Superplastic forming process research of front aluminum alloy opening and closing mechanism hatch for multiple units

Ranran Chen[1,a], Guangzhong He[2,b], Kefei Wang[2,c], Guofeng Wang[1,d*]

[1]School of Materials Science and Engineering, Harbin Institute of Technology,
Harbin 150001, China

[2]CRRC Changchun Railway Vehicles Co., Ltd., Changchun 130062, China

[a]rrchen1126@163.com,[b]heguangzhong@cccar.com.cn,
[c]wangkefei@cccar.com.cn, [d]gfwang@hit.edu.cn

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Abstract. In this paper, the forming process research of the front opening and closing mechanism hatch for multiple units was carried out, and the industrial grade 5083 aluminum alloy was selected as the original material. The uniform rapid superplastic forming process combined with hot stamping and direct-reverse superplastic forming was used to form the hatch body skin, the cold stamping and argon arc welding process were used to produce the connection support, and the hatch integral part was obtained by argon arc welding finally, which solved the problem of poor environmental protection and high ratio of traditional FRP hatch and high precision forming of the large complex thin-walled structural part that cannot be achieved by the traditional forming process. After process research and development, finite element analysis, and forming tests, the aluminum alloy hatch with good forming quality was successfully manufactured. The ultimate thinning rate of the part was 23.8%, the overall wall thickness was evenly distributed, the deviation of shape was controlled within 1 mm, and the mechanical properties met the relevant technical requirements.

1. Introduction

High-speed rail has become the main means of transport for people traveling near and far at this stage [1]. With the continuous development in the field of rail transportation, the modern performance requirements for rail vehicles such as safety and comfort, lightweight and high speed, green and environmental protection have been gradually improved, and the engineering and manufacturing technologies of vehicle components have been upgraded and optimized [2].

The opening and closing mechanism hatch, as an important part of the front end of the rolling stock, forms the streamlined shape together with the front hood to ensure aerodynamic performance. At this stage, the hatch is mainly made of FRP, but the difficulties of degradation, environmental pollution, high specific gravity, and insufficient strength make it impossible for the hatch to comply with the sustainable development trend in the field of rail train manufacturing. The aluminum alloy is widely used in the field of forming technology for rail vehicle coverings due to its high strength ratio, environmental friendliness, and machinability [3]. However, the plastic deformation limit of the aluminum alloy at room temperature is low and it is difficult to avoid rebound defects, so cold stamping cannot obtain complex thin-walled structural parts in a single forming [4,5]. Compared with cold stamping, stamping under hot conditions has improved the forming performance, but still cannot meet the quality requirements of complex spatially curved coverings. The superplastic forming process, which takes advantage of the unusually high elongation of aluminum alloys under specific tensile stresses, can solve the problem of large and complex sheet metal parts that cannot be manufactured by conventional stamping [6-8].

However, the traditional superplastic expansion process for forming large and complex three-dimensional components has the disadvantages of long forming cycles, uneven wall thickness distribution and high costs [9,10]. Based on the traditional process, the improved homogeneous rapid superplastic forming technology, which combines hot stamping and superplastic bulging, has shown excellent forming performance [11]. Firstly, hot stamping is used to make the material flow into the cavity of the concave die under the action of the convex die to achieve pre-deformation at high speeds; the reverse superplastic expansion is then used to allow the material to flow into the recesses reserved on the convex surface for further storage and dispersion of the deformation; finally, superplastic direct expansion is used to form localized complex features and difficult to form areas of the component. Therefore, the uniform rapid superplastic forming process can reduce the forming cycle time, improve the wall thickness distribution, reduce processing and manufacturing costs, and reduce energy consumption.

It can be seen that the study of the forming process for the opening and closing mechanism hatch made of aluminum alloy has a positive effect on the healthy and sustainable development of the rail transport industry. In this paper, the complex aluminum alloy opening and closing mechanism hatch of the front end of the intelligent rolling stock will be the object of study, and the forming process of the component will be studied to form a complete process flow and produce the part of qualified quality. It will provide a new manufacturing idea for the opening and closing mechanism hatch, and promote the development of the rail train field in the direction of lightweight and high speed.

