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Study on Key Joining Technology and Test Method of Steel/Al Hybrid Structure Body-in-White

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Abstract

Green and low carbon promote the application and development of lightweight materials in body-in-white. Large-scale die-casting Al alloy (DCAA) and high-strength thermo-formed steel sheet (TFSS) have put forward higher requirements for the application of joining technology of high-strength steel/Al dissimilar materials. Taking the new die-casting Al alloy body as an example, this paper systematically studies the progress of the latest joining methods of steel/Al dissimilar material with combination of two-layer plate and three-layer plate. By analyzing the joining technologies such as FSPR, RES, FDS and SPR, the technology and process characteristics of steel/Al dissimilar material joining are studied, and the joining technical feasibility and realization means of different material combination of the body are analyzed. The conditions of material combination, material thickness, material strength, flange height, preformed holes and joint spacing for achieving high-quality joining are given. The FSPR joining technology is developed and tested in order to meet with the joining of parts with DCAA and TFSS, especially for the joining of three-layer plates with them. It finds the method and technical basis for the realization of high quality joining of dissimilar materials, provides the early conditions for the application of large DCAA and TFSS parts in body-in-white, and meets the design requirements of new energy body.

Keywords

Body-in-White, Lightweight, Die-Casting Al Alloy, Thermo-Formed Steel, Joining

1. Introduction

Lightweight is the inevitable trend of body development, steel/Al hybrid structure is a significant feature of the future body, which can meet the requirements of safety and lightweight. The development and application of large DCAA and ultra-high TFSS parts can meet the needs of future body, improve the rigidity and strength of the body, and meet the safety of the car. It can also reduce the weight of the body obviously and simplify the process [1] [2] [3] [4] [5].

For the traditional body-in-white (BIW) materials, it is usually a joining of the same material, such as steel/steel joining. For these kinds of joining, the current welding methods can meet the requirements of product design. However, for the joining of dissimilar body materials such as steel/Al parts, there are a series of problems. Especially for the multi-layer plate joining of TFSS and DCAA parts, there is no mature, reliable and efficient joining method to realize the joining. As the most important resistance spot welding for body welding, it is difficult to realize the welding of steel/aluminum dissimilar materials, because hard and brittle intermetallic compounds will be generated in the joint area, reducing the fatigue strength of the joint. At present, only mechanical or riveting methods can be used to achieve joining of partial joint types [6] [7] [8].

For the current joining methods used for steel/Al materials, such as SPR and FDS, they are difficult to achieve two or three-layer plate joining of the TFSS and DCAA for their special strength and hardness. The strength of the TFSS is normally over 1500 MPa, and the hardness is over 55 HRC. The RES can realize some welding of them in special condition. For complex part combinations such as three-layer plates, more advanced and effective joining methods such as FSPR need to be developed and applied. For the joining of TFSS and DCAA, except for the newly developed RES technology, it is difficult to realize the joining with other joining methods. For the three-layer plate joining containing TFSS and DCAA, except the FSPR technology under development, the joint cannot be realized by other technologies at present. Therefore, it is of great significance to study the joining method of two- or three-layer plates containing TFSS and DCAA [9] [10] [11] [12].

Based on the above problems, this paper analyzes and studies the development trend, research direction and test methods of the related joining methods. In particular, the FSPR joining technology for TFSS and DCAA two-layer or three layer plates, is being developed, analyzed and studied.

2. Materials and Methods

With the application of DCAA structural parts, the body material is usually composed of DCAA, TFSS and other low-strength steel materials. The welded structure may face the welding of two or three layers of plates, and the welding plate combination may consist of TFSS + DCAA + other steel plates or DCAA + TFSS + other steel plates.

2.1. BIW Structure

Taking the steel/Al body of certain company as the research reference, the relevant steel/Al joining tests for the different material combination were carried out. The chassis structure of the body was similar to the rear structure of the Tesla floor, as shown in **Figure 1**, which was designed by large-scale DCAA part. DCAA, TFSS and other steel materials determine the choice of joining method and the complexity of joining process.

2.2. Materials

The materials tested in this paper include common steel, TFSS and DCAA, whose composition and mechanical properties are shown in **Tables 1-4**. The data comes from the German Volkswagen Materials Standard.

