Hot stamping process and mold design for integrated car body door rings

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With the continuous development of the automotive manufacturing industry and the growing demand for lightweight solutions, the utilization of advanced materials and forming processes to enhance the performance and quality of body components has become a prevailing trend. This paper investigates the forming process of laser welded plate vehicle door rings, along with the corresponding mold design and application. It provides an overview of the background of automotive lightweighting, advanced materials, and forming processes, and highlights the purpose and significance of the research. The structure and functional requirements of the vehicle door ring are extensively discussed, while the limitations of conventional manufacturing methods are analyzed. Furthermore, the distinctive features and advantages of laser welded plates, as well as the forming process of laser welded plate vehicle door rings, are elucidated. Using an integrated hot stamping door ring of a specific vehicle model as a case study, the mold design and testing methods required for the forming process of the vehicle door ring are investigated based on the material and geometric characteristics of the laser welded plate, and a design application plan is proposed. Finally, by summarizing the actual research and application cases of this project, the potential application prospects of the forming process and mold design of laser welded plate vehicle door rings are presented.

Keywords: High-strength steel; Vehicle door ring; Laser welded plate; Hot stamping; Process and mold.

1. Introduction

The development of lightweighting in the automotive industry aims to enhance fuel efficiency, reduce emissions, improve vehicle stability, and enhance collision safety, while simultaneously reducing manufacturing costs. In the process of automotive industry development, fuel consumption, environmental protection, and safety are the three major challenges. In response to the goals of carbon peaking and carbon neutrality, countries have begun to prioritize energy and environmental issues and have implemented corresponding regulations and improvement measures. Lightweighting technology, by reducing the weight of the vehicle itself, can effectively decrease fuel consumption, reduce emissions, and has become a global trend in the automotive industry [1]. Apart from its environmental significance, lightweighting technology can also enhance the power-to-weight ratio of vehicles, thereby improving their performance. This, in turn, positively impacts vehicle stability and collision safety. While maintaining the original performance in terms of driving safety, durability, shock resistance, and comfort, lightweighting technology can also reduce vehicle manufacturing costs. Therefore, lightweighting technology is an important technical measure for effectively reducing fuel consumption, decreasing

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emissions, and improving safety, which is critical for energy conservation, emission reduction, and the sustainable development of China's automotive industry [2].

To achieve automotive lightweighting, the widespread utilization of advanced high-strength steel (with a yield strength exceeding 770 MPa) and ultra-high-strength steel (with a tensile strength ranging from 1500-2000 MPa) in the body is indispensable [3]. Currently, the extensively used hot-formed ultra-high-strength steel in China's passenger cars is 22MnB5 (available as bare or Al-Si coated sheets).

Laser welding technology can be employed to join sheets of different materials and thicknesses, thereby improving the dimensional accuracy and consistency of components, as well as their strength and stiffness, to meet the performance requirements of vehicles under harsh conditions such as collisions and vibrations. It can further enhance the coefficient of lightweighting [4]. Laser welding technology originated in the 1980s, initially to address the issue of insufficient width of steel plates produced by steel mills. It gradually gained prominence in the automotive industry and is currently fulfilling domestic production needs in China for aluminum-silicon coated welding production lines.

2. Characteristics and Advantages of Laser Welded Plates

With the advancement of lightweighting technology in body structures, laser welded plate technology has also matured. By joining plates of different thicknesses and materials, laser welded plates improve material utilization and reduce manufacturing costs. The manufacturing process of laser welded plates is simpler compared to conventional stamped parts, resulting in fewer production processes and improved production efficiency. Laser welded plate technology can address challenges faced by traditional stamping processes, such as long mold debugging cycles and low part accuracy. By utilizing welded plates, mold structures can be simplified, mold manufacturing cycles can be shortened, and mold costs can be reduced. Laser welded plate technology significantly enhances the collision resistance of body components, thereby improving vehicle safety. It is a novel automotive manufacturing technology that promotes technological innovation and industrial upgrading in the automotive industry [5]. Furthermore, it not only reduces manufacturing costs and improves production efficiency but also optimizes mold production processes, enhances vehicle performance and safety, and promotes technological innovation and industrial upgrading in the automotive industry.