2. Experimental

Among the various grades of aluminum alloys, 5083 aluminum alloy shows high specific strength, low density, easy processing and good corrosion resistance, and presents excellent superplastic deformation performance under specific conditions, which has been developed as the preferred material for the superplastic forming process of rail vehicle coverings. Compared with the special aluminum sheet for superplasticity, the industrial state 5083 aluminum alloy has a lower cost and can meet the demand for superplastic deformation capacity of complex thin-walled superplastic components with the composition shown in Tab 1. In addition, the 5083 aluminum alloy is weldable and is mainly joined by means of argon arc welding and laser welding [12]. Liu et al.[13] learned through tests that 5083 aluminum alloy had high strength after argon arc welding, no obvious welding defects, showing good welding quality.

Tab 1 Chemical composition of industrial state 5083 aluminum alloy (wt%)

Elements	**Mg**	**Mn**	**Si**	**Fe**	**Cu**	**Cr**	**Ti**	**Zn**	**Al**
Content	**4.0~4.9**	**0.40~1.0**	≤ **0.40**	≤ **0.40**	≤ **0.10**	**0.05~0.25**	≤ **0.15**	≤ **0.25**	**Bal.**

The opening and closing mechanism hatch made of aluminum alloy studied in this project is an important exterior sheet metal part that has a matching connection with the front hood and the movement structure. The hatch includes not only the exterior hatch body skin (Fig.1(a)) but also the connecting support (Fig.1(b)). The uniform rapid superplastic forming technology was used to achieve efficient and precise forming of the large and complex thin-walled hatch body skin. The cold stamping process was used to form the transitional rounded joint profile of the connection support (red area in Fig.1(b)). The side wall plates were welded to the pressed parts using the argon arc welding process to obtain the connection support for the overall structure. Finally, the connection supports were welded to the corresponding reserved positions of the hatch body using argon arc welding to obtain an integral part of the hatch.

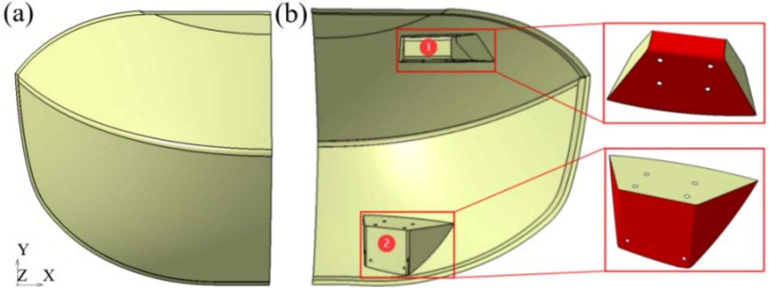

Fig. 1 Three-dimensional model of hatch: (a)the main body skin; (b)the connection support

3. Results and Discussion

3.1 Superplastic forming simulation of the hatch body

Marc software has been widely used in superplastic process simulation due to its powerful non-linear solving calculations and the availability of the dedicated superplastic forming module. The mould surface was extracted, the mould structure was simplified and the finite element geometric model was created by importing the software, as shown in Fig.2. The mould was set up as the rigid body, the sheet was the deformed body, and the coefficient of friction was 0.2. The initial thickness of the sheet was 4.7mm, the cell size was 10 mm×10 mm and the cell type was shell cell. The Backofen equation was used as the material model to describe the relationship between flow stress and strain in metallic materials during the steady-state rheological phase. The industrial state 5083 aluminum alloy exhibited excellent superplastic deformation properties at 480°C and $1\times10^{-3}s^{-1}$ with a material parameter of 155 MPa·s and a strain rate sensitivity factor of 0.35 [14]. The movement of the sheet unit in the sealing area was restricted in the X, Y and Z directions. Superplastic bulging pressure was applied to all unit faces and the contact was controlled using the Coulomb bilinear method.