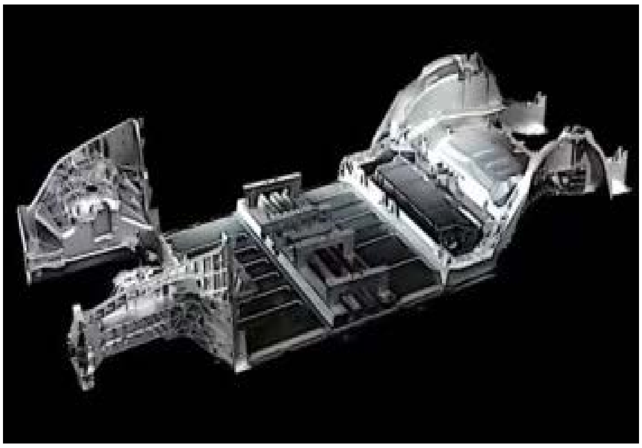


Figure 1. Large Al alloy die-casting underbody.

Table 1. Chemical composition of TL 4225 (w, %).

C	Mn	Si	Al	Ti	Cr	Ni	Mo
0.22 - 0.25	1.20 - 1.40	0.20 - 0.30	0.20 - 0.50	0.02 - 0.05	0.11 - 0.20	0.10	0.10

Table 2. Chemical composition of C611 (w, %).

Si	Mn	Mg	Fe	Zn	Cu	Zr	Ti	Na	Ca	Sr	Al
7.12	0.61	0.21	0.13	0.02	0.05	0.05	0.05	0.0001	0.0007	0.008	The rest

Table 3. Chemical composition of CR5 (w, %).

C	Si	Cu	P	Mn	S	Ti	Al	Fe
≤0.02	≤0.50	≤0.20	≤0.02	≤0.30	≤0.02	≤0.30	≥0.01	The rest

Table 4. Mechanical properties of TL4225, C611 and CR5.

Mechanical property	Yield strength/MPa	Tensile Strength/MPa	Hardness/HV	Elongation/%(A80)
TL 4225	1100% ± 5%	1475% ± 5%	400 - 520	≥5%
CR5	110 - 170	260 - 330	—	≥41%
C611	≤140	340% ± 5%	≤120	≥23%

2.3. Method of Joint Test

For BIW products, the test methods of joints include shear strength, tear strength and cross tensile strength. The tensile type and test sample design are shown in **Figure 2**.

Considering the workload of the test and the characteristics of the tensile test, only the tensile and tearing strength were analyzed in this test.

3. Key Joining Technology of Steel/Al BIW

3.1. Characteristics of NEV Body Material

The new energy vehicle must have the characteristics of lightweight and high strength. The application of steel/Al hybrid BIW of large DCAA and TFSS, such as the application of CTC or CTB technology, not only simplifies the body manufacturing process, but also strengthens the body strength.

The application of DCAA has led to the combination of dissimilar materials, such as steel/Al two-layer plate, steel/steel/Al, steel/Al/steel and Al/Al/steel and so on. The welding of steel/Al dissimilar materials, especially using methods such as resistance spot welding, will face a series of difficulties. New joining methods and innovative joining methods must be developed.

