Heat treatment and granule medium internal high-pressure forming of AA6061 tube

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Abstract: The new forming process of AA6061 alloy tube, including solution treatment, granule medium internal high-pressure forming and aging treatment, was developed. The AA6061 alloy tube via heat treatment satisfied the forming requirement, and the granule medium internal high pressure forming method for AA6061 alloy tube was also realized by using convenient implementation with low requirement of equipment and flexible design of product. At a solution temperature of 560 °C and time of 120 min, the elongation of the AA6061 extruded tube increases by 300% and the strength and the hardness dramatically decrease too. Therefore, the AA6061 alloy tube meets the requirement of internal high-pressure forming because of the improvement of formability. The experiments shows that the strength and hardness of AA6061 alloy workpiece recover to that of the as-received alloy at an aging temperature of 180 °C and time of 360 min, and the strength of AA6061 alloy workpiece is equal to the base alloy. The typical parts of convex ring tube, stepped shaft tube and hexagonal tube were successfully produced in lab by using the present forming method. The forming tests show that the maximum expansion ratio (MER) of the AA6061 extruded tube increases by 25.5% and the material properties of formed AA6061 alloy tube reached the performance of as-received alloy.

Key words: aluminum alloy tube; solution treatment; aging treatment; granule medium; internal high pressure forming

1 Introduction

AA6061 is one of the most widely used Al–Mg–Si alloys [1]. It is applied in extreme conditions such as aerospace, transportation and petrochemical for low density, high impact toughness, excellent machinability and good corrosion resistance [2, 3]. In profile preparation process of AA6061 such as extrusion and rolling, massive nano-precipitates are formed with dispersive distribution in grain inner by heat treatment, making its strength increase [4]. This material can not be formed into complex parts for its high strength and poor plasticity at room temperature. So, the application range of AA6061 is restricted seriously. Therefore, a feasible method for plastic processing in high-strength aluminum alloy like AA6061 is sought, making it a hot issue on current engineering community.

Recently, warm forming processes of high-strength aluminum alloy are the main direction to solve the problem of poor formability at room temperature [5]. HE et al [6] studied the free bulging test carried out at high temperatures to evaluate the formability of AA6061 extruded tube, which reveals that the MER reaches the maximum value of 86% at 425 °C, namely the MER at high temperature increases significantly. However, low forming efficiency, high requirement of die set and temperature control system are the main problems in warm forming processes of aluminum alloy tube. Meanwhile, the improvement of elongation in most of high-strength aluminum alloy at high temperature is less than 20%, which can not meet the requirement of tube forming [7].

6xxx series aluminum alloy is a kind of high-strength aluminum alloy which can be strengthened by heat treatment. The mechanical properties can be adjusted by solution treatment and aging treatment with the content of precipitates controlled. XIAO et al [8] studied the heat treatment process of AA6061 extruded bars and proved that Mg2Si dissolving, Cr phase and GP zone forming are the main reasons for alloy strengthening. SHANG et al [9] studied the solution and aging treatment of AA6082 extruded bars. Their result showed that the strength decreases and the plastic...
processing property increases after solution treatment, and the hardness and the strength rise again by subsequent aging treatment. The supersaturated solid solution, which is formed by solution treatment, can decrease strength and increase toughness; Consequently, the formability of AA6061 increases. Meanwhile, the deformation resistance of this material reduces and the requirement of equipment capacity sequentially decreases. Unfortunately, it can not meet the requirement of engineering application because the strength and the hardness of shaped tubes are very low. However, the defects can be made up through aging treatment. The second phase particles precipitate again in grain inner, causing precipitation strengthening. Due to the double effects of work hardening and precipitation strengthening, the strength and the hardness of tube increase remarkably, making the application requirements satisfied. In this respect, ZHOU et al [10] studied the spinning process of AA6061 extruded tube and found that half solution treatment before spinning makes the spinning properties better, subsequent aging treatment after forming makes the strength of spinning product meet the operating requirement of no less than 245 MPa. Therefore, the internal high-pressure forming of 6xxx series aluminum alloy at room temperature can be realized by changing mechanical properties by the method of solution treatment before manufacturing and aging treatment after forming.