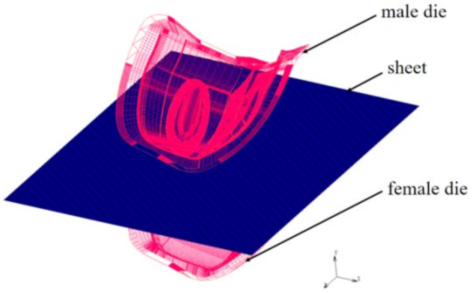

Fig.2 Finite element geometric model

The wall thickness distribution after hot stamping is shown in Fig.3(a). The minimum thickness on the part profile appeared in the area of maximum stretching depth, with a thickness of 4.293 mm and a thinning rate of 8.7%. The thinning rate was small due to the material flowing into the cavity under the action of the convex die during the stamping process, which carried out a certain degree of replenishment. After hot stamping, superplastic reverse expansion was carried out to a certain extent, with the thickness distribution shown in Fig.3(b). The minimum thickness of the profile was 4.071 mm and the maximum thinning rate was 13.4%, which was an increase in the thinning rate but still within the reasonable value. Finally, superplastic direct expansion was carried out and the material flowed into the concave model cavity until it was fully laminated, with the wall thickness distribution shown in Fig.3(c). The largest reduction in wall thickness of the formed part was at the sharp end of the concave die, with a wall thickness of 3.318mm and a thinning rate of 29.4%, which was the supplementary part of the process, not part of the profile and could be removed by cutting after the actual forming. The thinnest position on the part profile was the deep cavity circular transition area, with a wall thickness value of 3.532mm and a thinning rate of 24.8%, which was still within the thinning rate of ≤25%.

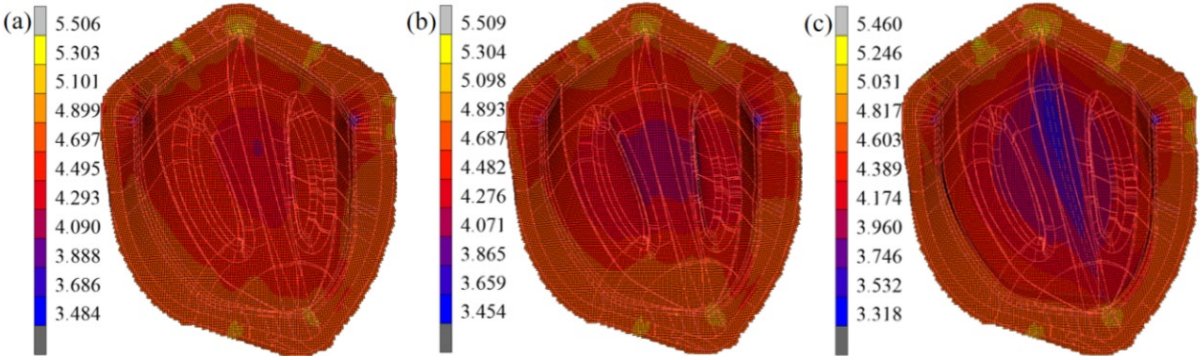

Fig.3 Thickness distribution: (a)hot stamping; (b)superplastic reverse bulging; (c)superplastic direct bulging

3.2 Superplastic forming test of the hatch body

The superplastic mould is shown in Fig.4. To avoid excessive high-temperature flow resistance adversely affecting the final forming quality of the part, the graphite lubricant was applied to the original aluminum alloy sheet. The production trial was carried out at the deformation temperature of 480℃ and the deformation rate of $0.001s^{-1}$ using superplastic forming equipment obtained by modification on the basis of the 1000t hydraulic press. The temperature of the sheet was monitored in real-time to reach the target value and then held for a period of time to achieve the uniform temperature distribution in all areas of the sheet. The upper die was then driven down by the hydraulic press at a speed of 5 mm/s to complete the hot stamping. The sealing force was then applied to ensure that the expansion cavity was airtight. The reverse expansion pressure was slowly applied according to Fig.5(a) and the pressure was released when the forming reached a certain level. The direct expansion pressure was then applied according to Fig.5(b) and the strain rate was reasonably controlled so that the material was finally fully fitted to the concave cavity and the formed part was obtained.