2.1. *Limitations and Issues of Traditional Manufacturing Methods*

Conventional door rings are typically formed by independently hot stamping multiple components, followed by meticulous spot-welding assembly. The forming and assembly processes of these components are complex. The reliability of the spot-welding connections between these components is not high, resulting in reduced overall collision strength of the door ring. The connection points between the conventional door ring components may become weak points in the event of a collision. In accidents, these connection points may deform or fracture, compromising the door ring's ability to protect the safety of passengers inside the vehicle. Gaps and protrusions may exist between the components of conventional door rings, adversely affecting the vehicle's aesthetics. The production process of conventional non-integrated door rings is cumbersome and inefficient due to the separate production and assembly of components.

Conventional non-integrated door rings exhibit limitations and issues such as structural complexity, safety concerns, maintenance difficulties, unattractive appearance, and low production efficiency. In contrast, integrated door rings can effectively address these problems, improving the safety performance, structural integrity, aesthetics, ease of maintenance, and production efficiency of vehicles.

2.2. *Advantages of the Integrated Hot Stamped Vehicle Door Ring*

The integrated door ring enhances the safety performance of the vehicle. In the event of a collision, the integrated door ring can better withstand impact forces and reduce deformation, thereby ensuring the safety of passengers inside the vehicle. The integrated door ring helps preserve the structural integrity of the vehicle. In accidents such as collisions or rollovers, the integrated door ring can better maintain the structural integrity of the vehicle and minimize damage to the main body structure. The integrated door ring plays a crucial role in improving the safety performance of the vehicle, maintaining structural integrity, facilitating maintenance, enhancing aesthetics, and improving production efficiency.

3. Laser Welded Plate Solution for Integrated Door Rings

This study focuses on the research and application of hot stamping technology for a specific vehicle model's body structure component, specifically investigating the material, process, and mold design of the core technology. The material used is B1500HS+AS, and its composition is shown in Table 1. The blank size design of the door ring is depicted in Figure 1, achieved by combining five different sheet combinations. All the combined sheets have a strength of 1500 MPa, but the thickness of each functional part varies. Part A has a thickness of 1.2mm, Part B is 1.2mm, Part C is 1.5mm, Part D is 1.8mm, and Part E is 1.4mm.

Table 1 Composition of Hot Stamped High Strength Steel B1500HS (w%)

C	Mn	P	S	Si	Al	Ti	B
0.2-0.25	1.1-1.4	<0.25	<0.008	0.15-0.35	>0.015	0.02-0.05	0.002-0.005

The specific forming process of the door ring is similar to the conventional hot stamping process of high-strength steel (22MnB5). The blank is initially heated in a furnace to 930°C and held for 350s to achieve a uniform fully austenitic structure. Subsequently, the blank is transferred to a press by a robot, and during the forming and holding stages, the temperature is maintained at around 700°C. The forming holding time is 20s to ensure the rapid transformation of austenite into fine martensite during the stamping process. The cooling system in the mold maintains a surface temperature of approximately 50°C, and rapid heat conduction cooling through the mold exceeds the ambient temperature at a rate of more than 27°C/Sec, enabling the formed part to obtain a fully martensitic structure. Figure 2 illustrates the layout design of the door ring plates' blanking. The use of laser welding eliminates the challenges associated with overall blanking and optimizes the plate layout. The weight of the material pieces is presented in Table 2. The total weight of the welded plates is 14.1 kg, compared to the conventional solution of 17.2 kg, resulting in an 18% weight reduction. The tooling cost is reduced by 19.6%, the component manufacturing cost is reduced by 7%, and the development cycle is reduced by 12.5%.