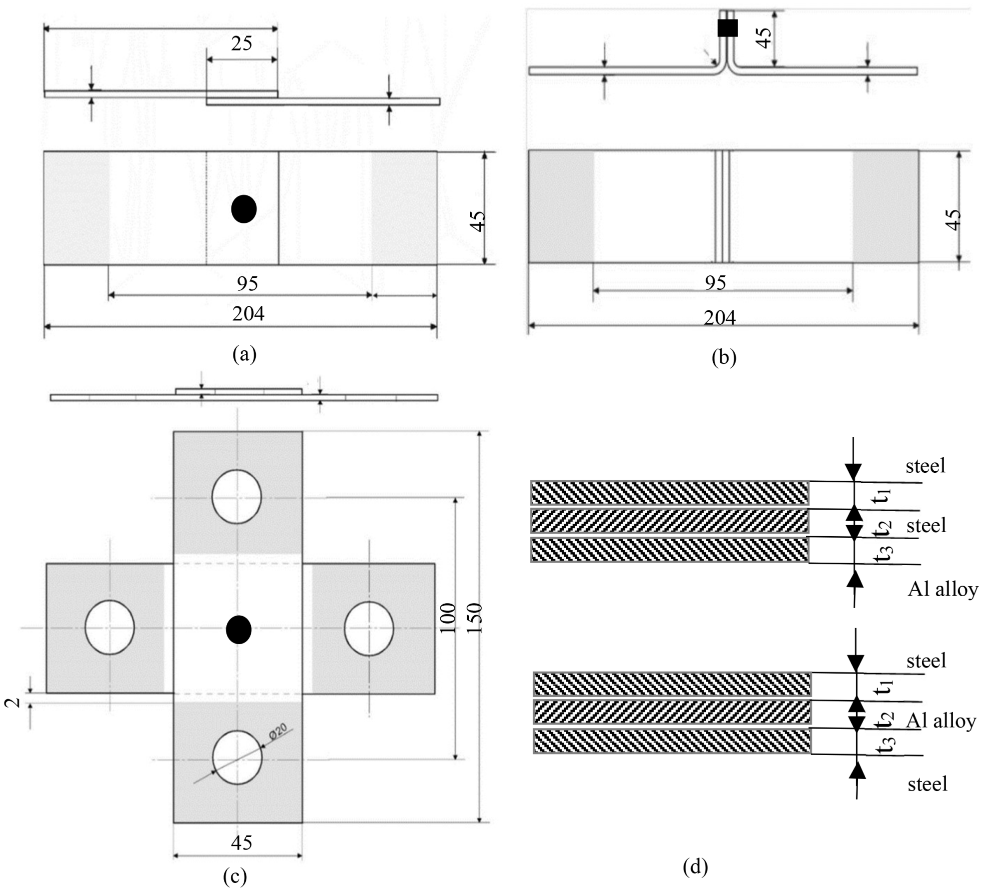


Figure 2. Test sample design of mechanical properties. (a) Shear strength sample; (b) Tear strength sample; (c) Cross test sample; (d) Types of plate combination.

Combined with the material distribution and thickness of DCAA, the DCAA is C611, the TFSS is TL 4225, and the covering material is CR5. Their thickness is 2 mm, 1 mm and 0.75 mm, respectively. The combination above is a common plate thickness of DCAA and peripheral parts.

3.2. Resistance Spot Welding

Medium frequency resistance spot welding (MFRSW) can solve almost all the joining of BIW steel plate, has mature process and quality standards. For joining of Al alloys, the joining can also be realized by using the MF or sub-high frequency power. At present, the application of MFRSW is applied mainly to the parts that bear non-dynamic loads, such as the joining of the battery housing. Due to the particularity of Al alloy spot welded joints, the fatigue strength is difficult to reach the level of steel materials, so the application is limited, and other joining methods must be used [13] [14] [15].

Due to the special material properties of DCAA, that is, it has a large affinity for water or hydrogen, it is easy to produce pores and hydrogen polymerization cracks in the process of welding. In addition, in view of the softening phenomenon of Al alloy material, namely, it is easy to produce a "plastic ring" in MFRSW process. The strength of the hot affected zone (HAZ) will be greatly reduced, resulting in breaking here. Therefore, it must be welded with the DC power, which has higher current density and shorter welding time. The welding time has an effect on the porosity and crack as well as the "plastic ring" of the HAZ. The relationship between the two phenomena must be balanced to choose the welding time reasonably. In addition, Al alloy spot welding also has the phenomenon of nugget core "shift", the nugget will shift to the anode side. It is because, for the Al alloy spot welding, the current is larger, the Peltier effect is more obvious, and namely, the anode side of the joint will produce more heat. The reason for this phenomenon is that the resistivity of Al alloy is low and the current is high during welding. On the other hand, the adhesion of the electrode cap surface during welding will generate P and N type semiconductor materials, such as various inter-metal compounds on its surface, triggering the physical conditions generated by the Peltier effect.

To solve the problem caused by the Peltier effect, the most effective technical means is to use variable-polarity power to eliminate the physical conditions of Peltier effect. In addition, if Peltier effect cannot be eliminated, the design of plate thickness combination should be considered reasonably.

3.3. Principle of RES Joining Technology

Medium frequency resistance spot welding (MFRSW) can solve almost all the joining of BIW steel plate, has mature process and quality standards. For joining of Al alloys, the joining can also be realized by using the MF or sub-high frequency power. At present, the application of MFRSW is applied mainly to the parts that bear non-dynamic loads, such as the joining of the battery housing.

Due to the particularity of Al alloy spot welded joints, the fatigue strength is difficult to reach the level of steel materials, so the application is limited, and other joining methods must be used [13] [14] [15]. RES (Friction element welding) is a new joining technology that can realize the welding of Al alloy and TFSS. It makes the "element" with high-speed rotation to penetrate the upper lower-hardness plate, and realizes the friction spot welding with the higher-hard plate such as TFSS. Through the principle of rotating friction melting, completes the welding of the "element" (steel) with the TFSS under the effect of pressure, and form a solid joining [16] [17] [18].

Its principle is shown in **Figure 3**. RES can solve the problem that the NEV DCAA cannot be joined with the TFSS, and can get the high quality joining of steel/Al dissimilar materials.