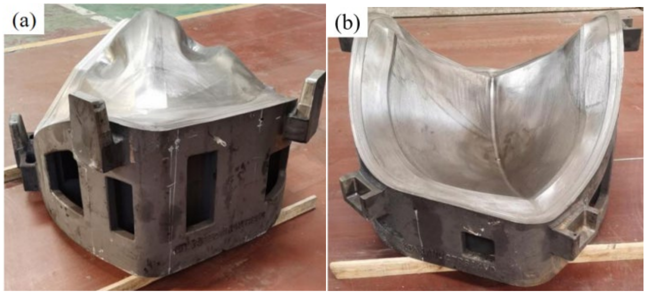

Fig.4 Superplastic mould: (a)punch; (b)die

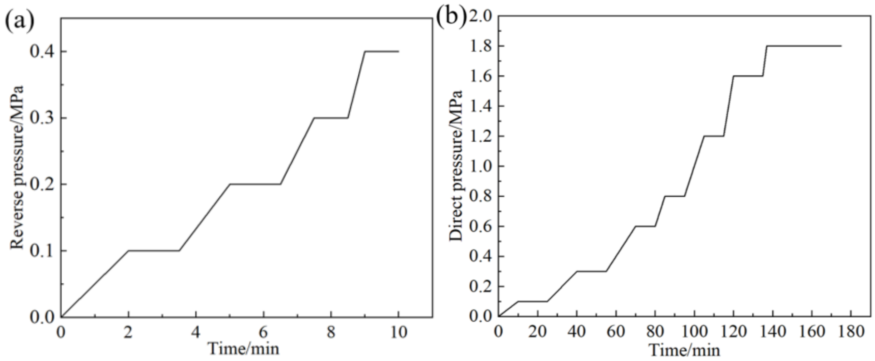

Fig.5 Pressure loading control curve: (a)superplastic reverse bulging; (b)superplastic direct bulging

The superplastic formed part was cut and polished to acquire the hatch body skin as shown in Fig.6. The physical diagram of the test visually showed that the material that flowed into the reverse-expansion cavity in advance had been fully expanded, and the surface quality of the part was good, without obvious scratches, wrinkles, breaks or other defects.

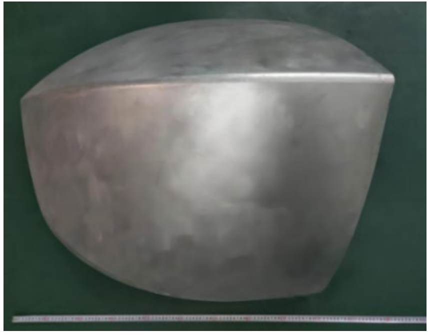

Fig.6 The hatch body skin

3.3 Forming test of the connection support

The cold punching die was mounted on the press for cold stamping. Due to a certain degree of springback in cold punching parts, manual shaping was required to ensure that the shape of the formed part matched the side wall plates to facilitate welding and reduce shape deviations. After straightening the shape, the formed part was trimmed to a certain extent to reduce dimensional deviations, in accordance with the positioning notch reserved on the mould. The cold stamping parts are shown in Fig.7. The side wall panels were finally joined to the formed parts by argon arc welding to obtain the complete joint supports as shown in Fig.8. To avoid defects such as porosity in the weld seam, the surface oxide film was polished and removed before welding to reveal the silvery-white metallic luster [15]. The welding method of ER5356 wire and AC manual tungsten arc welding was used to achieve the butt welding of 5083 aluminum alloys, which was flexible in operation and highly suitable for welding complex structures. By observing the macroscopic shape of the weld seam, it could be seen that the joint was uniform and neat, the weld seam had basically the same width and no significant defects.

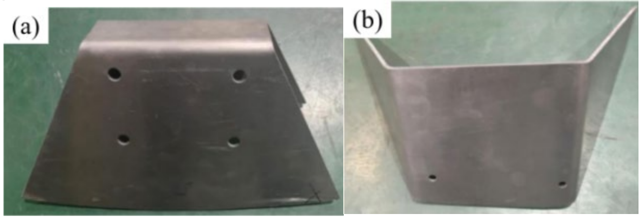

Fig.7 Cold stamping parts: (a)no. 1 connection support; (b)no. 2 connection support

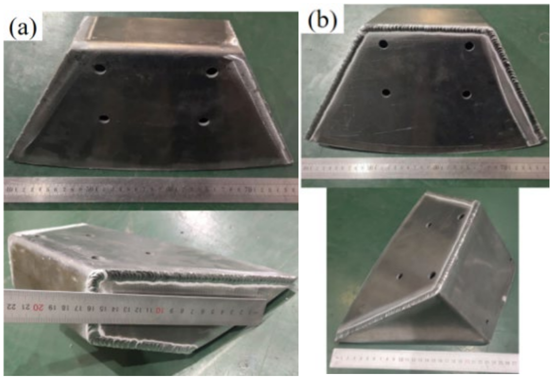

Fig.8 Integral structures of connecting supports: (a)no. 1 connection support; (b)no. 2 connection support

