Effect of heat treatment conditions on mechanical properties and springback of 6061 Aluminum alloy sheets

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Abstract. The mechanical properties and bending deformation behaviors of homogenization treated (HT), solution treated (ST), natural aging (NA) treated and T6 6061 aluminum alloy sheets were investigated by tensile tests and three-point bending tests, respectively. The results showed that the heat treatment conditions have a significant impact on mechanical properties and bending characteristic. Bending radius and thickness of the HT alloy is the highest, and its springback angle is the lowest. However, the deformation mechanism of T6-8h alloy is just the opposite. The bending characteristics are attributed to the combined effects of yield strength, strain-hardening exponent and coefficient of the neutral layer. The simulation results are in good agreement with the experiment.

Keywords. 6061 aluminum alloy, Heat treatment conditions, Mechanical properties, Three-point bending, Springback, Simulation

1. Introduction

Aluminium alloy is widely applied in aerospace, automobile industries, railway vehicles, bridges, offshore structure topsides and high speed ships due to its lightweight and good corrosion resistance to weight ratio [1]. The mold surface of automobile parts is relatively simple, generally only simple bending deformation, such as three-point bending, V-bending, U-bending, and etc [2]. Several researchers have conducted studies on the basic understanding springback behavior of sheet metal in V-bending through experiment [3-6]. Kim [7] investigated the effect of temperature gradients on the final part quality in warm forming of lightweight materials by FE analysis. Grèze [8] investigated the influence of the temperature on residual stress and springback in AA5754 aluminium alloy by splitting tests. Tang [9] implemented a mixed hardening model based on Lemaitre and Chaboche non-linear kinematic hardening theory, which can well reflect stress and strain distributions and give a more favorable springback angle prediction. Hopper-Stad [10] studied the influence of material mechanical property parameters on springback. The effects of stress and hardening properties are significant, but not anisotropy big. Jin [11] simulated the forming process of large closed section AA6082-T1 aluminum alloy profiles under different bending radii. Leu [12] studied springback in plastic bending of anisotropic sheet metals using theoretical approach. It is found that springback decreases sharply with respect to smaller strain hardening. Jin [13] studied the springback of AA6082-T5 aluminum alloy hollow rectangular section profile in tension bending.
To date, the bending behavior of many aluminum alloys has been investigated during the bending process, while the effect of heat treatment conditions on bending properties has not been studied. The aim of this paper is to study the effects of different heat treatment conditions on the mechanical properties of 6061 aluminum alloy and the springback mechanism.

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.

Table 1. Chemical composition of 6061 Al-alloy (wt%)

| Element | Cu  | Mn  | Mg  | Zn  | Cr  | Ti  | Si  | Fe   | Al   |
|---------|-----|-----|-----|-----|-----|-----|-----|------|------|
|         | 0.20| 0.15| 0.95| 0.25| 0.20| 0.15| 0.50| 0.70 | Bal. |

2.2. Heat treatment test
The heat treatment tests were carried out on a resistance furnace. For the ST alloys, the initial NA alloy was treated at 535 ºC for 1 h to make sure that the Mg2Si phase entirely dissolved into the aluminum matrix, and then followed by water quenching to obtain the constituent in solution. To reduce the impact of parking time as much as possible, for the T6 temper, the ST alloy was quickly placed in an air circulation oven at 180 ºC for 8 h. For the HT alloys, the initial NA alloy was treated at 565 ºC for 12 h.

2.3. Tensile test
At room temperature, the tensile tests were performed at a tensile speed of 2 mm/min on an electronic universal testing machine. The tensile loading was oriented perpendicular to the rolling direction of specimens cut by a wire cutter. The detailed dimensions of standard specimens are shown in figure 1.

Figure 1. Dimensions of tensile test specimen (unit:mm).

2.4. Three-point bending test
The three-point bending tests were conducted on an electronic universal testing machine with a punch speed of 10 mm/min and a punch radius of 7.5 mm under displacement control. The schematic view is illustrated in figure 2. The specimen sizes of sheet were 160 mm × 20 mm × 2 mm. In the beginning, the specimen was placed on the two same cylindrical supports with the same radius. The punch is slightly in contact with the upper surface of the specimen. The displacement between two supports was set to be 120 mm. During the forming, the specimen is always located in the middle of the supports. The unloading process was carried out once the punch displacement reached to 30 mm. The bending force versus displacement data was acquired automatically by computer during the bending tests. Before unloading, the profile of bending specimen is captured by a camera and then imported into the measurement software Photoshop. The parameters, interior angle $\theta_f$, bending thickness $t_i$ and bending radius $R_i$, are determined. After unloading, the interior angle $\theta_f$ is measured by a universal goniometry. The springback angle is defined by the equation: $\Delta \theta = \theta_i - \theta_f$. 

