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REVIEW PAPER

Progress in automobile body processing technology: multi-material and lightweight strategies for saving energy and reducing emissions

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Abstract
The automobile industry is an important pillar of the national economy. In response to the increasingly serious problems of energy depletion and environmental pollution, saving energy consumption and reducing pollutant emissions have become urgent requirements for the automotive industry. The most important solution at present is to reduce the weight of the car body through the application of new and multiple materials. As far as the structural materials of automobiles are concerned, they have been developed from traditional steel and aluminum to high-strength steel, high-strength aluminum alloy, fiber-reinforced polymer matrix composite (PMC), ceramic matrix composite (CMC), and other new materials. The advancement of materials and processing methods has greatly contributed to the overall safety and performance improvement of vehicles. However, the main challenges faced by the automobile industry during this transition include higher manufacturing costs for new materials, lower production efficiency, and greater difficulty in material recycling. Correspondingly, in this review, we try to explore the processing methods that have been improved in recent years and outlook the challenges that the automobile industry is facing.

Keywords Body molding · Multi-material · Lightweight · Automotive materials · Processing technology

Abbreviations

3D	Three-dimensional
AM	Additive manufacturing
BHF	Blank holder force
BIW	Body in white
BJ	Binder jetting
BPD	Blown powder deposition
CAD	Computer-aided design
CAE	Computer-aided engineering
CF	Carbon fiber
CFRP	Carbon fiber-reinforced polymer
CMC	Ceramic matrix composite
CO_2	Carbon dioxide
DC	Direct current
DED	Direct energy deposition
EBM	Electron beam melting
FML	Fiber/metal laminate
GF	Glass fiber
GFRP	Glass fiber-reinforced polymer
HPRTM	High-pressure resin transfer molding
ME	Material extrusion
NNS	Near-net shape
NX	Next generation
PA6	Polyamide 6
PBF	Powder bed fusion
PET	Polyethylene terephthalate
PMC	Polymer matrix composite
PP	Polypropylene
RVE	Representative volume element
SiC	Silicon carbide
SLM	Selective laser melting
TEM	Transmission electron microscope
TEMP	Thermal expansion molding process

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THTB	Tailor heat-treated blank
TRB	Tailor-rolled blank
TWB	Tailor-welded blank
WAAM	Wire arc additive manufacturing
WCM	Wet compression molding
Y_2O_3_SiO_2	Yttrium trioxide–silicon dioxide

1 Introduction

The automobile industry is one of the important pillar industries of the national economy, and it reflects a country's high-end manufacturing technology level with outstanding demand for high-tech and financial talents [1]. In the past half century, energy depletion and environmental pollution have become increasingly serious, especially in the developing countries [2]. Vigorously promoting electric vehicles that use batteries as the main energy source and restricting the production of fuel vehicles are being adopted by more and more countries as their basic policies, and the developed countries such as the US, Europe, and Japan have formulated specific timetables [3]. As an interim measure, hybrid vehicles equipped with both fuel and batteries are also becoming popular [4]. Whether it is a fuel vehicle, an electric vehicle, or a hybrid vehicle, reducing its body weight and improving its driving safety have become urgent needs for the automobile industry [5].

As far as the structural materials of automobiles are concerned, the traditional automobiles mainly use steel and iron materials [6], and then, their titanium–magnesium alloys were prepared to provide better mechanical properties with lighter weight. Currently, a large number of new materials such as the high-strength steel, high-strength aluminum alloy, polymer matrix composite (PMC), and ceramic matrix composite (CMC) are increasingly being used in automobiles, and some of them are originally borrowed from the aerospace industry [7–9]. Matching the application of these new materials, traditional steel stamping and welding technologies certainly cannot meet the needs of multiple materials, and new processing and forming technologies urgently need to be developed [10, 11].

The advancement of materials and processing methods has greatly contributed to the overall safety and performance improvement of vehicles. Firstly, the lightweighting brought by new materials can improve the vehicle's carrying capacity, driving speed, and mileage. Secondly, the improvement of the vehicle's mechanical performance brought by new processing methods is conducive to the increase in passenger safety factor. However, the main challenges faced by the automobile industry during this transition include higher manufacturing costs for new materials (due to the more complex production processes, longer production time, and higher raw material costs), lower production efficiency (due to the more complex production processes requiring multiple steps), and greater difficulty in material recycling (due to the more complex composition).

Based on this background, and by searching the journal publications in recent years, we attempt to explore and summarize the improvements in processing and molding methods and technology for the body materials in the automotive industry made by the scientific research community and industry, as well as the new methods that they have developed. The specific content in this review will be divided into three sections as shown in Fig. 1. In the first section, for the overall construction of the car body, the modular configuration and non-standard cam design systems will be discussed; while for the preparation of parts, the tailor-rolled blank (TRB) and the additive manufacturing (AM) of high-entropy alloy components will be discussed. In the second section concerning the forming process of different body materials, the laser welding technology, tailor-welded blank (TWB), three-dimensional (3D) thermal bending, and direct quenching will be discussed for the processing of steel materials; the hot stamping technology, rigid-flexible coupling forming, and selective laser melting (SLM) will be discussed for other metal materials such as aluminum and titanium; the special design and the mechanical issues of its connection with steel parts such as pins and bolts will be discussed for the PMC materials; while a new type of AM technique and diamond abrasive wire cutting technology will be discussed for the CMC materials. In the third section, for the simultaneous use of multiple materials, the deep drawing forming of fiber/metal laminate (FML) and the mechanical

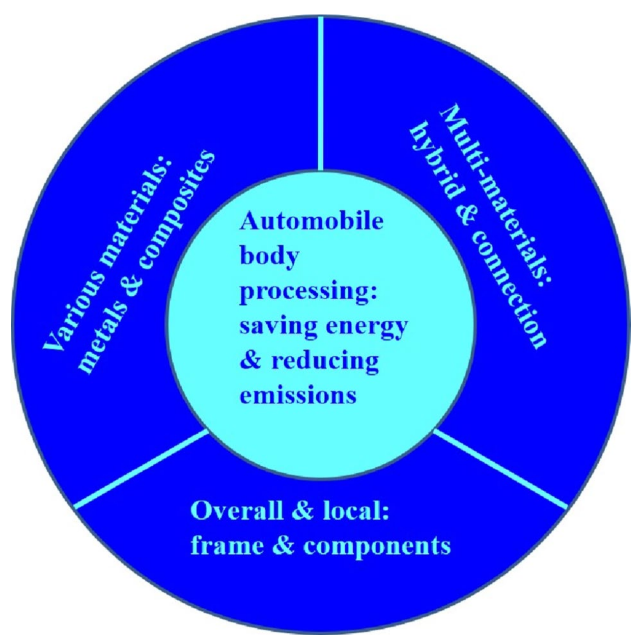


Fig. 1 Schematic presentation of the main content of this review

properties of metal/polymer fiber core micro-sandwich panels will be discussed; while for the connection of different materials, the shear clinching technology, tailor heat-treated blank (THTB), two-stage welding process, flat clinching, and lug connection structures will be discussed. At the end of this review, there will be a brief conclusion and outlook on all the above content. This review is expected to provide some theoretical guidance and practical basis for the further development of the automotive industry.

2 Overall molding of automobile body and preparation of parts

A car is composed of a body and thousands of different parts. The body is the largest part of the car and the basis for other parts to depend on. The performance matching between them is an important issue to be considered in the construction of the entire vehicle, and the overall weight reduction of the vehicle is also achieved through the synergy of the body and components [12, 13]. In this section, the different processing and forming characteristics of the entire body and parts will be mainly discussed.

2.1 Overall forming of the automobile body

The frame is the skeleton of the car and the largest component of the body and the basis for attachment of other components. Its main function is to absorb the static and dynamic loads acting on the car, so it requires sufficiently high strength and toughness. In order to ensure the safety of passengers, reinforcement and toughening are the main directions to improve the mechanical performance of the frame. Regarding the frame, an important concept is body in white (BIW), which refers to a specific stage in automobile design and manufacturing. At this stage, the sheet metal parts of the body have been welded together, but the moving parts (such as doors, hood, decklids, fenders, etc.), electric motors, chassis subassemblies, and trim parts (such as glass, seats, interior trim, electronic equipment, etc.) have not been installed and have not been painted [14].