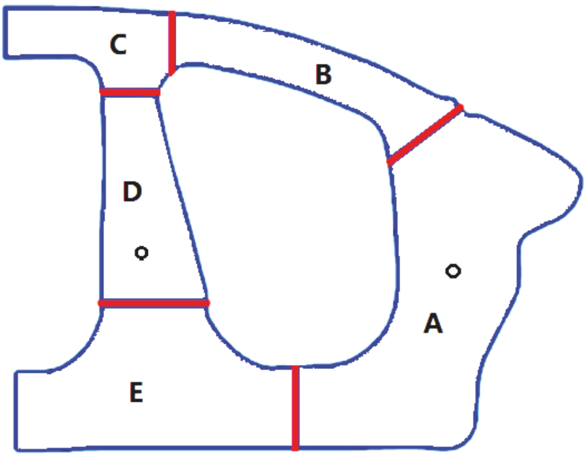

Figure 1. Blank size design of the door ring plates

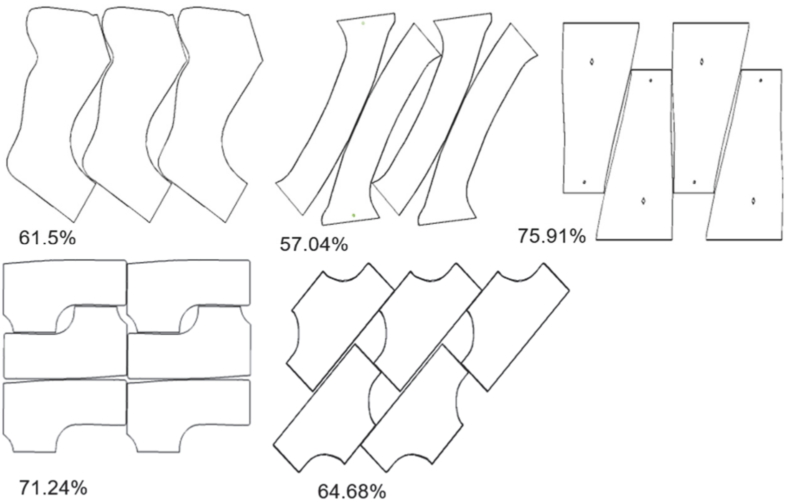

Figure 2. Blanking and utilization rate of spliced welded sheet materials

Table 2. Strength grade, thickness, and weight of the door ring welded plates

Welded Plate Area	Material	Thickness (mm)	Weight (kg)
Area A	B1500HS+AS	1.2	4.89
Area B	B1500HS+AS	1.2	1.10
Area C	B1500HS+AS	1.4	1.56
Area D	B1500HS+AS	1.8	2.45
Area E	B1500HS+AS	1.4	4.10
Total Weight	-	-	14.1

4. Mold Design for the Hot Stamping Process of the Integrated Door Ring

4.1. *Principles and Methods of Welded Plate Mold Design*

The design of the welded plate mold should adhere to specific principles and methods, taking into account various factors such as product requirements, production processes, material selection, and machining and debugging, to ensure the precision and performance of the mold.

Firstly, the structure and dimensions of the welded plate need to be determined based on product requirements and production processes, including the welding method. Secondly, the mold type and structure should be determined, considering the structure of large molds, the casting structure of the base, the mold steel for the concave and convex molds, and the mold frame. The appropriate mold material and surface treatment method should be selected based on product requirements and production processes to enhance the mold's lifespan and accuracy.

Finally, the mold design should be revised based on trial molding to address any deficiencies. The mold should be processed and debugged according to design requirements, ensuring the mold's precision and performance.

In conclusion, the design of the welded plate mold should adhere to specific principles and methods, considering various factors such as product requirements, production processes, material selection, machining and debugging, to ensure the precision and performance of the mold.

4.2. *Mold Design for the Laser Welded Plate Integrated Door Ring*

The design of the forming mold for laser-welded body door rings involves considering the structural characteristics of the laser-welded door rings and designing a rational thermal stamping process route. This includes determining the material pressing area, pressing force, pressing stroke, GAP clearance, and positioning. The forming process of the door ring is illustrated in Figure 3.

To ensure consistent cooling for the thermo-stamped parts, cooling simulation is conducted using the water flow-heat flow calculation method. The cooling rate and consistency of the workpieces are verified to prevent distortion and deformation of the thermo-stamped parts, while ensuring synchronized transformation of the microstructure of the billet under cooling conditions that aim to maintain the synchronous transformation of the microstructure of the billet as much as possible.

The water channel system design in Figure 4 consists of two main water channels, simulating water flow velocities ranging from 1.50 to 5.00m/sec, water channel diameters of 10-12mm, and a water temperature of 20°C. The average water flow velocity is 3.25m/sec. We redesigned the water channel system to have four independent main water channels (four inlets and four outlets) in order to design the sub-channel system with a total length of the independent water channels as close as possible. After optimization, the flow velocity of the water flow is 0.4-0.8m/sec, and the Reynolds number is 4000-8000. This is relatively close to the recommended flow rate in the literature.

Experimental mold trials have demonstrated that the designed water-cooling system can meet continuous production with a cycle time of 45 seconds when the mold temperature is in the range of 90-190°C.