$\Delta \theta = \theta_i - \theta_f$.
The offset of the neutral layer due to asymmetrical deformation between the outer and inner regions, which can be expressed by neutral layer coefficient \((k\)-value\). While the \(k\)-value is less than 0.5, it means 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. The more the \(k\)-value deviates from 0.5, the larger the offset of neutral layer shifts. According to a theory of stamping process manual [14], the \(k\)-value can be given by the following equation:

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

where \(k\), \(\beta\), \(R_i\), and \(t_0\) are the coefficient of neutral layer, the coefficient of incrassation, the inner bending radius and the initial thickness, respectively. \(\beta = (t_0 - t_i)/t_0\) and \(t_i\) is the thickness of specimen after bending.

### 3. FE simulation for three-point bending

The commercially available finite element software LS-DYNA was used for simulating the three-point bending test. The size of finite element model illustrated in figure 3 is coincident with experiment. In the model, the punch and supports were meshed adopting eight-node hexahedral solid elements and rigid body material model MAT_20 of LS-PrePost software on account of they have high elastic modulus and negligible deformation compared with the sheet. The material model of the sheet is a multi-linear plastic model MAT_24, and the mechanical properties are defined by the elastic phase and plastic phase of the material, respectively. The effective stress-strain curves shown in figure 4 were input into the DEFINE command.
Figure 4. Effective stress-strain curves of 6061 aluminum alloys.

The sheet was meshed using shell elements, which adopt the 16th full integration algorithm 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 a factor of 0.1. To simplify the computational complexity, the local mesh refinement of the sheet was performed on the main area of the force deformation contacted with the punch. The mesh size of the main deformation area was set to be 0.5 mm × 0.5 mm, while the mesh size of the other area was set to be 0.5 mm × 1.0 mm.

The contact type *AUTOMATIC_SURFACE_TO_SURFACE_MORTAR was utilized for the punch-sheet and support-sheet contacts. 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 punch displacement was constrained using the keyword *BOUNDARY_PRESCRIBED_MOTION_RIGID. The dynamic explicit analysis was utilized in the forming process, while the subsequent springback process adopted the static implicit analysis. The keyword *INTERFACE_SPRINGBACK_SEAMLESS_THICKNESS was used to simulate the springback process. Table 2 shows the simulation conditions for the three-point bending test.

Table 2. Simulation conditions.

| Simulation conditions         | Value   |
|------------------------------|---------|
| Punch speed/(mm·ms⁻¹)        | 1.0     |
| Punch displacement/mm        | 30      |
| Friction coefficient between punch and sheet | 0.20 |
| Friction coefficient between supports and sheet | 0.15 |

4. Results

4.1. Tensile properties
Form figure 5, the curves have no obvious yield platform, which can be divided into three stages: elastic deformation stage with linear growth, instability stage and plastic deformation stage after instability.
The tensile mechanical properties of 6061 aluminum alloys under different heat treatment conditions are listed in table 3. It can be obviously seen that heat treatment conditions have a great impact on the mechanical properties of material. Compared with the NA alloy, the HT and ST alloys exhibit the lower strength and the higher elongation. Looking at the whole, the HT alloy has the lowest strength, and the yield strength and tensile strength are 35.01 MPa and 150.74MPa, respectively. The elongation of ST alloy is the largest, reaching 21.37%, which is about 2 times than that of T6-8h and NA alloys. With the increase of artificial aging time. The strength of T6-8h alloys increases, but the plasticity decrease.

4.2. Bending deformation behavior

The final formed specimens under different material conditions after bending tests are shown in figure 6. It can be seen from figure 6 that bending deformation behavior of sheet are sharply sensitive to the heat treatment conditions. Obviously, the bending deformation of all specimens mainly occurs at the position in contact with the punch, while the straight edges near the punch position are essentially undeformed. For the HT and ST alloy sheets, the bending deformation region has more materials to participate in the coordinated deformation, and their shape of bending region is similar to the U-shape. On the contrary, the deformation behavior of NA and T6-8h alloy sheets show poor uniformity and coordination in the punch position, and their shape of bending region is similar to the V-shape.
Figure 6. Final formed specimens under different material conditions after bending tests.