Traditionally, the standard frame structures are manufactured by welding (including manual arc welding, gas shielded welding, laser welding, etc.) separate tubes, which makes some maintenance operations difficult because the traditional welding techniques make it very difficult to enter some internal areas of the vehicle; while modular configurations can solve these maintenance problems. For example, Acanfora et al. proposed an innovative modular frame concept by using the custom additively manufactured steel joints to design a modular frame [15]. They also combined Abaqus finite element numerical simulations and tested the torsional stiffness to demonstrate the feasibility of the modular frame with a synergistic composite shell. Figure 2 shows the numerical modular frame model with and without this collaborative composite shell (the geometric dimensions: 307 mm × 330 mm × 2 mm). The enhanced performance and structural integrity of the modular frame by using the collaborative composite shell is through the replacement of the point force by the surface force. As a result, the torsional stiffness is increased, and the out-of-plane displacement is reduced. Therefore, the new concept can also achieve the multi-purpose configurations by replacing modules, achieving the goals of

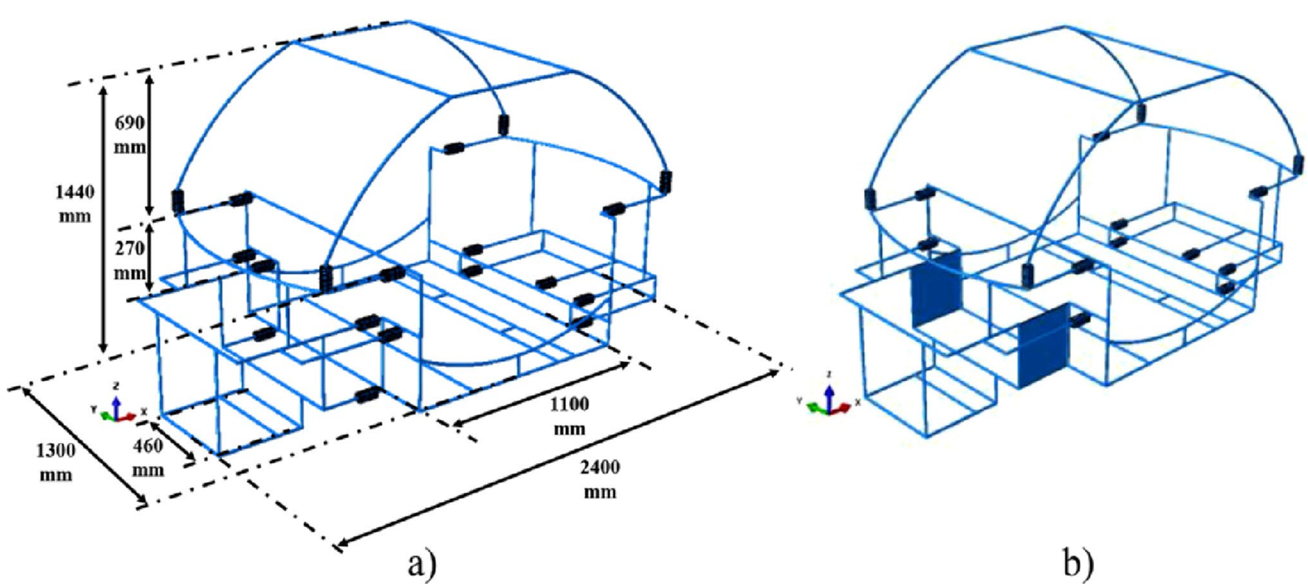


Fig. 2 Modular frame without (**a**) and with (**b**) collaborative composite shells (reproduced with permission from [15])

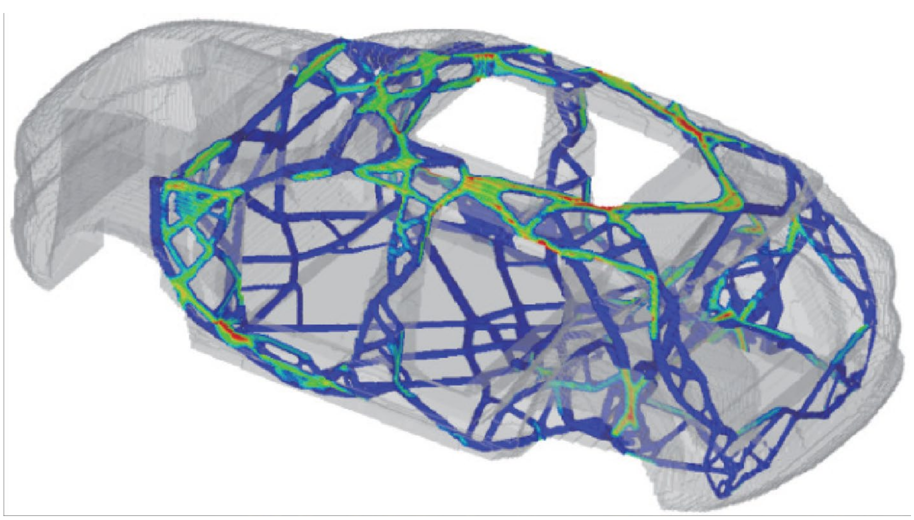
both enhancing the mechanical performance and reducing the overall weight. Their findings have potential benefits for the weight reduction and mechanical enhancement of the vehicle structures, as well as the simplification and shortening of vehicle preparation processes. The further work could be to optimize the structural design based on the numerical simulation results, including the geometric dimensions and placement positions of the modules.

To achieve the rapid parametric modeling of vehicle bodies, implicit parametric modeling technology has been applied in the conceptual development and detailed design stages. It mainly adopts a parametric description method of geometric expression, which intuitively expresses parametric models through the most basic geometric elements: points, lines, and surfaces, rather than transforming them into complex mathematical relationships. The biggest difference between it and explicit parametric modeling is that the assembly relationships between the components in its model are mainly established through mapping. This avoids the problems such as grid distortion, assembly relationship failure, and mutual interference, ensuring that the parametric modeling can automatically perform closed-loop optimization calculations. In addition, it can seamlessly transform the modified computer-aided design (CAD) parameter models into the computer-aided engineering (CAE) analysis models, effectively shortening the development cycle of BIW. The multidisciplinary collaborative optimization algorithm decomposes a complex objective function into simple sub-objective functions and then collaboratively optimizes these sub-objective functions, that is, while optimizing each sub-objective function, it comprehensively considers the results of other sub-objective functions, so that the optimization results between sub-objective functions can be consistent. The sequential quadratic programming algorithm and multidisciplinary collaborative optimization algorithm can be combined to find the optimal section size and thickness, so as to reduce the BIW mass without reducing the basic performance.

For the lightweighting of automobile bodies, Zhu et al. proposed a structural lightweight design model based on sequential quadratic programming algorithm, which could minimize the body weight without reducing the BIW performance (i.e., bending and torsional stiffness) [14]. As shown in Fig. 3, during the conceptual design stage of BIW, topology technology was used to determine its load transfer path, and then, the implicit parametric modeling technology was combined to establish a full-parameter model, and the cross-sectional size, position, and thickness of the lower body were determined through a multidisciplinary optimization method. Finally, the sequential quadratic programming algorithm was combined with the multidisciplinary collaborative optimization algorithm to perform the multi-objective optimization design of the BIW structure, thereby obtaining the Pareto optimal solution set. The sequential quadratic programming algorithm is to solve one or several quadratic programming subproblems at a certain approximate solution of the problem, and then use the solutions of these subproblems to find better approximate solutions. The results showed that this topology optimization technology could be applied in the early stages of body design to provide design guidance for design engineers. In addition, the body performance could be improved through structural replacement, and the lightweight of the body could be achieved by optimizing the cross-sectional size and thickness. Their work showed that the weight of the vehicle body could be reduced from 425.7 to 421.6 kg, with a weight reduction of about 1 wt%.

The parameterization of non-standard cams is complicated, the automatic design is difficult, and the preparation cost is also high. Therefore, the cam mold is the most complex type of automotive panel stamping mold. Li et al. developed a non-standard cam design system for automotive panel molds based on feature reuse and group

Fig. 3 Topology optimization results of BIW (reproduced with permission from [14])



assembly technology [16]. As shown in Fig. 4, the upper part of the side body is a large arc shape, which is welded together with the other three panels (front windshield, roof, and rear windshield). Due to the relatively large arc and length, one huge non-standard cam cannot complete the entire process, but three medium non-standard cams corresponding to the overlapping panels are required. Except for these three key positions, the others are collectively called “other positions,” in which the standard cams can be used. The system leverages a well-organized design case history knowledge base and feature library, and seamlessly integrates with the next-generation (NX) operating platform to generate cammed mold base designs in the form of an assembly. The system can also realize the external structure design of non-standard cams and can improve the design efficiency of non-standard cams in automotive panel stamping molds, thus greatly reducing the time and cost of mold manufacturing.

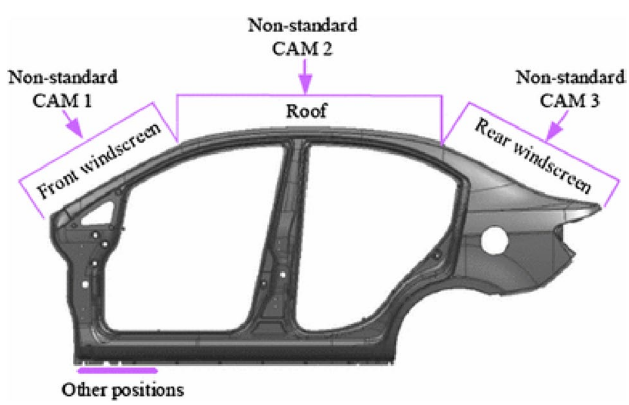


Fig. 4 Analysis of the cam design features in the sedan side body outer panel (reproduced with permission from [16])

2.2 Preparation of parts

At present, most parts of automobile bodies are made of metal sheets, and generally, the load-bearing capacity is not large, so there is still room for optimization and weight reduction. For example, Klinke et al. used the TRB strategy to further reduce the sheet thickness of components in less loaded areas, thereby achieving weight reduction [17]. Specifically, they proposed a priori selection method taking into account the computational effort of optimization in the case of crash loads, then selected the correct candidate component based on the formal engineering rules, and finally evaluated the load non-uniformity based on that component.