3.4 Welding connection of the integral part for hatch

To achieve the opening and closing action of the hatch, the connecting supports were mechanically connected to the movement mechanism and integrated into the hatch body using the welding process. The hatch body and the connecting supports were made of 5083 aluminum alloy and were connected by argon arc welding. The inspection tool played a positioning role in the welding position, as shown in Fig.9. The welding position of the hatch body and the connecting supports had the same spatial curved surfaces to ensure connection accuracy. Firstly, the connecting supports were placed in the reserved position of the inspection tool, then the hatch body was placed in the inspection tool, covering the connecting supports. The two were fixed and marked for spot welding in position and fully welded to obtain the complete aluminum hatch component as shown in Fig.10. It could be seen that the welding wire was well filled, the welding seam was flat and consistent, no cracks and other defects appeared, and the welding quality was good.

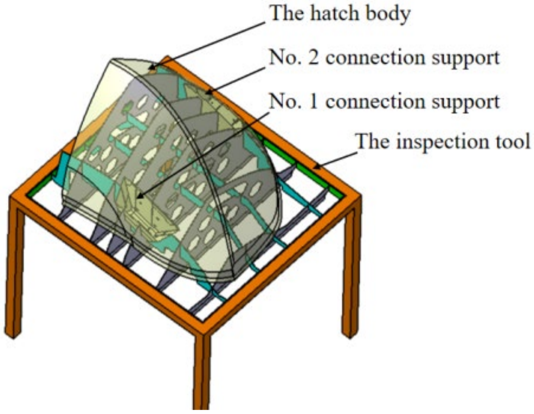

Fig.9 3D model of the inspection tool

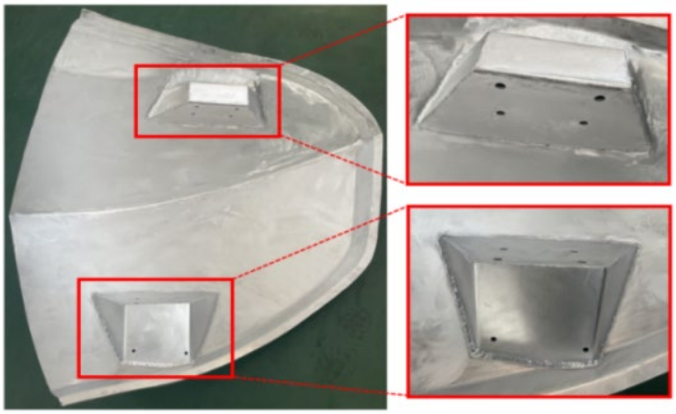

Fig.10 The hatch integral part

3.5 Quality assessment for the part

The hatch was of good quality in appearance with no obvious defects, but further evaluation was required to ensure the strength of the part in use. The wall thickness distribution affects the mechanical properties of the part, and the areas of severe thinning are prone to stress concentration, which can have a detrimental effect on the performance of the component. The ultrasonic thickness gauge was used to test the local feature points of the hatch body and the measurement results are shown in Fig.11. The thinnest thickness was at the bottom deep cavity area, which was consistent with the simulation result, where the deformation was the most intense with the wall thickness value of 3.58mm and the thinning rate of 23.8%. The ultimate thinning rate was controlled within the permitted limits and the overall wall thickness distribution was homogeneous.

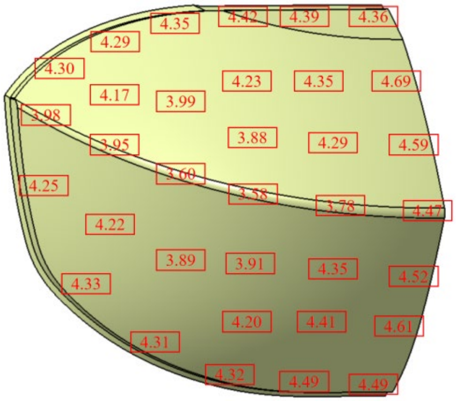

Fig.11 The thickness distribution of superplastic forming part

The final lamination of the part was achieved by using superplastic bulging with excellent deformation properties and good lamination performance. However, further precise measurements with the aid of gauges and moulds were required to ensure shape and dimensional accuracy, the assemblability and coordination with the front hood. The whole hatch was placed on the inspection tool as shown in Fig.12. After measuring, the shape and dimensional deviations were controlled within 1mm, showing good shape and dimensional accuracy.