Because the yield strength of DCAA is not high, and has a high elongation, DCAA parts do not need prefabricated hole treatment. In principle, if the yield strength of the upper plate is higher than 780 MPa, prefabricated hole must be done, otherwise it is difficult to achieve RES connection.

RES can realize the connection of DACC and TFSS with higher joint strength. However, due to the influence of the yield strength of the light alloy side, it has certain limitations, the equipment price is high, and the process is relatively complicated.

3.4. Principle of FSPR Joining Technology

FSPR is a special riveting method. It is to send automatically a special rivet into the riveting head through riveting equipment. In the joining, the connected base

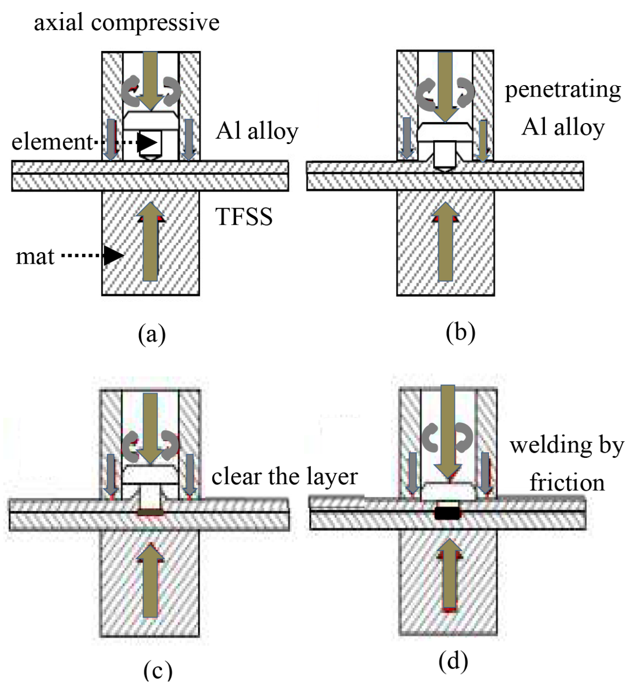


Figure 3. Principle of RES welding. (a) Preheating; (b) Penetrating; (c) Interface cleaning; (d) Friction welding.

metals are punched and discharged by the rivet, and then the lower die is squeezed around the rivet to form a reliable joining, the principle of FSPR shown as in **Figure 4**.

FSPR can rivet various materials, such as high-strength Al alloy, TFSS, etc. It can achieve multi-layer riveting and good forming effect. It can be used for joining whose joint appearance without convex hull after riveting. Punch riveting is completed at one time without pre-punch for the riveting hole, having fast riveting speed, high efficiency and stable riveting appearance. It has an irreplaceable role in solving the two-layer or three-layer plate joining between TFSS and DCAA.

The FSPR joining process must meet the following conditions:

Firstly, the thickness of the down plate is at least 1/3 of the total thickness of the plate combination. Secondly, the high-hardness material is on the punch side, and the low-hardness material is on the die side. Thirdly, the thin plate is on the punch side, and the thick plate is on the die side. In addition, the maximum strength of the upper plate can reach 1500 MPa. The harder the upper plate, the lower plate needs to have lower strength and better plasticity. There is a certain lower limit on the thickness. Moreover, the maximum strength of the lower plate cannot exceed 600 MPa.

The FSPR enables multi-layer riveting of DCAA and TFSS up to a total thickness of 9.1 mm. The joining appearance is good, and can be applied for covering parts. Punching and riveting is done in one go, without pre-punch the riveting hole. In addition, in terms of joint strength, the shear strength of the joint is

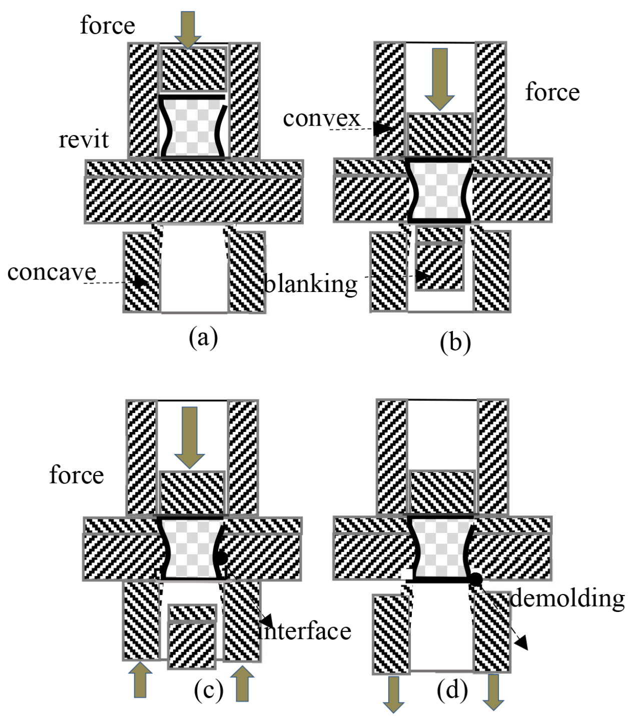


Figure 4. Principle of FSPR joining. (a) Workpiece pressing; (b) Punching nail embedding; (c) Extrusion forming; (d) Stripping.

high, and the riveted appearance is stable.