The unique and excellent mechanical and environmental resistance properties of high-entropy alloys allow them to be used in various harsh conditions, so they have good application prospects in the automotive industry. However, its traditional production processes, such as arc melting, mechanical alloying, plasma sintering, and physical vapor deposition, all have shortcomings such as complex production processes and high costs. The AM technology has received great attention in recent years (as shown in Fig. 5) and can also be used to produce high-entropy alloy components. Ron et al. had a good review on this aspect [18] and pointed out that the AM technologies that could be used for high-entropy alloys mainly included powder bed fusion (PBF), direct energy deposition (DED), material extrusion (ME) and binder jetting (BJ), etc. Among them, the PBF technologies, such as SLM and electron beam melting (EBM), can be widely used to produce high-entropy alloy parts with good dimensional accuracy and surface finish; while the DED technologies with higher deposition rate, such as blown powder deposition (BPD) and wire arc additive manufacturing (WAAM), can be used to produce large custom parts with relatively low surface finishes; the ME and BJ technologies can be used to produce the green body that subsequently requires sintering

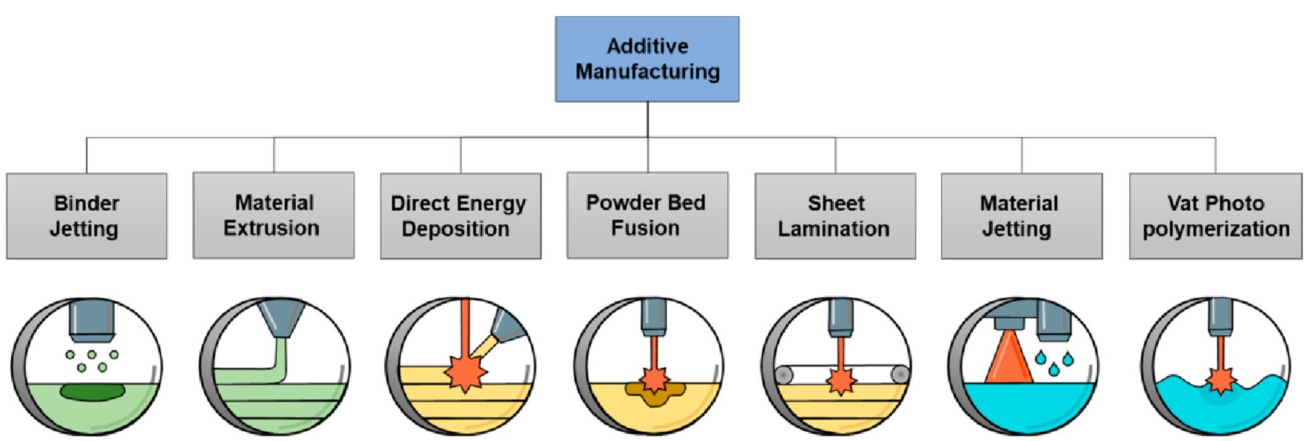


Fig. 5 Main types of AM processes according to ASTM F2792-12a (reproduced with permission from [18])

to obtain sufficient density. They also pointed out that the AM provided the possibility to manufacture complex-shaped devices, but the microstructure and mechanical properties of the devices prepared were significantly affected by the production process and post-processing. They also highlighted the good economic feasibility of using raw materials in the form of mixed element powders or wires rather than prealloyed materials.

3 Processing and shaping of different body materials

The thermal transition temperatures of different body materials, such as steel and iron (about 1500 °C), aluminum (about 660 °C), titanium–magnesium alloys (about 1300 °C), ceramics (about 1000–1700 °C), and polymers (about 100–350 °C), vary greatly, reaching hundreds and even thousands of °C, so their mechanical properties at the same temperature also vary widely [19]. More importantly, the different thermal transition temperatures of different materials lead to very different processing temperatures and molding equipment [20]. Processing different materials at the same time poses great challenges to the processing methods and techniques. In this section, the processing and forming characteristics of different materials will be examined.

3.1 Processing and shaping of steel and iron materials

As an advanced welding technology for opto-electromechanical integration, the laser welding technology has advantages over traditional automotive body welding technology, such as high-energy density, fast welding speed, low welding stress and deformation, and good flexibility. It can adapt to the welding of automobile body components with different joint forms, thicknesses, and material types, meeting the flexibility requirements of automobile body manufacturing. Its main types include laser deep penetration welding, laser wire filling welding, laser brazing welding, laser-arc composite welding, laser spot welding, laser swing welding, multi-laser beam welding, and laser flying welding. The laser welding technology can achieve the high-quality welding of commonly used automobile body materials such as steel and iron, aluminum alloys, and magnesium alloys, which is of great significance in promoting the development of lightweight automobile bodies and flexible manufacturing. Based on the characteristics of the automobile body structure and materials, Wang et al. introduced in detail the principles of laser welding processes and pointed out that the lightweight of automobile bodies had led to the wider use of new materials such as lightweight alloys and composites [21]. However, the conventional laser welding processes such as laser deep penetration welding, laser wire filling welding, laser brazing welding, and laser-arc composite welding are difficult to meet the new welding requirements. The recently emerging laser welding techniques such as laser spot welding, laser swing welding, multi-laser beam welding, and laser flying welding still need further development. In addition, the laser welding technique for automobile bodies needs to be deeply integrated with the intelligent technique to obtain the real-time perception of welding status and the feedback control of process parameters.

The TWB can be used in the areas where BIW requires extra strength or stiffness, thereby reducing the weight. The production process of TWB involves welding metal plates of different thicknesses, surface coatings, and even raw materials together based on the strength and stiffness requirements of the automobile body components design, and then stamping them. The carbon dioxide (CO_2) laser has outstanding characteristics such as high power, high energy, high efficiency, and versatility. Therefore, the CO_2 laser welding has unique advantages in connecting different thicknesses of steel in TWB. For example, Ozturk et al. used the CO_2 laser welding to connect 1.8-mm DP600 steel with 0.8-mm and 1.5-mm DP800 steel, and studied the effects of laser power and welding speed on the mechanical properties of the traveling wave tube [22]. Figure 6 shows a schematic diagram of the CO_2 laser welding process of two different types and thicknesses of steel, where the spot diameter (d_s) represents the diameter of the beam reflected from the focusing lens in the laser head, and the focal length (f_L) is the distance of the laser beam from the lens to the focus. In all the welding operations, the distance (S_d) from the unfocused laser beam to the sheet surface was taken to be 15 mm. Both the d_s and f_L affect the size and energy density of the laser spot on the weld, thereby affecting the depth of the weld and the mechanical and microscopic structure of the welded joint. During the welding, different welding parameters were used to detect the mechanical and microstructural changes of the welded joints. The laser power and welding speed were selected as variable parameters. They found that the stress distribution and strain localization varied significantly with the grain size of the components and the thickness ratio of the TWB at the micro- and macro-scales, respectively, while the numerical flow curves obtained using the representative volume element (RVE) method were well consistent with the experimental results.

In order to meet the higher requirements for collision safety of the electric vehicles and other new energy vehicles, Tomizawa et al. developed the 3D thermal bending and direct quenching technology, which could form hollow tubular steel parts with a tensile strength of up to 1.47 GPa [5]. They also studied the collision characteristics of the prepared fully quenched and partially quenched automotive parts by using the finite element

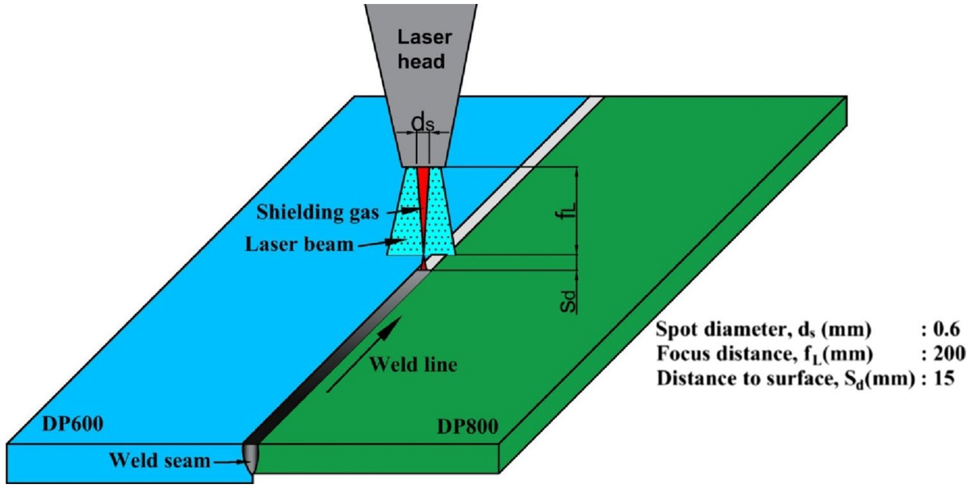


Fig. 6 Schematic representation of the CO_2 laser welding process (reproduced with permission from [22])

