T6–8 h alloy is maximum, and its peak force is 241.30 N, which is 329.8% higher than that of the ST alloy. However, the bending force of the HT alloy is minimum, and its peak force is 54.58 N, which is 374.3% lower than that of the NA alloy. Consequently, with the increase of material strength,
the bending force required for the sheet increases, and the bending radius and thickness decrease. When the tensile strength of the material is greater than 300.41 MPa, the bending radius after unloading is 27.5 mm, showing the V-shape. However, when the tensile strength of the material is lower than 200.91 MPa, the bending radius after unloading is 34.2 mm, showing the U-shape.

4. FE simulation for three-point bending

4.1. Establishment of FE model

4.1.1. Geometry modeling and meshing

The three-point bending consists of four tools, namely the punch, the sheet and the two supports (shown in figure 4).

The commercially available FE software package LS-DYNA was used for simulating the three-point bending test. The size of 3D FE model shown in figure 8 is coincident with experiment. In the FE model, the punch and supports were meshed by adopting eight-node hexahedral solid elements, while the sheet was meshed using shell elements, which used the type 16 fully integrated shell element formulation and 11 integral points in the thickness direction to ensure the accuracy of solution. Meanwhile the corresponding element algorithm used the No. 8 control mode with an hourglass coefficient of 0.1. To reduce the computational complexity, the local mesh refinement of the sheet was performed on the main area of the force and deformation contacted with the punch. The mesh size of the main deformation area of the sheet was set to be 0.5 mm × 0.5 mm, and the number of elements is 5600. However, the mesh size of the other areas was set to be 0.5 mm × 1.0 mm, and the number of elements is 4400. The number of hexahedral elements for the punch and supports is 4200.

4.1.2. Keyword definition

The punch and supports exhibit high elastic modulus and negligible deformation compared with the sheet. To simplify the FE model, the punch and supports were assumed as rigid bodies, which were defined using material model MAT_20 (i.e. *MAT_RIGID). Translation and rotation constraints were applied to all rigid bodies except for the stamping translation direction of the punch. The material model of the sheet was confirmed using a multi-linear plastic model MAT_24 (i.e. *MAT_PIECEWISE_LINEAR_PLASTICITY), and the mechanical properties were defined by the elastic-plastic phases of the material. The effective stress-strain curves were plotted in figure 9.

The keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MORTAR was utilized for the punch-sheet and support-sheet contacts. The classical coulomb friction model was used to describe the contacts between the punch, the supports and the sheet. Static friction coefficient and dynamic friction coefficient were defined as 0.20 and 0.15 for the punch-sheet and supports-sheet contacts, respectively. The dynamic explicit analysis was utilized in the stamping process, while the unloading springback process adopted the static implicit analysis. Constraints were removed and the formed specimen achieved equilibrium after unloading. Table 4 shows the detailed material properties and simulation conditions.

4.2. Verification of FE model

In order to verify the accuracy of the established FE model in this article, the FE analytic prediction and experimental results for sheets under different material states are compared. Two representative specimens were chosen to compare experimental and simulated results. The outlines of the HT and T6–8 h alloy sheets before and after springback from experiment and simulation are shown in figure 10. The results show good consistency between experiment and simulation. In figure 11, there is no obvious difference between quantitative analysis of springback angle and radius of sheets obtained by experiment and simulation under different material states. It
can be seen that the springback angle and radius of almost all simulated sheets are slightly larger than those of the experimental ones, which may be ignoring the anisotropy of the materials in the FE model. During the bending process of the sheet, the material of the inner region is in a state of compression deformation in the fillet region, while the material of the outer region is in a state of tensile deformation. The tensile properties of the material are used to simulate the compressive side in the FE model, and the yield strength of the aluminum alloy when compressed is slightly less than that of the tension. According to figure 13(a), the springback of the sheet can be motivated by yield strength of the material. Therefore, the springback angle and radius obtained by the simulation may be a little higher. The maximum relative errors of springback angle and radius between experiment and simulation are 5.7% and 9.6%, respectively. So the reliability of the FE model is confirmed.
5. Discussion