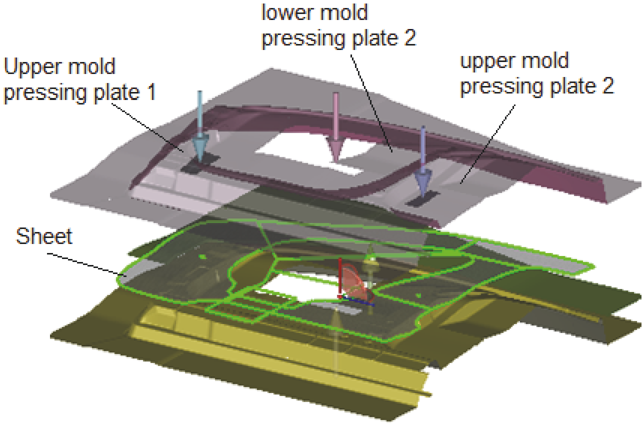

Figure 3. Schematic diagram of the forming process of the door ring

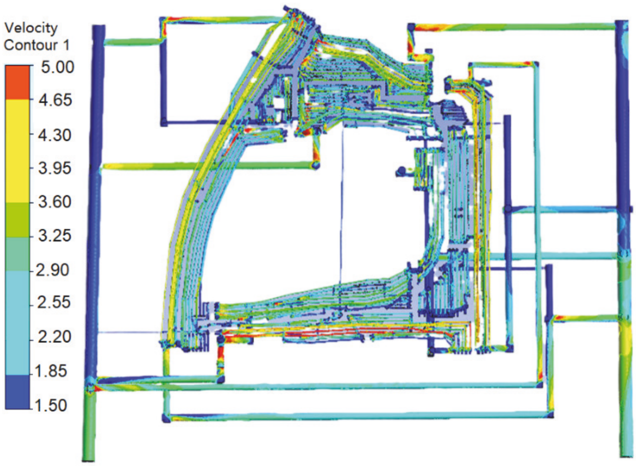

Figure 4. Simulation results of the cooling system for the door ring mold

According to the structural characteristics of the laser-welded door rings, CAE simulation is conducted to analyze the forming performance of the parts. Through water analysis, the mechanical properties of the mold after thermal forming are completely transformed, and the residual stress of the part transformation is eliminated to ensure the stability of the product production process. Simultaneously, the forming analysis of the product is carried out to ensure that the thinning rate of the product remains within 10%. Figure 5 illustrates the simulation results of the part wrinkling before and after optimization, as well as the actual mold trial results [6].

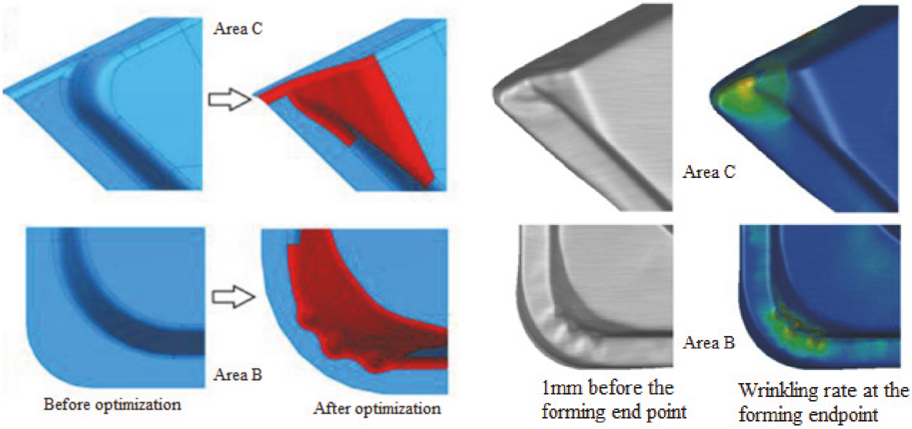

Figure 5: Comparison of simulation results before and after structural optimization