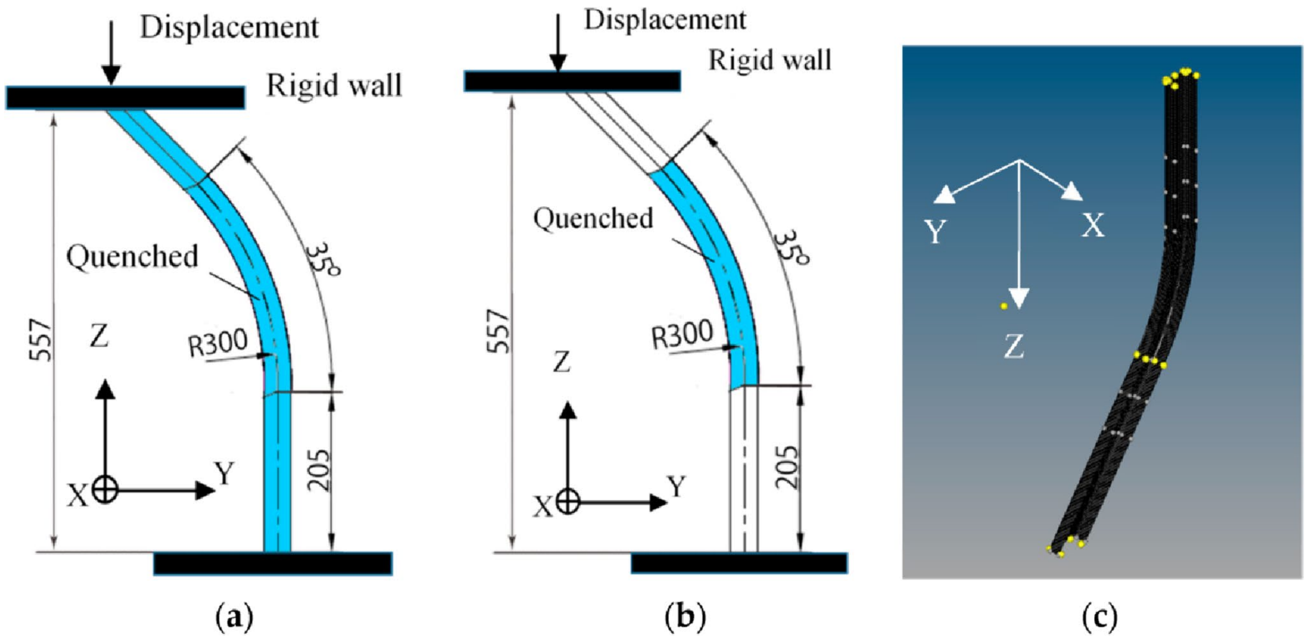


Fig. 7 Initial product shape in axial crash test of overall quenched pipe (**a**), partially quenched pipe (**b**), and finite element model (**c**) (reproduced with permission from [5])

analysis (as shown in Fig. 7). The results showed that the bending controllability of the non-quenched part in the axial impact test was poor, and the energy absorption capacity was low; the bending controllability of the overall quenched product was improved, and the energy absorption capacity could be increased by 59.3%; while the complete controllability of the partially quenched sample was the best, and the energy absorption capacity could be further increased to 84.6%.

3.2 Processing and shaping of other metal materials

Aluminum has been widely used as a lightweight material to replace steel and iron, but its coupling with steel and iron is an important issue in its use. Park et al. studied the mechanical properties of its connection part with steel pins or bolts by creating holes and cracks in the 6061 aluminum, and found that the aluminum had higher stress concentration than the carbon fiber (CF)-reinforced polymer (CFRP), making it less suitable for the structures that require intensive design under frequent fatigue loads [23].

Although aluminum alloys are popular in the automotive industry due to their high specific strength, their low formability makes it difficult to form complex-shaped panels and bodies. By using hot stamping technology, the ideal high strength can be obtained by plastically deforming the heated aluminum alloy plate at the solution heat treatment temperature, and then through the subsequent aging treatment. Xu et al. studied the effects of high-temperature pre-straining and pre-aging on the mechanical behavior and microstructure of AA6082 aluminum after natural aging, paint baking treatment, and artificial aging [24]. Among them, the sample piece of AA6082-T6 was pre-strained under uniaxial tension at 5%, 8%, and 13% levels at the solution temperature, and then pre-aged at 140 °C for 10 min, naturally aged for 2 weeks, and baked at 180 °C for 30 min or finally artificially aged at 180 °C for 6 h. They obtained the yield strength, tensile strength, and elongation of the post-aged sheets through the standard uniaxial tensile tests and analyzed their microstructure using a transmission electron microscope (TEM). It was found that the dislocations caused by the high-temperature pre-straining reduced the concentration of quenching in vacancies and avoided the aggregation during natural aging. At the same time, due to the preferential formation of large precipitates on the dislocation lines during the paint baking and artificial aging, the uniform precipitation in the matrix was inhibited. The combined effect of high-temperature pre-straining and pre-aging resulted in both high-temperature pre-straining and pre-aging, thereby inhibiting the natural aging of AA6082.

Wang et al. proposed another method for manufacturing complex aluminum alloy body panels: the rigid-flexible coupling forming process [25]. They introduced the principle of the method and studied the key process parameters such as hydraulic loading path and rigid-flexible effect, blank holder force (BHF), and tie bar settings through numerical simulation and experiments. This method combined the hydroforming and rigid forming and had the dual advantages of forming. Through theoretical calculations, they gave the relationship between local fillet characteristics and hydraulic pressure, which provided a theoretical basis for the design of the hydraulic loading path. They obtained the forming window of BHF by conducting the rigid-flexible coupling tests on the aluminum alloy inner plates. As the BHF increased, the amount of material flowing into the mold cavity decreased, while the reduction in specimen thickness increased significantly. As shown in Fig. 8, it is a complex inner panel of 5182-O aluminum alloy engine hood developed using such a rigid-flexible coupling forming process. Its dimensions are 1378.4 mm × 481.7 mm × 81.1 mm. It has large overall size, small local size (minimum corner radius is only 2.0 mm), many features, and complex shape, which bring some challenges to the forming process, mainly including high requirements for processing equipment and

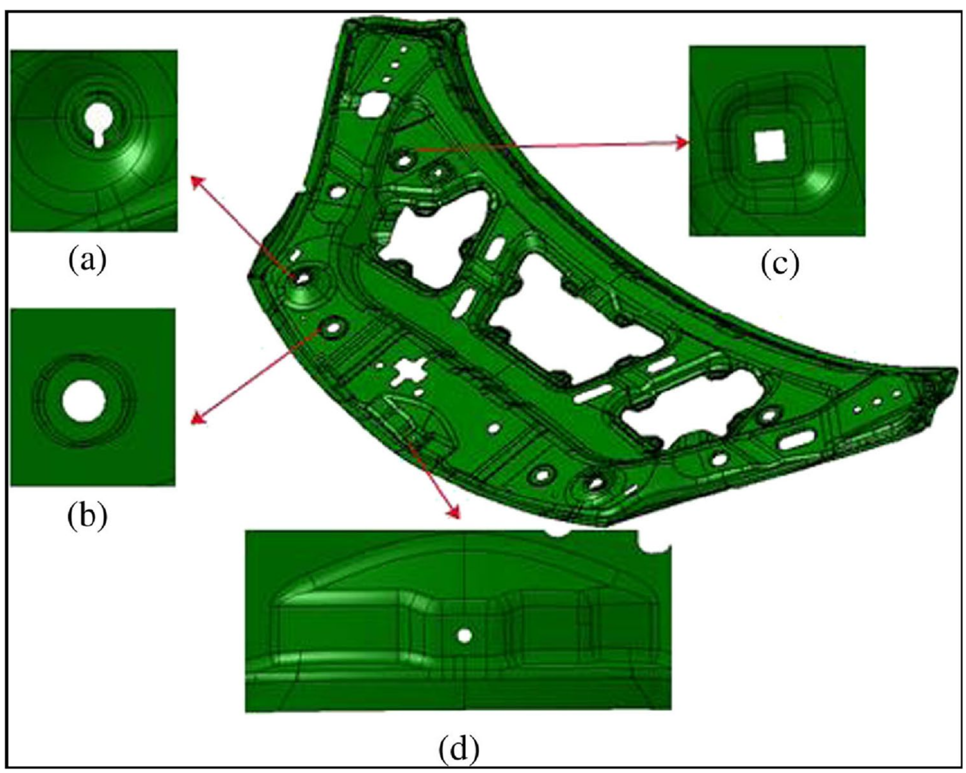


Fig. 8 Overall dimensions and key local features of the part (reproduced with permission from [25])

technology, multiple processes, and long time. Also shown in the figure, there are four key local feature locations that are retained locations for the rigid-flexible coupling molds to ensure the accuracy and consistence of the forming effect. The hydraulic loading path has a significant impact on the rigidity and flexibility of the parts and the forming quality, and the size of the fillet feature is a key factor in designing hydraulic systems. They provided the relationship between local fillet characteristics and hydraulic pressure through theoretical calculations, that is, the smaller the radius of convex and concave fillet, the greater the hydraulic pressure required for the forming process. This provides a theoretical basis for the design of hydraulic loading paths.