5.1. Deformation behavior analysis

Strain-hardening exponent, $n$, that indicates the ability of the material to distribute the strain uniformly prior to diffuse necking was calculated for all the combinations. A material with a larger value of strain-hardening exponent shows greater uniform plastic deformation ability and hence greater formability [27]. As the indenter stroke advances, the hardening effect in the bending deformation region becomes more severe. When in the plastic stage, the increase of strain-hardening exponent can not only improve the local strain ability of the sheet, that is to say, strain-hardening exponent can increase the instability limit strain, but also make the strain distribution tend to be uniform and improve the overall forming limit of the sheet. As shown in figure 12(a), the strain-hardening exponent of the ST and HT alloys is larger than that of the NA and T6 alloys. The ability of uniform plastic deformation increase, leading to more materials participate in the bending deformation. Meanwhile a larger bending radius will be formed in the fillet region, and the bending thickness also will be increased. However, the uniform plastic deformation ability of the NA and T6 alloys is poor, resulting in severe local deformation (shown in figure 6). From figure 12(a), with increase of strain-hardening exponent, the bending radius before unloading and bending thickness increase. Therefore, the strain-hardening exponent is an important indicator of deformability in stamping of sheet.

Figure 12(b) shows the effect of yield ratio on bending radius before unloading and bending thickness. With the increase of yield ratio, the bending radius before unloading and bending thickness decrease. This is mainly due to yield ratio can reflect the ability on the resistance to plastic deformation. Low yield ratio means that the plastic deformation stage from yielding to fracture is very long, enhancing stamping performance of the sheet [28].

The relationship of effect of material’s elongation on bending radius before unloading and bending thickness is shown in figure 12(c). Generally, an increase in elongation will improve the plastic deformation ability of the material, and the fracture resistance and stretching ability will be also enhanced. According to the principle of invariable volume, the thickness thinning of sheet in the fillet region can be decreased, and the bending deformation region is enlarged to form a larger bending radius [29].

From figures (a), (b) and (c), the variation trend of the bending radius before unloading is substantially the same as the bending thickness with the increase of material properties. Strain-hardening exponent, yield ratio and elongation together affect the deformation behavior of the sheet, and the effect of strain-hardening exponent is the greatest. A material with higher strain-hardening exponent, lower yield ratio and larger elongation shows higher stamping performance. From above figures, the HT and ST alloys have a larger bending radius and thickness, so their stamping performance is superior to that of the NA and T6 alloys.

5.2. Effect of material parameters on springback

According to related research [30] and material properties of aluminum alloy, the effect of parameters, yield strength, strain-hardening exponent and strength factor $K$, on springback are discussed as follows.

After bending, a portion of the material in the bending deformation region undergoes plastic deformation and another portion undergoes only elastic deformation. As a result of the punch unloading, elastic deformation of the material needs to restore the original state, leading to the sheet springback. Therefore, the elastic deformation of material plays an important role in springback. However, the amount of elastic deformation depends on the yield strength of material. The higher the yield strength of the material is, the poorer the ability of...
the material entering the plastic stage is. The effect of yield strength of aluminum alloys under different material states on springback angle is depicted in Figure 13(a). Obviously, with the increase of yield strength, the springback angle and radius increase. Among these materials, the T6–8 h alloy exhibits the highest yield strength, the springback angle and radius are 20.3° and 6.6 mm, respectively.

Figure 13(b) shows the effect of strain-hardening exponent under different material states on springback. With the increase of strain-hardening exponent, the springback angle and radius decrease. The reason is that the larger strain-hardening exponent is, the larger work hardening effect is, and the more difficult is follow-up deformation of the deformed material compared to the undeformed material. Accordingly, the deformation of the material with larger strain-hardening exponent more easily extends to the undeformed zone than that of the material with lower strain-hardening exponent under the same deformation degree [31]. So the deformation zone becomes more uniform. Therefore, the springback decreases with strain-hardening exponent increasing. From the figure, the strain-hardening exponent of the HT alloy is higher than that of other alloys, the springback angle and radius are 10.0° and 3.6 mm, respectively.