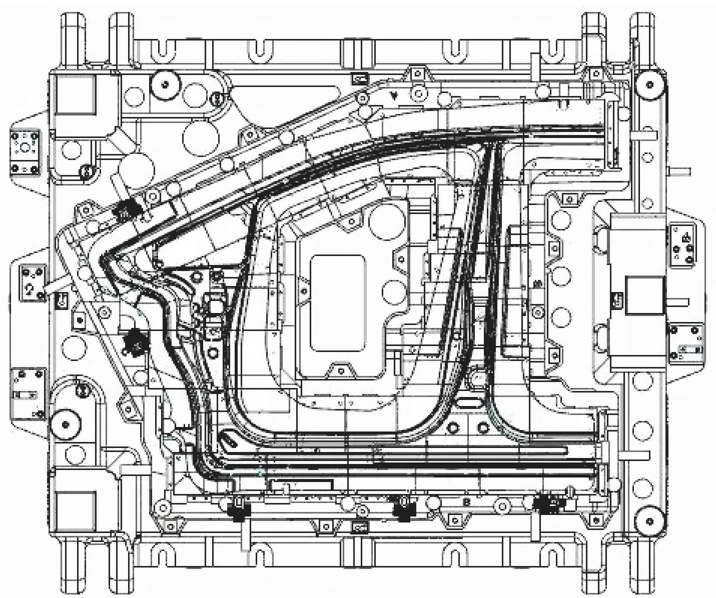

Figure 6. Structural diagram of door ring mold

The structure of the laser-welded door ring mold is comprehensively designed from multiple dimensions, including mold division, water channel design, positioning design, reference design, fixing method design, limit balance design, guiding design, and material return design. Figure 6 presents the structural diagram of the door ring mold. The mold steel used is D600, primarily composed of the following elements (W %): C, 0.47-0.51%; Si, 0.25-0.30%; Mn, 0.25-0.30%; Cr, 4.20-4.50%; Mo, 2.90-3.10%; V, 0.50-0.60%; Al, 0.01-0.03%; Fe, and other unavoidable impurities. The heat treatment process for samples of this mold involves heating to 1050-1080°C, oil cooling, and quenching to 50-80°C [7].

4.3. *Mechanical Property Testing of the Hot Stamped Door Ring Parts*

Figure 7 illustrates the sampling positions and sample numbers. Positions 3-7 are in the weld area for tensile testing, while the remaining positions are for tensile samples corresponding to different positions of the door ring components. Hardness positions 1-11 are located in the weld area. Table 3 presents the results of the strength and elongation tests for the door ring parts, while Table 4 displays the hardness test results for the weld area of the door ring parts. The test results indicate that the mechanical properties of the door ring components in various areas meet the design requirements, and the mechanical properties in the weld area also meet the required performance.

Figure 8 showcases the results of the three-dimensional dimensional measurement of the door ring. The test results indicate that the dimensional accuracy of various parts of the door ring meets the design requirements, and the pass rate for dimensional accuracy is above 98%.

Ensuring the production stability of laser-welded plate vehicle door rings requires considering various technical factors, including process route planning, performance simulation, mold performance simulation optimization, mold surface compensation, gap compensation, and mold engineering design. A multi-dimensional and comprehensive mold design is necessary to meet the mechanical properties, dimensional accuracy, and quality requirements of the door ring product for its use in various vehicle conditions and quality.

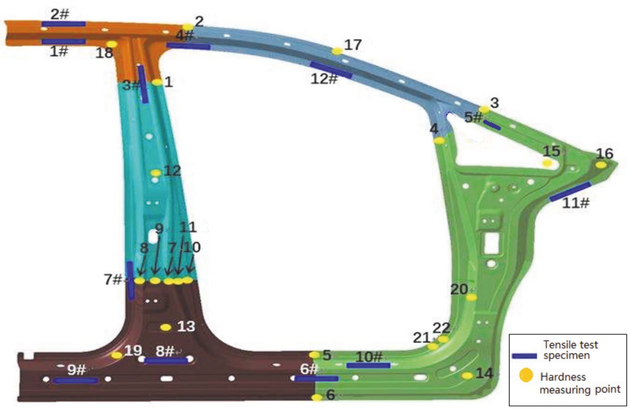

Figure 7. Sampling positions and sample numbers for the door ring

Table 3. Results of strength and elongation tests for the door ring parts

Test Number Standard Value	Tensile Strength (MPa) 1350-1650	Yield Strength (MPa) 950-1250	Elongation (%) A30≥6%
Position 1	1466	1197	7.9
Position 2	1464	1171	9.5
Position 3	1410	1227	6.4
Position 4	1379	1201	6.4
Position 5	1408	1162	6.6
Position 6	1425	1245	6.0
Position 7	1379	1200	7.2
Position 8	1440	1172	7.4
Position 9	1433	1180	7.1
Position 10	1439	1214	6.8
Position 11	1394	1245	7.4
Position 12	1463	1232	7.3