The SLM mentioned above can be used to manufacture the parts in near-net shape (NNS), which can significantly reduce the weight of the body and provide the opportunity to integrate some functions. Cecchel et al. developed a process for SLM production of Ti_6Al_4V NNS alloy engine parts (as shown in Fig. 9) and achieved the topology optimization of the parts through finite element analysis, thereby reducing weight while maintaining the same safety performance [26]. The results showed that the SLM multi-branch structure could achieve weight reductions of 45 wt% and 15 wt%, respectively, compared to the steel and titanium forgings.

3.3 Processing and shaping of PMC materials

Polymer materials can be divided into thermosets and thermoplastics according to their high-temperature fluidity, and their chemical basis is the presence or absence of a chemical cross-linked network in the system [27]. Both glass fiber (GF)-reinforced polymer (GFRP) and CFRP materials can be used in the manufacturing of large-volume body structures, which facilitates the so-called "skeleton design" [28]. To this end, Maier et al. used pultrusion and tape laying processes to study the performance of GF and CF unidirectionally reinforced composites based on thermoplastic polymer materials of polyamide 6 (PA6) and polypropylene (PP) [29]. By measuring the interlaminar shear strength at different temperatures (−35 °C, 23 °C, and 85 °C), it was found that after heating from −35 °C to 23 °C, the interlaminar shear strength decreased by about 25%. When the temperature was further increased to 85 °C, the interlaminar shear strength decreases by about 65%. They also found that due to the different properties of the fiber/polymer matrix interface, all the PA6-based composites performed better than all the PP-based composites at all the tested temperatures.

By using CF-reinforced PMC, Bere et al. designed, prepared, and tested two front hoods for small electric vehicles

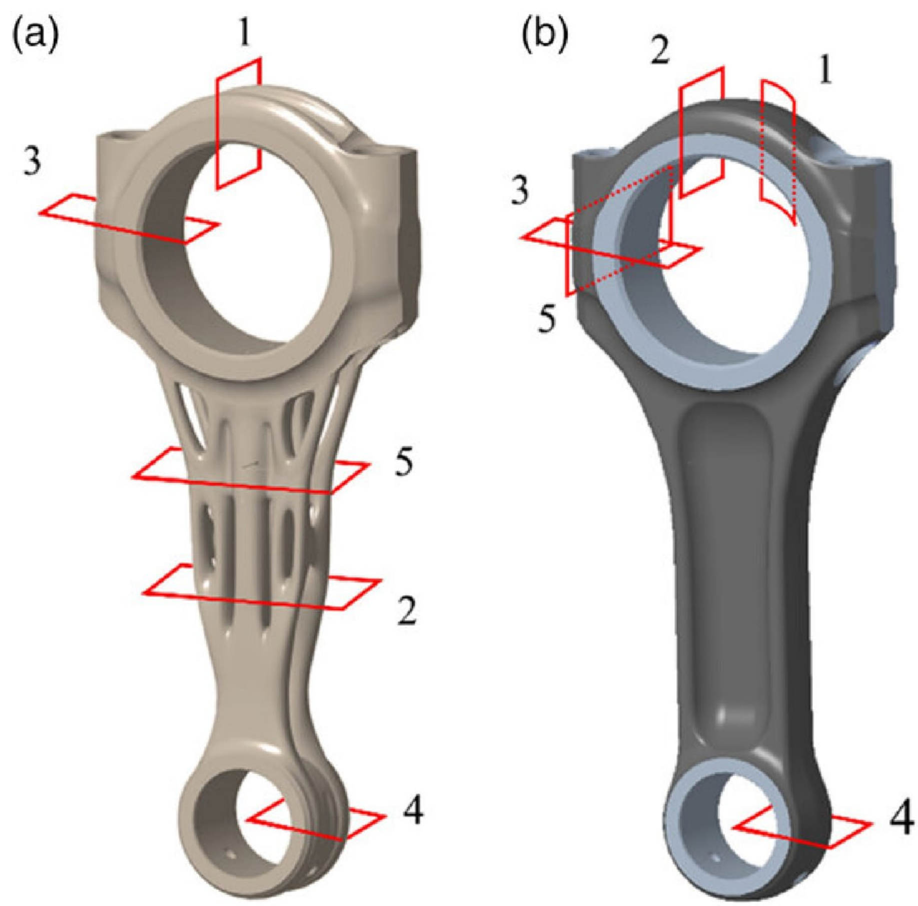


Fig. 9 Microstructural samples from Ti6Al4V SLM (**a**) and hot forged conrods (**b**) (reproduced with permission from [26])

[30]. They compared two different design concepts: The variant A was based on a similar geometry to the black metal design, replicating the same geometry and stiffeners, while the variant B had a special design in composite material, using the lightweight sandwich structure on the outside and changing the back frame (as shown in Fig. 10). Compared to variant A, variant B had optimized the design in terms of material and shape. In terms of design, variant A had a separate rib in the middle, while variant B inserted two less obvious ribs on the central side. Although both used CFRP, their prepreg models and layers were different, and variant B used a sandwich structure with a smaller rear frame size to reduce the weight. They proposed five different stacking sequences of CF cloth materials and CF cloth covers (the layer structures of these five composite materials were the same as those used for the hood manufacturing). The five different stacking sequences include sequences 1A and 2A for variant A and sequences 1B, 2B, and 3B for variant B. Their manufacturing includes vacuum bag technology and autoclave curing. Through the experiments (using load displacement measurement sensors and strain gauges) and the numerical methods (using finite element software), analysis and comparison were made (including the static stiffness and strain values under transverse, and longitudinal and torsional loading cases). Among them, 3D scanning technology was used to reveal the manufacturing dimensional accuracy relative to the initial CAD model. The results showed that the hood A was 2.54 times lighter than a similar steel hood, while the hood B was 22 wt% lighter. In terms of lateral stiffness, compared with the black metal design concept, the hood with a sandwich structure and an improved rear frame was improved by about 80% and 157%, respectively. Compared with a similar steel hood, the longitudinal stiffness was increased several times, and the torsional stiffness was increased by about 62%. It was also found that the vacuum bag technology and autoclave curing process were good processes for producing the high-quality CF-reinforced PMC parts, which could further reduce the costs and expand the application to other components such as doors, front and rear fenders, and trunk lids. They had three key findings. Firstly, replicating the same geometric shape and reinforcing ribs to replicate metal parts could reduce the weight while ensuring similar or higher stiffness. Secondly, the use of sandwich structures could achieve both high stiffness and lightweight structures simultaneously. Finally, the appropriate stacking order of layers could achieve the weight reduction while meeting the complex requirements.

The PMC materials reinforced by continuous fiber not only have good lightweight potential, but are also particularly suitable for the structural components due to their excellent mechanical properties. Different from their application in the aerospace field, the PMC materials reinforced by continuous fiber used in the automotive field need to consider higher production volume and lower production cost, and the component size is smaller and the shape is more complex, which make their preparation more challenging. Their common processing techniques include high-pressure resin transfer molding (HPRTM), tape molding, and wet compression molding (WCM). Henning et al. predicted the injection, curing and molding steps of continuous CF-reinforced PMC through the process simulation, and systematically studied the WCM process [31]. As shown in Fig. 11, one method of reducing processing forming defects is to segment the formed fabric into the so-called sub-preforms, which are then assembled into the final preform in a sequential preforming process. Although cutting of the fabric interrupts the continuous fibers and thus reduces its mechanical properties, with proper assembly, this loss can be minimized, and the draping can be improved.

It should also be recognized that although the CF-reinforced PMC materials can replace the steel materials to achieve the weight reduction in automobiles, its specific fiber structural orientation causes it to exhibit weaknesses in the direction perpendicular to the fibers. Park et al. produced

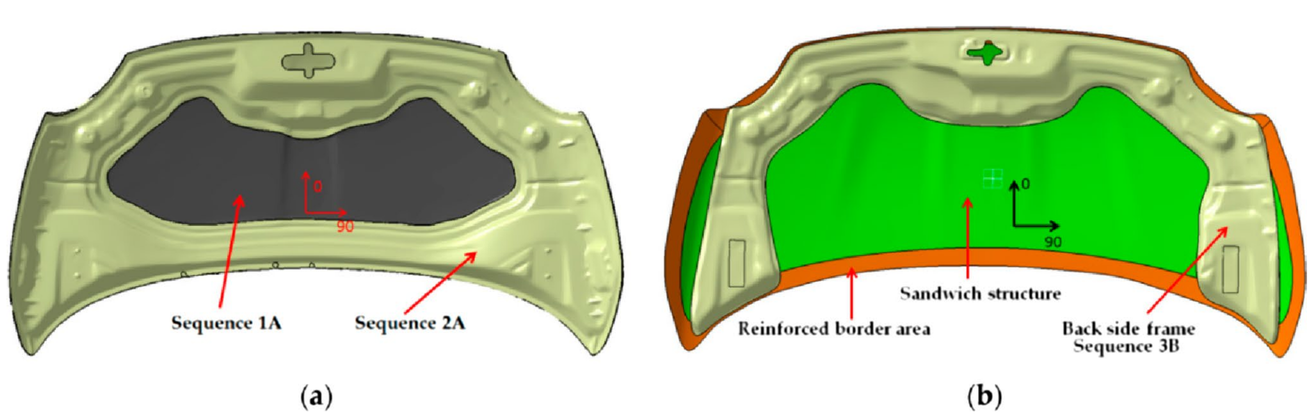


Fig. 10 The CAD model of the backside of hoods showing the positioning of the CF-reinforced PMC sequences on hood: front hood variant A (**a**) and front hood variant B (**b**) (reproduced with permission from [30])