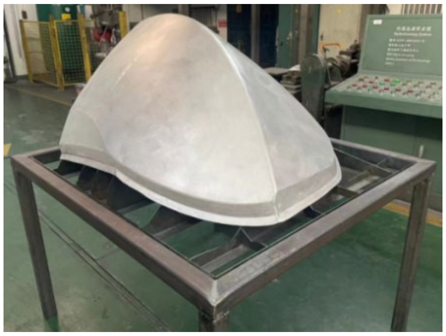

Fig.12 The hatch placed on the inspection tool

After the superplastic deformation of the aluminum alloy, the microstructure will change and the mechanical properties will change to some extent. To ensure that the formed part has sufficient strength for service at room temperature, the samples were taken from the formed part and tested for tensile mechanical properties. The results of the mechanical properties tests are shown in Tab 2. It could be seen that mechanical property parameters had been reduced, but none of them had been reduced to 90% of the original material mechanical properties, which could meet the room temperature service requirements.

Tab 2 Mechanical properties of room temperature before and after forming

Test subjects	**Pre-forming**	**Post-forming**	**Reduction rate**
Tensile strength/MPa	**332**	**301**	**9.3%**
Yield strength/MPa	**155**	**140**	**9.7%**
Maximum elongation/%	**34**	**33**	**2.9%**

To study the effect of the entire deformation process on the microstructure of the material, EBSD testing of the microstructure before and after deformation was carried out and the test results are shown in Fig.13. After the statistical summary, the average grain size of the original plate was approximately 14.12 μm and the average grain size of the part was approximately 18.97 μm, which was an increase in grain size. The material was deformed in the high-temperature environment at around 4h and the grains grew to reduce the total interface energy. However, the grain shape of the part was approximately equiaxed, without obvious holes, cracks or other microscopic defects, with good overall performance.

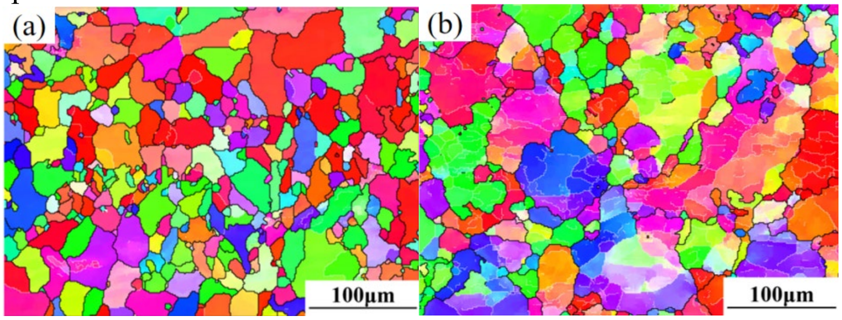

Fig.13 Microstructure before and after forming: (a)before forming; (b)after forming

4. Conclusions

Through the process of preliminary technical research and development, forming simulation, and trial production, the aluminum alloy hatch with good quality was successfully produced. The minimum wall thickness of the part was 3.58mm, which was a reasonable wall thickness distribution; the shape and dimensional deviations of the hatch were less than 1mm, with high shape and dimensional accuracy; the mechanical properties of the formed part were reduced to different degrees compared with the raw material, but were within reasonable values; the microscopic grain size increased slightly, but no obvious microscopic defects appeared. It can be seen that the uniform rapid superplastic forming process can be successfully applied to the production and development of the aluminum alloy hatch body, and combined with cold stamping, argon arc welding, and other processes to obtain the overall lightweight component for opening and closing mechanism hatch of acceptable quality, to promote the development of the rail transit parts manufacturing industry to high-speed, energy-saving, environmental protection and other directions.

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