In this work, the AA6061 extruded tube is selected as the research object. The formability is characterized by uniaxial test and free bulging test. The corresponding strength is measured by Vickers hardness test. The microstructure is observed by metallurgical test. The typical parts of AA6061 tube are trial-produced by the combination of heat treatment and granule medium internal high pressure forming. This study lays a basis on the preparation of high strength aluminum alloy tube.

2 Experimental

2.1 Material

The experimental material was AA6061 extruded tube produced by a domestic company with 2 mm in thickness and 100 mm in diameter. The alloy sample was tested by ADVANT X’P-381 type X-ray fluorescence spectrometer. The main chemical composition is listed in Table 1.

![Table 1 Chemical composition of as-received material](image)

<table>
<thead>
<tr>
<th>w(Si)%</th>
<th>w(Mg)%</th>
<th>w(Cu)%</th>
<th>w(Fe)%</th>
<th>w(V)%</th>
<th>w(Ti)%</th>
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<tbody>
<tr>
<td>0.815</td>
<td>0.181</td>
<td>0.136</td>
<td>0.08</td>
<td>0.023</td>
<td>0.019</td>
</tr>
<tr>
<td>w(Al)%</td>
<td>w(Cr)%</td>
<td>w(Ga)%</td>
<td>w(Zn)%</td>
<td>w(Mn)%</td>
<td>Al</td>
</tr>
<tr>
<td>0.011</td>
<td>0.01</td>
<td>0.083</td>
<td>0.054</td>
<td>Bal.</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Experimental methods

1) Heat treatment process steps. AA6061 tubes were cut into axial tensile specimens, ring tensile specimens and metallographic specimens by line cutting machine. The solution treatment was carried out in SX-G16103 type heat furnace. Solution temperatures (T_S) were 530, 540, 550, 560 and 570 °C respectively and holding time (t_s) was 30, 60, 90, 120 and 150 min respectively. The specimens were put into furnace at specified temperature. The temperature was fluctuant in this process. Begin timing when the temperature stabilised again. Quenching was carried out in HH-2 type constant temperature water bath pot. In this process, the transfer time was less than 5 s and the water temperature was lower than 25 °C. After solution treatment, all the AA6061 specimens were kept in a freezer. It is very important to avoid the natural aging of the alloy at room temperature.

Following the solution treatment, the specimens were artificially age hardened in DHG-9070A type thermostatic air-blower-driven drying closet and subsequently cooled in air. Aging temperature (T_A) was 180 °C. Aging time (t_A) was 0.5, 1, 2, 4, 6 and 8 h.

2) Tube performance test. Axial tensile specimens and ring tensile specimens were clamped by different fixtures. Three samples were performed in one state and the values were averaged. The sizes of axial tensile specimen and ring tensile specimen were determined by the international standard of tensile specimen and the accuracy of experimental equipment (See Fig. 1 and Fig. 2). A kind of fixture, which was designed for tube with 96 mm inner diameter, was applied to this research to ensure the integrity of the specimen, as shown in Fig. 1(d). The clamped part of the axial tensile fixture is circular-arc. Compared with traditional fixture, the experiment result is more accurate by using this fixture. The working principle of ring specimen fixture is conducted through deformation produced by the relative motion of D shaped blocks after two D shaped blocks inserted into ring specimen. HE et al [11] believe that in the process of hoop tension test, radial normal force, tangent tension force and tangent friction distribute regularly. In order to reduce the influence of friction and make deformation focus on the gauge length, the gauge length of ring specimen was located at the top point of D shaped block with lubrication. The mechanical properties were tested by Inspekt-Table100 type electronic universal testing machine and the strain rate was 0.001 s⁻¹. Microhardness measurements tests were also carried out to investigate the mechanisms responible for solution treatment and artificial aging. The samples were ground with SiC paper and hardness measurements were carried out using a micro vickers hardness (HMV) instrument with 100 g load and a dwell time of 15 s. Five hardness readings were performed per sample and they