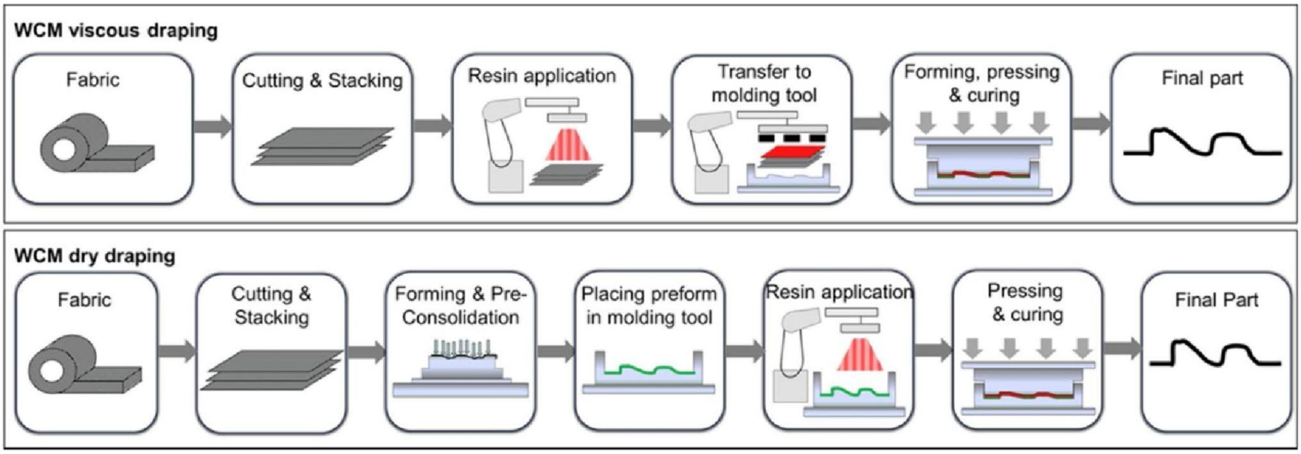


Fig. 11 Two variants of WCM process routes with viscous and dry draping (reproduced with permission from [31])

holes and cracks in the braided and unidirectional CF-reinforced PMC specimens to study the mechanical properties of the connection between the specimen and the steel pins or bolts [23]. They also used finite element analysis methods to compare and verify with experimental results to provide theoretical guidance for the lamination process of CF-reinforced PMC materials.

3.4 Processing and forming of CMC materials

The CMC materials have excellent properties such as fire resistance and damage resistance. Although they originally originated from the aerospace industry, they have found increasingly widespread use in areas such as high-performance brake disks in automotive structures. In order to produce the CMC materials faster and more economically, Polenz et al. developed a new AM process [32], in which the silicon carbide (SiC) ceramic fiber bundles were infiltrated with yttrium trioxide–silicon dioxide (Y_2O_3-SiO_2) ceramic suspension, and then dried and applied to form a shape. During the application, the matrix material could be melted by CO_2 laser (wavelength of about 10.6 μm) radiation, while the fiber material was not damaged (as shown in Fig. 12). They also conducted systematic research and optimization on each processing parameter.

Although the CMC materials have excellent performance, when they are cut with common cutting methods such as laser cutting, water jet cutting, and electric corrosion, the delamination and strength reduction can easily happen. Wisniewska et al. used the diamond abrasive wires to cut

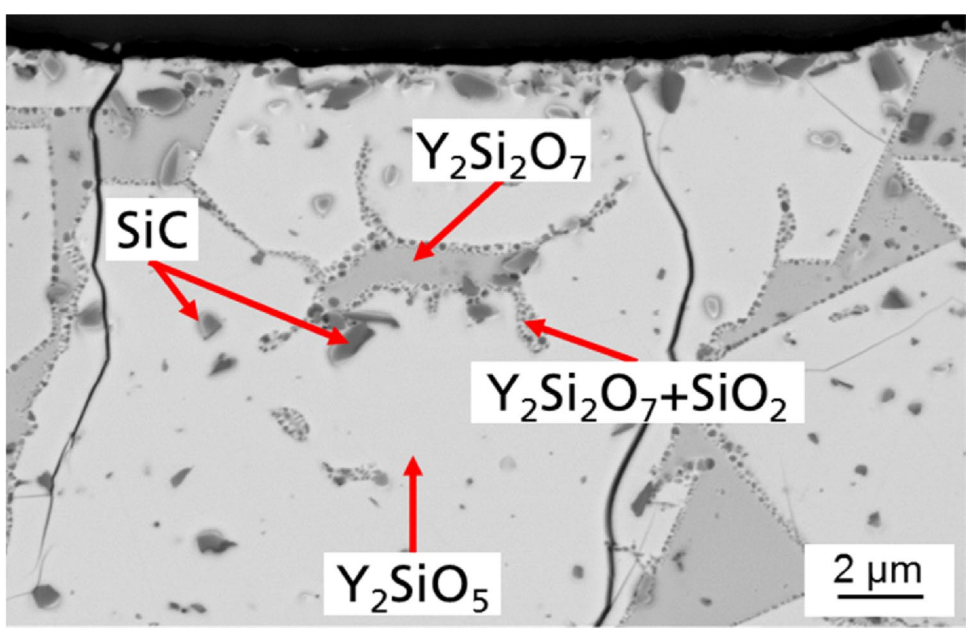


Fig. 12 Cross-section of the Y_2O_3–SiO_2 sample with 10 vol% SiC melted with wavelength of about 10.6 μm (reproduced with permission from [32])

the CMC materials (such as liquid silicone resin-infiltrated C/C-SiC composite pipes) based on the cutting method of silicon substrate wafers and its industry standards, and systematically studied the impact of process parameters on the surface quality, edge damage, and tool wear [33]. The main challenges included three aspects. Firstly, the method generated a large amount of dust, so it was necessary to actively remove dirt and use personal protective equipment. Secondly, the subsurface machining defects generated by this method were difficult to observe. Finally, it was difficult to evaluate the wear condition of cutting tools, which might lead to sudden breakage of the cutting wire. The main criteria for inspecting the cutting effect were the surface quality after processing, such as surface roughness, surface processing defects, subsurface processing defects, edge damage, burrs, and delamination. The evaluation methods for the edge quality, surface quality, and material delamination mainly included roughness measurement, three-dimensional profile imaging, and microscopic observation. Their optimized processing parameters were the diamond particle diameter of about 120 and 140 μm, cutting speed of about 5–15 m/s, and linear pressure of about 4.4 and 5.5 N. Their inspection of the cutting effect mainly focused on the edge quality, surface quality, and material delamination. It was found that the diamond wire cutting was very suitable for the CMC materials, and the surface roughness could reach less than 2 μm, which was significantly better than the other processing methods such as water jet cutting.

4 Processing and molding of multiple materials

The simultaneous use of multiple materials in the body structure not only allows the most appropriate material to be selected according to the local performance requirements, but also may produce synergy between different materials, which is also beneficial to the overall performance of the car. This section will focus on the simultaneous processing of hybrid materials and the connection between different materials.

4.1 Simultaneous processing of hybrid materials

Although the PMC materials reinforced by GF and CF are lightweight, they generally require manual processing, so the production cost is high, and it is difficult to mass-produce. To achieve the automated, mass production of lightweight automotive structures with high specific stiffness (stiffness/weight ratio), one strategy is to combine high-strength steel alloys and PMC prepregs in one, forming the so-called FML. One of the great advantages of this material is that it can be further processed through forming techniques such as deep drawing. Heggemann et al. systematically studied the tools, processes, and material design of high-strength automotive structural components prepared by FML, focusing on the failure types such as structural buckling and wrinkles when the combined tensile and compressive stresses were applied the PMC patches during the molding [34]. As shown in Fig. 13, the second layer of prepreg has the same design as the first layer, but the fiber direction is rotated by 90°. This rotating multi-layer design resulted in the components with very high specific stiffness.

The metal/polymer fiber core micro-sandwich panels similar to the above-mentioned FML are also considered to be one of the most promising materials for the automotive industry (as shown in Fig. 14), but the accurate testing of their mechanical properties is difficult. To address this problem, Pimentel et al. proposed a strategy to infer the mechanical properties of fiber cores from symmetric or asymmetric micro-sandwich panels (i.e., sandwich panels with the same or different thicknesses) [35]. The specific method was to conduct uniaxial tensile tests in three different directions according to the ISO 6892-1:2009 standard, and then establish a structural model. Finally, different modeling strategies and finite element methods were compared to obtain the reliable data.