Table4 Hardness test results at the base material and circumferential weld of the integrated hot stamping door

Item	P 1	P 2	P3	P 4	P 5	P 6	Remark
	Standard Value ： HV1/HV10(410-520)						
1	471	475	479				Base Material
				489	491	490	Weld seam
2	462	467	470				Base Material
				471	469	473	Weld seam
3	482	485	480				Base Material
				472	468	467	Weld seam
4	472	470	467				Base Material
				471	475	468	Weld seam
5	503	501	504				Base Material
				467	465	473	Weld seam
6	497	494	490				Base Material
				489	481	490	Weld seam
7	486	483	481				Base Material
				471	477	479	Weld seam
8	487	488	483				Base Material
				425	441	450	Weld seam
9	477	470	472				Base Material
				481	475	479	Weld seam
10	480	487	486				Base Material
				483	488	486	Weld seam
11	467	474	470				Base Material
				465	468	467	Weld seam

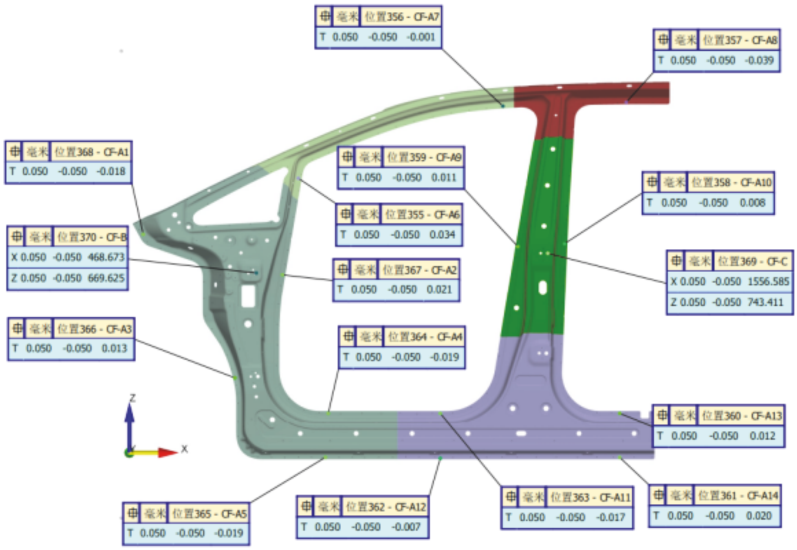

Figure 8. Results of the three-dimensional dimensional measurement of the door ring

5. Conclusion and Outlook

This paper has investigated the forming process and mold design of laser-welded plate vehicle door rings, as well as their application cases. It introduced the background of automotive lightweighting, advanced materials, and forming processes, and stated the purpose and significance of the research. The structure and functional requirements of the vehicle door ring were discussed in detail, and the limitations of traditional manufacturing methods were analyzed. The characteristics and advantages of laser-welded plates, as well as the forming process of laser-welded plate vehicle door rings, were explained. Taking the integrated hot stamping door ring of a specific vehicle model as an example, the mold design and testing methods required for the forming process of the vehicle door ring were studied based on the material and geometric characteristics of the laser-welded plate, and a design application plan was provided. Finally, through the summary of the actual research and application cases of this project, the application prospects of the forming process and mold design of laser-welded plate vehicle door rings were presented.

In the future, there are still areas for improvement and further research in the forming process and mold design of laser-welded plate vehicle door rings. Firstly, the material and process parameters of laser-welded plates can be further optimized to improve the strength and dimensional accuracy of the products. Secondly, mold design can be further improved to enhance the lifespan and production efficiency of the molds. Additionally, further exploration of the application of laser-welded plates in other body components to expand their application in automotive manufacturing can be conducted. Furthermore, the mechanical and durability properties of laser-welded plate vehicle door rings can be further studied to verify their reliability and stability in practical use.

In conclusion, the forming process and mold design of laser-welded plate vehicle door rings have broad development prospects and can provide more choices and solutions for automotive lightweighting and advanced manufacturing technology.

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