The FSPR can reduce the requirement for material elongation and can be applied to materials with less than 10% elongation. It is also suitable for scenes where the thickness of the die fluctuates on the material. In addition, FSPR rivets will not slip due to uneven material thickness, which will affect the joining strength.

SPR belongs to the material stretch forming, and FSPR belongs to the material compression forming. The material does not crack after the riveting is completed. The essence of material cracking in the riveting process is that the crack extends to the entire cross section that leads to the fracture. The crack expansion requires a certain intensity of tensile stress during the period. If the material is subjected to compressive stress, then the crack tip is not easy to reach the stress intensity required for crack expansion, the crack cannot expand, and the material will not be damaged.

3.5. Joining Technology of FDS

FDS is an effective method to join plate and blind structure, and has the characteristics of high welding efficiency. This method is suitable for the joining of steel/Al mixed structure with yield strength lower than 780 MPa. At present, the joining method is also in continuous innovation, and by some innovation, it is hoped to solve the joining of materials with yield strength of 980 MPa. The increase in material strength will inevitably affect the FDS welding head and drive motor, reduces life. For joining high-strength materials, there is no perfect process and quality standard at present and it needs to be further improved [19] [20] [21].

4. Test and Results

4.1. Research Method

4.1.1. Joining Method of Large DCAA Parts

Traditional BIW materials, mostly composed of steel material, even based on weight-reducing requirements, steel/Al alloy joint can be carried out by means of reasonable design of joining combination. SPR, FDS, spot welding and RES can realize joining.

In the application of large DCAA parts, in some areas, such as the B-column, the threshold and other collision areas, there will be three or even four layers of dissimilar material combinations. In these areas, a large number of TFSS and large DCAA parts will produce a variety of dissimilar plate combinations. "Sandwich" sheet combination, steel/steel/Al combination, etc., put forward higher technical requirements for SPR and FDS joining methods.

New materials and product structures require not only the improvement of existing joining technology, but also the development of new joining technology to solve the problem of special structural steel/Al combination joining.

4.1.2. Study on Weldability of Special Structures

Almost all the problems of traditional body joining can be solved, especially for the joining of homogeneous materials or low strength dissimilar materials. The development of NEV has put forward new requirements for materials and product structure, especially the applications of DCAA and TFSS, and the existing joining technologies are difficult to solve the problems, thus restricting the application of new materials.

By studying the materials and plate combination of the latest BIW, several types of them can be known as shown in **Figure 5**. The innovation of the existing joining technologies and the development of new technologies are based on them.

FDS and SPR have been constantly innovating with the needs of products, especially continuously meeting the requirements of new materials and structure body. When the joining technologies cannot meet certain requirements of product design and material combinations, they will promote the generation of new joining methods and processes. RES, FSPR and other joining methods are developed and applied under this condition.

The application boundaries of each method are constantly expanding and deepening, for example, SPR. The generation of SPR is mainly to solve the joining of BIW covering parts. So its main application scenarios are generally the joining of steel or steel/Al dissimilar materials with strength levels lower than 780 MPa. It has been widely used and developed in this field. However, in view of the joining characteristics of SPR, it is hoped that it can join the dissimilar materials with higher strength, greater thickness, and even more plate combinations. Therefore, the innovation of SPR technology has been ongoing.

4.2. FSPR Test and Results

As a new joining method, FSPR is still in the stage of laboratory testing and local