4.2 Connection of different materials

Although the simultaneous use of multiple materials can provide a lightweight solution for the car body, different materials are usually difficult to be connected directly through welding due to their different melting temperatures; therefore, additional fasteners are usually required to make connection, which undoubtedly increases the production cost and preparation time. Wiesenmayer et al. used the shear clinching technology, which combined the shear cutting and the clinching in the same stage of the process to achieve connections between materials with widely different mechanical properties [36]. Through the shear clinching of different materials, they achieved the joint strength comparable to the pre-drilled clinching and proved that the technology could be used to connect the stamped side aluminum and the stamped side high-strength steel.

Considering that the THTB technology can improve the formability of high-strength aluminum alloys in the sheet forming process, Graser et al. studied the applicability of THTB technology in the shear clinching technology and found that it was not only suitable for the connection of the tough aluminum alloys and the high-strength steels, but also can achieve the connection of the high-strength aluminum and the high-strength steel [37]. The shear clinching process starts with positioning the aluminum alloy on the stamping side and the steel plate on the stamping die side between the blank holder and the stamping die. Afterward, the

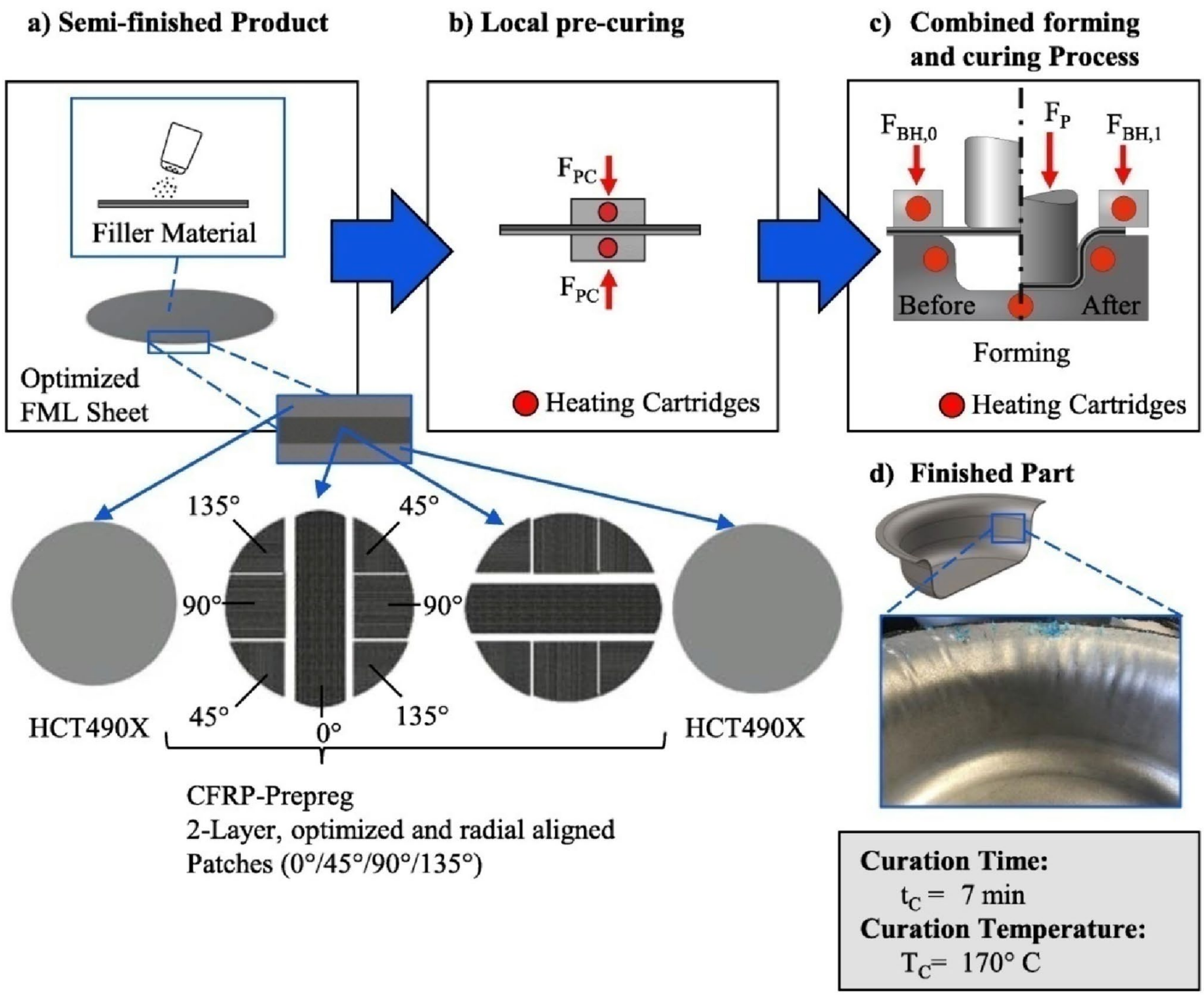


Fig. 13 Schematic presentation of the optimized material and process design (reproduced with permission from [34])

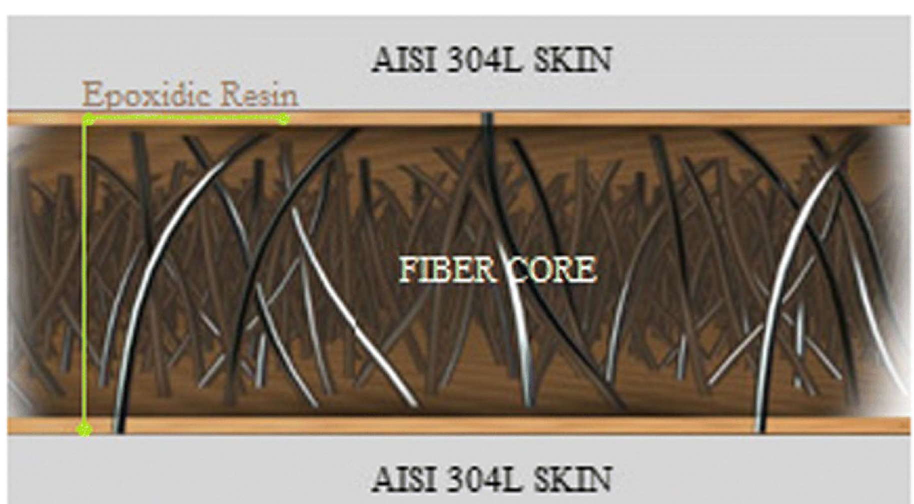


Fig. 14 Scheme of the hybrix micro-sandwich sheet material, comprising two stainless steel layers and an intermediate composite core (metallic/polymeric fibers embedded in an epoxy resin) (reproduced with permission from [35])

simultaneous travel of the inner and outer punches causes stress in the steel plate on the mold side and allows for indirect cutting operations without significantly thinning the aluminum plate. The stroke of the internal punch will generate the force of material combination and shape matching joint. Finally, the waste is pushed out. The difficulties in connecting the materials with different mechanical properties first lie in the large difference in their deformation under the same stress, which leads to shape mismatch. Secondly, their different heat treatment temperatures can make it difficult to choose the processing temperature. Finally, differences in cooling rate and cooling shrinkage rate can also lead to internal stress at the connection. By using the aluminum specimens with different heat treatment layouts, they successfully connected the AA7075 aluminum alloy and the-HCT780X steel on the punch side, and also successfully connected the AA7075 aluminum alloy on the punch side and the stamp-hardened 22MnB5 manganese–boron steel on the die side (as shown in Fig. 15). The main way to obtain high joint strength through the shear clinching is to heat treat the connection before or during the clinching and control the temperature distribution. In addition, the material flow during the clinching is controlled by improving the geometric shape of the mold to achieve higher joint strength. Compared with the pre-drilled clinching methods, the shear clinching can connect different materials with significant differences in mechanical strength without any pre-stamping operation. Therefore, its joint strength may be slightly affected, but the process is simpler and time-saving.

Zvorykina et al. developed a new technology for connecting aluminum–silicon coated hot-stamped ultra-high-strength steel and aluminum based on the resistance welding process [38]. It consisted of a two-stage projection welding process with additional insert elements, allowing the use of extremely short welding times, high-energy concentration, and adhesive bonding to connect aluminum and steel plates (as shown in Fig. 16). Due to the low heat input during the welding, the adhesive around the inserted component was significantly less damaged than with conventional resistance spot welding. Depending on the size and orientation of the