The bending force versus displacement curves for the different material states are plotted in figure 7. From the whole graph, the NA and T6-8h alloys have a similar tendency, whose bending force rise rapidly from zero to the point corresponding to the elastic behaviour of the material where the load increase almost linearly with the punch stroke the onset of plastic deformation. Compared with the HT and ST alloys, the bending force of the NA and T6-8h alloys rapidly reach a maximum value with advancement of the punch stroke.

Figure 7. Force-displacement curves of 6061 Al-alloy sheets under different material state.

Table 4 presents parameters of different material states after bending. The T6-8h alloy sheet has the maximum bending interior angle before and after unloading, and their values are 122.2° and 142.5°, respectively. With the increase of aging time, the interior angle before and after unloading increase. In contrast, the bending radius and bending thickness occurred with the plastic deformation zone has the opposite tendency. The bending radius and bending thickness of T6-8h alloy sheet are the smallest of all alloy sheets. At this point, for the T6-8h alloy sheet, the bending radius and bending thickness of alloy sheets decrease with the increase of aging time.

Table 4. Parameters of different material states after bending.

| Materials | Interior angle before unloading (°) | Interior angle after unloading (°) | Bending radius/mm | Bending thickness/mm |
|-----------|------------------------------------|-----------------------------------|-------------------|---------------------|
| HT        | 109.0                              | 119.1                             | 32.1              | 1.99                |
| ST        | 112.1                              | 124.4                             | 31.8              | 1.98                |
| NA        | 119.3                              | 136.9                             | 25.4              | 1.87                |
| T6-8h     | 122.2                              | 142.5                             | 23.6              | 1.85                |
5. Discussion

5.1. Validation of FE model
In order to verify the reliability and accuracy of the established FE model in this article, the comparison of simulated and experimental springback angles is shown in figure 8. The results show that the simulated springback angle are in good agreement with the experiment. The maximum relative error is within 2.5%.

![Figure 8. Comparison of simulated and experimental springback angles under different material states.](image)

5.2. Effect of yield strength on springback
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 to restore the original state, leading to the sheet springback. Therefore, the elastic deformation of materials plays an important role in springback. However, the amount of elastic deformation depends on the yield strength of materials. The greater 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 on springback angle is seen in figure 9. Obviously, with the increase of yield strength, the springback angle increases rapidly. Among them, the T6-8h alloy has the highest yield strength, and the maximum springback angle reaches 19.2°.

![Figure 9. Effect of yield strength on springback angle.](image)
5.3. Effect of strain-hardening exponent on springback
Figure 10 shows the effect of strain-hardening exponent on springback angle. With the increase of strain-hardening exponent, the springback angle decreases. The larger the strain hardening exponent is, the greater the material's ability to enter the undeformed area is. From Table 5, the HT alloy sheet has the largest bending radius, reaching 32.4 mm. Meanwhile the strain of the material with larger strain-hardening exponent is smaller than that of the material with smaller strain-hardening exponent. From the picture, compared with other alloy sheets, the springback angle of HT alloy sheet is minimum, being 19.2°.

![Figure 10. Effect of strain-hardening exponent on springback angle.](image)

5.4. Neutral layer offset
From figure 11, the $k$-value of T6-8h alloy sheet with the lowest bending radius (23.6 mm) is minimum, indicating that the offset of the neutral layer to the inner side is the most significant. However, the $k$-value of HT alloy sheet with the largest bending radius (32.1 mm) is closest to 0.5. The neutral layer has nearly no migration, closing to the geometrical middle layer of sheet.

![Figure 11. Comparison of $k$-value of experiment and simulation under different material states.](image)

6. Conclusions
- The HT alloy exhibits the lowest yield strength, tensile strength and yield ratio. However, the T6-8h alloy is just the opposite. With the increase of aging time, the strength of the materials increase.
Compared with HT and ST alloy sheets, the T6-8h alloy sheet deform seriously in the fillet region. The uniformity of the sheet in the deformation area can be improved by increasing the strain-hardening exponent of the material.

The springback mechanism of the sheet is determined by various factors. With the yield strength and strain-hardening exponent of materials increase, the springback angle increases.

The HT alloy sheet exhibits the smallest $k$-value and the neutral layer is substantially not offset. However, the neutral layer of the T6-8h alloy sheet is farthest from the geometric middle layer.

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