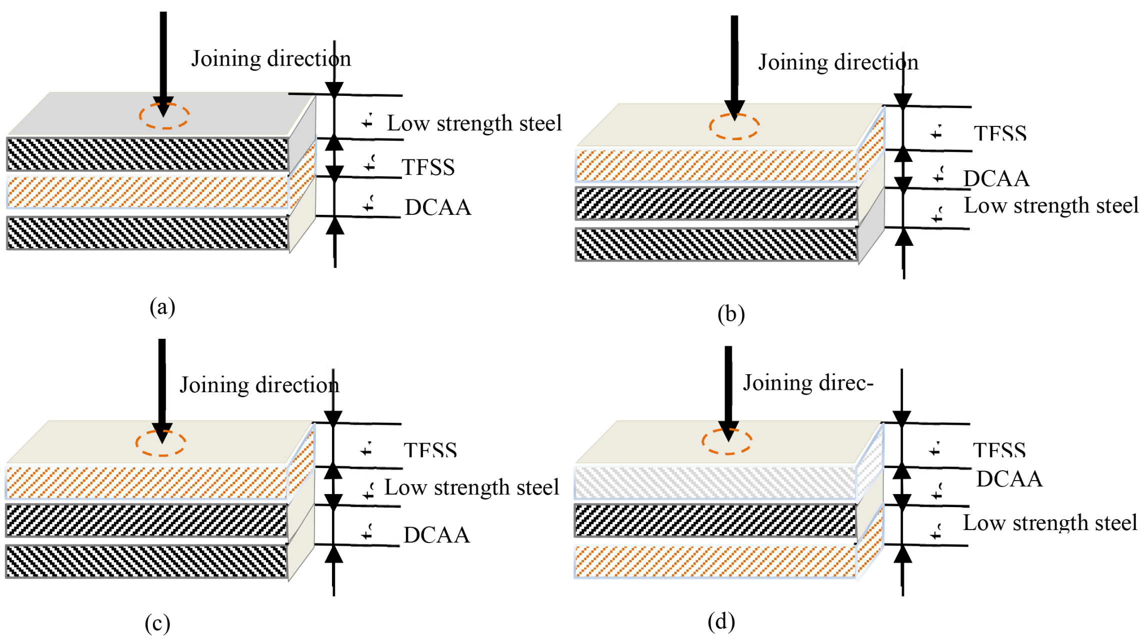
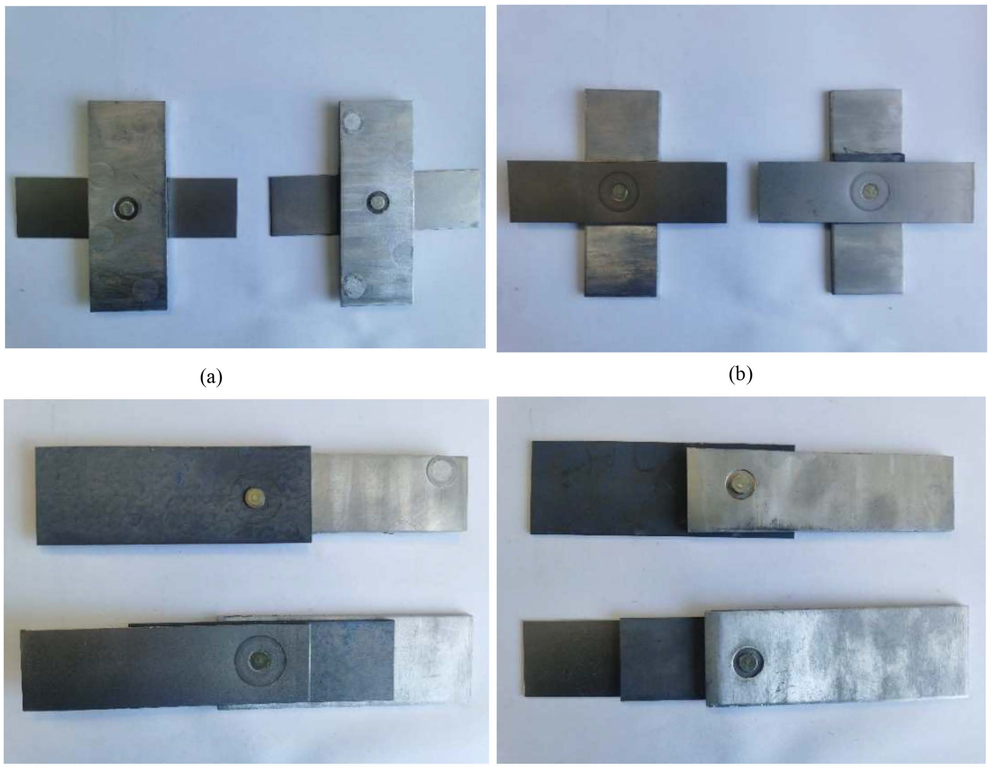


Figure 5. Key plate combinations of lightweight BIW. (a) Low strength steel/TFSS/DCAA; (b) TFSS/DCAA/Low strength steel; (c) TFSS/low strength steel/DCAA; (d) TFSS/DCAA/low strength steel.

application in BIW, some experiments were done in order to set up the process and quality standards. The test samples are shown in **Figure 6**.