The variation curves of springback angle and radius versus strength factor under different material states are shown in Figure 13(c). With the increase of strength factor, the springback angle and radius increase. In the bending process, an increase in punch load needed of the sheet becomes larger with strength factor increasing, which leads to higher bending stress and bending moment in the bent section. Therefore, the springback angle and radius are larger.

It can be clearly seen from figures 13(a), (b) and (c) that the variation trend of the springback angle is substantially the same as the springback radius with the increase of material parameters. The slope of the curve in figure 13(c) increases at a higher rate, indicating that the strength factor has greater influence on the springback compared with figures 13(a) and (b).

5.3. Principal stress distribution
Essentially, springback is a process by which stress is released from the sheet in order to achieve self-balancing. The paper [17] showed that the springback of sheet was closely related to principal stress. To further investigate the effect of heat treatment conditions on springback, the distributions of principal stresses for the upper and lower layers of sheets before unloading is obtained from the simulation as showed in figure 14. As a result of bending deformation, the upper layer of the sheet is in a state of compression, while the lower layer is in a state of...
tension. The half sheet is classified into two regions, the punch fillet region OA and the side wall AB, respectively. In the region OA, there are differences in principal stress between the upper and lower layers of different material states, which create inner bending moment to promote springback. The larger the difference between the upper and lower layers, the higher the residual stress and inner bending moment after unloading are. The principal stresses of the T6–8h alloy sheet with the largest springback are maximum, while the HT alloy sheet is minimum. Additionally, the principal stresses of the T6 alloys can be improved by aging time, motivating greater springback. In the region AB, with the increase of x-coordinate, the principal stresses of the sheets gradually decrease, and they are almost zero when the x-coordinate is about 60 mm.
5.4. Neutral layer offset

The comparison of k-values of experiment and simulation under different material states is presented in figure 15. The calculated k-value by simulation is almost identical with the experiment. The k-values under different material states are less than 0.5, their neutral layers shift toward the inner region. The reason is that the amount of expansion on the outer region is greater than the amount of shrinkage on the inner region. From the picture, the k-value of the T6–8 h alloy sheet ($R_i = 19.1$ mm) is minimum, indicating that the migration of neutral layer to the inner side is the most significant. However, the k-value of the HT alloy sheet ($R_i = 32.1$ mm) is closest to 0.5, which indicates that the neutral layer is almost no migration, closing to the geometrical middle layer of sheet. The migration of neutral layer is mainly related to the bending radius and plastic deformation capacity of the sheet. With the decrease of bending radius, the plastic deformation ability is enhanced, and the migration of neutral layer increases. The similar results are achieved in researching and verifying on neutral layer offset of bar in two-roll straightening process [32].

6. Conclusions

(1) The bending radius and thickness of the sheet increase with the increase of strain-hardening exponent and elongation, while decrease with the increase of yield ratio, and the influence of strain-hardening exponent is the largest. The high strain-hardening exponent, low yield ratio, and high elongation are beneficial to stamping performance of the material. Therefore, the stamping performance of the sheet can be enhanced according to the material parameters. With the increase of aging time, the local deformation of the T6 alloy sheets becomes more severe, which is manifested as the decrease of bending radius and thickness and the increase of neutral layer offset. In contrast, the bending radius, bending thickness and k-values of the ST and HT alloy sheets are larger, presenting better material fluidity. In other words, the stamping performance of the HT and ST alloys is higher than that of the NA and T6 alloys.

(2) Springback increases with the increase of yield strength and strength factor, while decreases with the increase of strain-hardening exponent, and the influence of strength factor is the largest. Therefore, the material parameters are selected by heat treatment conditions, thereby reducing the springback. Aging time can motivate the springback of the T6 alloy sheets. The springback of the T6–8 h alloy sheet is the largest, while the HT alloy sheet is the lowest.

(3) With the increase of material strength, the principal stresses of the sheet in the fillet region increase, thus motivating greater springback.

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