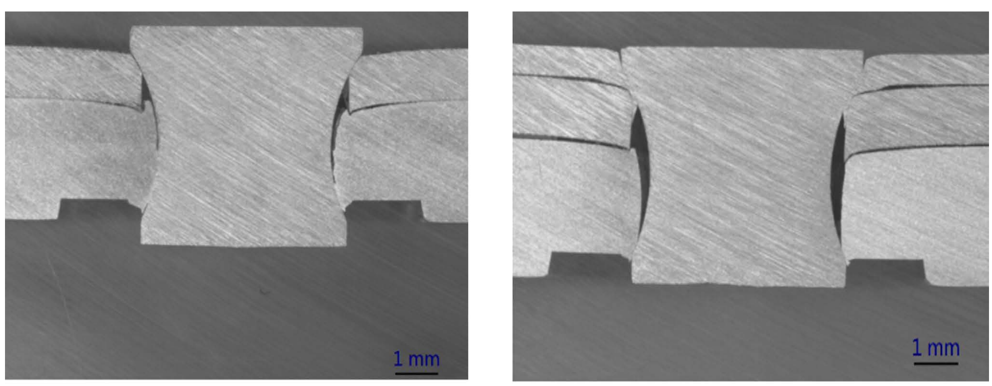
The test carried out the joining of TFSS and DCAA with two-layer plate, as well as the three-layer plate of TFSS, DCAA and covering plate, which is the most common plate combination. The strength and surface state have different requirements, for other joining methods, they are difficult to meet the requirements of product design.

The FSPR joints of two- and three-layer plates are shown in **Figure 7**, from which the final forming results and joint morphology of the joint can be seen.



(a) (b) (c) (d)

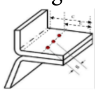
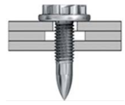
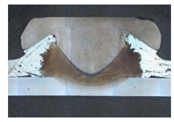
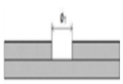
Figure 6. Joints of FSPR. (a) Cross joint (front); (b) Cross joint (back); (c) Stretch joint (front); (d) Stretch joint (back).



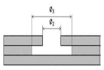
(a) (b)

Figure 7. Joint metallographies. (a) Two-layer plate joint; (b) three-layer plate joint.

Table 5. Design principles of steel/Al body joining.

Joining method Schematic diagram of joint 				SPR 	FDS 	RES 	FSPR 
Joint of two-layer	Material interval of joint			TL 4225/C611			
				22 mm	20 mm	20 mm	>16.5 mm
	Strength	Al alloy	δ_{min}	Strength is not required, elongation has certain requirements, generally should be >8%	Not require	150 MPa	<600 MPa
			δ_{max}			320 MPa	
		Steel	δ_{min}	Not require	<780 MPa	>270 MPa	<1800 MPa
			δ_{max}	<1600 MPa		<1800 MPa	
	Thickness	Steel	t_{min}	Cold-formed sheets are generally not required	<1.5 mm (780 MPa)	0.8 mm	t_1 < 2 mm (1800 MPa)
			t_{max}	1.7 mm (1600 MPa)		3 mm	
		Al alloy	t_{min}	>0.8 mm	Do not do special requirements, meet the total thickness requirements	1 mm	< $(t_1 + t_2)/3$
			t_{max}	Abide by $t_1 + t_3 + t_3 < 6.5$ mm		4 mm	
		Total		6.5 mm	<7 mm (Based on the length of the rivet)	<6 mm	<5.3mm
	Flange 	Steel	t_{min} t_{max}	E > 7.5 mm, C > 15 mm	E > 10 mm, C > 20 mm	E > 7 mm, C > 14 mm	E > 8 mm, C > 16.8
		Al alloy	t_{min} t_{max}	E > 12.5 mm, C > 20 mm	E > 10 mm, C > 20 mm	E > 7 mm, C > 14 mm	E > 15 mm, C > 30 mm
	Preformed hole 	Steel	t_{min} t_{max}	Not require	<1.0 mm (340 MPa)	no	Not require
		Al alloy	t_{min} t_{max}	Not require		Don't need prehole, according to product requirements	Not require
Joint of three-layer	Material interval of joint			TL 4225/CR5/C611			
				22 mm	20 mm	60 - 70 mm	>16.5 mm
	Strength	Al alloy	δ_{min}	Strength is not required, elongation has certain requirements, generally should be >8%	Not require	>150 MPa	<600 MPa
			δ_{max}			<320 MPa	
		Steel	δ_{min}	Not require	<780 MPa	>270 MPa	<1800 MPa
			δ_{max}	<780 MPa		<1800 MPa	

Continued

Thickness	Steel	t_{min}	<1.7 mm (1600 MPa)	<1.5 mm (780 MPa)	0.8 mm	$t_1 < 2$ mm (1800 MPa)
		t_{max}			3 mm	
	Al alloy	t_{min}	>0.8 mm (底层)	Do not do special requirements, meet the total thickness requirements	1 mm	$< (t_1 + t_2 + t_3)/3$
		t_{max}	Abide by $t_1 + t_2 + t_3 < 6.5$ mm		4 mm	
	Total		6.5 mm		<7 mm	<9 mm
Flange	Steel	t_{min}	E > 7.5 mm, C > 15 mm	E>10mm, C>20mm	E > 7 mm, C > 14 mm	E > 8 mm, C > 16.8
		t_{max}				
	Al alloy	t_{min}	E > 12.5 mm, C > 20 mm	E > 15 mm, C > 25 mm	E > 7 mm, C > 14 mm	E > 10 mm, C25
		t_{max}				
Preformed hole 	Steel	t_{min}	Not require	Hole requirements: the first layer of plate is diameter +2 - 3 mm; Middle layer top layer +2 mm	Depending on the thickness, the first layer is required, diameter +2 - 3 mm	Not require
		t_{max}				
	Al alloy	t_{min}	Not require			Not require
		t_{max}				

Through the action of the forming die, the metal of the rivet attachment at the end of the die has local plastic deformation and squeegees into the gap at the side depression of the rivet, thus forming the effect of riveting.

As can be seen from the figure, the TFSS has less deformation due to its high hardness and yield strength, and the gap filling in its corresponding region is supplemented to a certain extent by the deformation of low-strength materials such as DCAA below.

Through the strength test, the tensile and shear strength of the joint with two layers can be obtained: 7500 - 9000 N and 3500 - 4000 N respectively. The tensile strength and shear strength of the joint with three layers are 2000 - 2200 N and 400 - 500 N, respectively.

For the shear strength of the three-layer plate, it is characterized by the strength of the outermost steel plate. Because of its thin thickness, the strength of the base metal is also low, so the strength of the joint is not high, especially for the shear strength, the reduction is more obvious. However, for covering parts, there is no need for the outer plate and the assembly to have higher strength.

As can be seen from **Figure 7**, the filling of the arc gap around the rivet has an important impact on the strength of the joint, especially the tearing strength. It is also of great significance to study the relationship between the filling amount and the feeding depth of the forming die, as well as the influence of the elastoplastic deformation of the DCAA and the TFSS part on the filling, if a physical and mathematical model can be established to reflect the internal relationship. This simplifies the selection of process parameters.

Through joint strength and welding accessibility test, general laws such as joint spacing, flange edge, strength, ratio of elongation and thickness in the joining methods such as FSPR, SPR, FDS and RES, can be summarized, as shown in **Table 5**.

Data verification and analysis has been done for two-layer plate and three-layer plate.

This is very important, if these parameters or material selections are not reasonable, it will bring a huge impact on the choice of welding methods, the complexity of the welding process, the weldability of the joint and the quality of the joint, and even difficult to achieve the high quality of the product joints. Therefore, the verification and subsequent improvement of these parameters are of great significance for the future development of the body.

5. Conclusions

In this paper, the key joining technologies and application scenarios of lightweight body with large DCAA parts are systematically analyzed, and the research method of FSPR is studied and verified, and the weldability of FSPR joint of the main material combination DCAA + TFSS + other steel plate structure is analyzed, and the following conclusions are obtained:

1) This paper studies two-layer plate and three-layer plate joining solutions of steel/Al hybrid body of the NEV. The principle and process of the newly developed joining technology are analyzed. The weldability analysis of the joint is studied, and the most advanced joining methods of steel/Al hybrid structure are given.

2) The technical principles and characteristics of FSPR were analyzed, and a systematic analysis was carried out for the solution of two-layer steel/Al connection and three-layer steel/Al hybrid joining. In combination with the characteristics of the plate and the characteristics of the product, the product design and material properties, as well as the related weldability of the joint were tested and analyzed. Through the analysis and verification of this test, it can solve the joining of the hybrid body structure using large DCAA and TFSS parts, and meet the requirements of product design.

3) For the welding of plates containing DCAA and TFSS, this paper gives the requirements of SPR, FDS, RES and FSPR joining technology on parameters such as flange size, elongation, yield strength, joint spacing and plate thickness, which has guiding significance for product joint size design and material selection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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