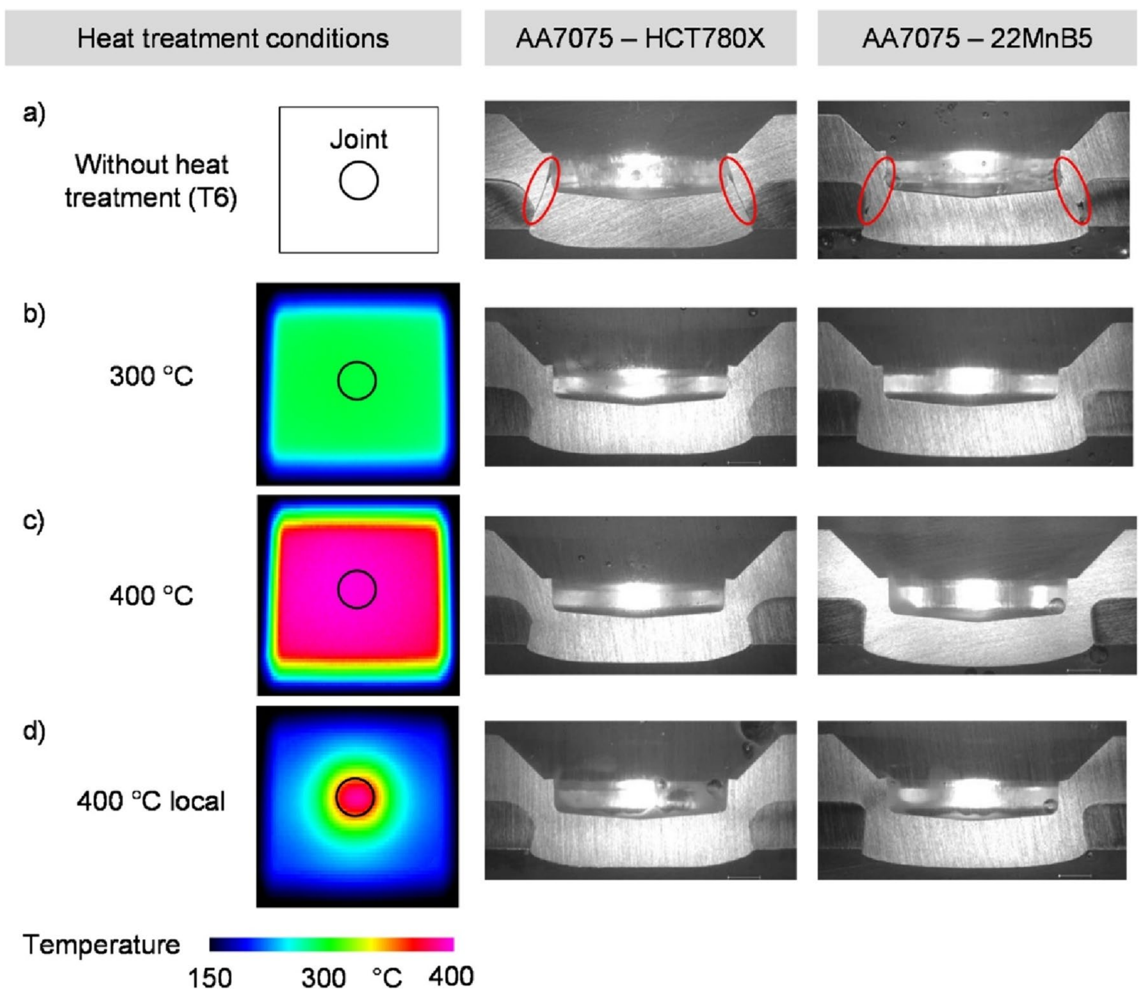


Fig. 15 Shear clinching joints with different joining material and heat treatment conditions (reproduced with permission from [37])

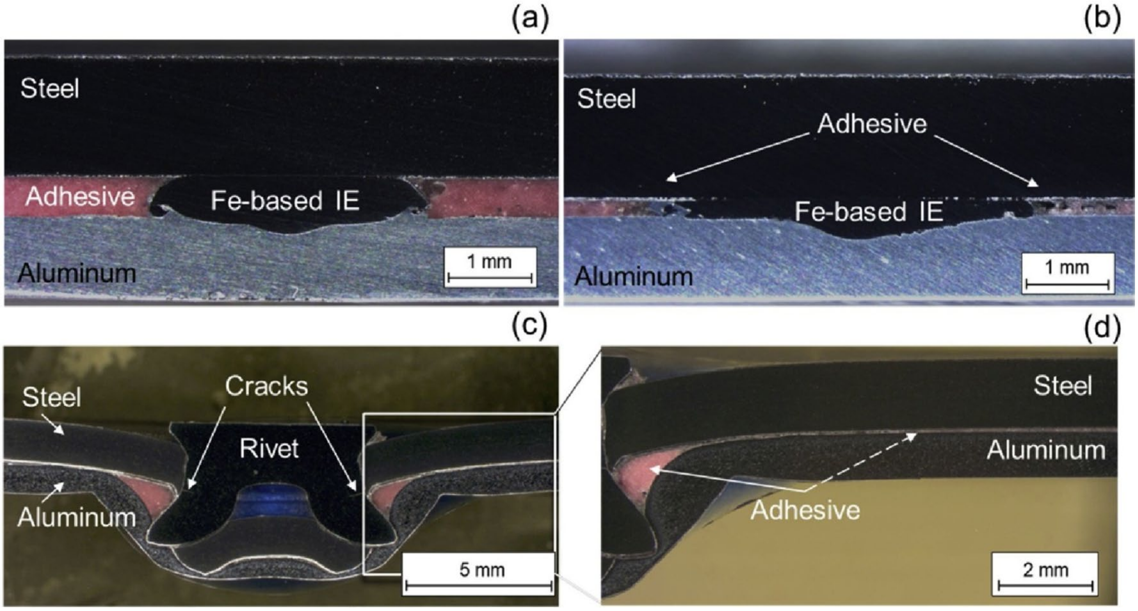


Fig. 16 Cross-sections of joints with adhesive bonding: with iron-based insert elements and welded with lower welding current (**a**), with iron-based insert elements welded with upper welding current (**b**), and riveted steel–aluminum (**c**, **d**) (reproduced with permission from [38])

inserted elements, short flanges could be connected, offering the potential for further reductions in body weight. This process could use a two-stage welding process on an ordinary medium-frequency direct current (DC) welding machine to create a new hybrid bonding and the use of projection welding process for the aluminum–steel connection.

The traditional clinching technology cannot be used on the visible areas (such as body shells, etc.) or the functional surfaces (such as sliding surfaces, etc.), while the flat clinching is used for the single-sided flat connections of the same or different types of materials (for example, metal and metal, metal and plastic, or metal and wood). Contrary to traditional clinching, it places the metal sheet on a flat anvil instead of a forming die. The process involves first moving the blank holder downwards and securing the workpiece in place. Subsequently, the punch moves downwards and forms the material, thereby establishing a feature interlock within the total material thickness. Compared with the shear clinching, the advantage of flat clinching is that there is no local separation of the material on the mold side, making it a non-destructive method. In addition, its tool load and wear are significantly reduced. Compared with the metal plate preheating method, the flat clinching does not have a preheating step, thus shortening the processing time. Gerstmann et al. studied the flat clinching technology, which was characterized by combining two processes of flat clinching and bonding (as shown in Fig. 17) [39]. After applying the adhesive, the metal sheets were mechanically fixed by the flat clinching, thus ensuring the strength of the assembly operation. The combination of flat clinching and gluing ensured the handling strength of the hybrid joint, and the components could be further processed directly after the mechanical connection.

In the molding of automobiles, the complex lifting lug connection structure often hinders the overall molding of the main load-bearing components, thus limiting its lightweight realization. Min et al. proposed using thermal expansion molding process (TEMP) to prepare the web-reinforced sandwich composite lifting lug structure of the new energy vehicles and established a connection failure analysis model to verify the relationship between the process and structural performance [40]. They found that the web-reinforced structure significantly increased the strength and stiffness of the

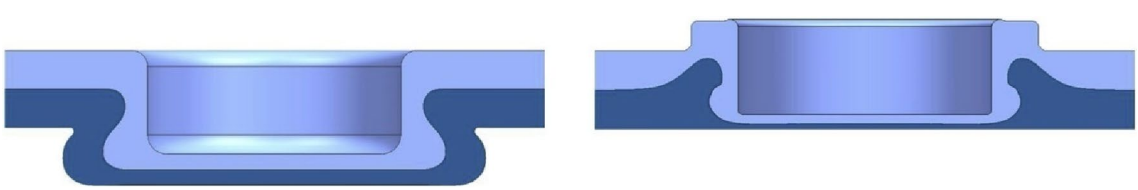


Fig. 17 Schematic cross-sections of conventional clinching (left) and flat clinching (right) (reproduced with permission from [39])

lifting lugs. To this end, they designed a hybrid connection mode of steel casings through the thermal expansion membranes and glass fiber-reinforced plastics, and verified the comprehensive connection performance of the lifting lugs through connection compression tests, finite element model analysis, and macroscopic failure modes (as shown in Fig. 18). The results showed that compared with the pure foam sandwich structure, the effective bearing capacity of the single-web structure and the double-web structure increased by about 38.2% and about 65.2%, respectively, and the specific strength increased by about 24.2% and about 37.2%, respectively. The maximum pressure load of the steel casing reached about 11.2 kN, which was about 52.3% higher than that of pure CF-reinforced PMC material connection, which indicated that the combination of the expansion adhesive film and GFRP with the steel casing yielded the most effective connection. The comprehensive connection strength of the lifting lug could meet the static load of the battery boxes of more than 6000 kg. By employing the web structure, the maximum carrying capacity of a single lifting lug can reach 666 kg, and the comprehensive carrying capacity of the entire battery box lifting lug can exceed 6000 kg, which meets the statics requirements and proves the effectiveness of the web structure. The web structure in the lifting lug improves the integration, transfers the load, and enhances the strength and stiffness. Consequently, the displacement at the initial failure load is smaller, and the failure load is higher. The double-web structure even has higher specific strength and effective bearing capacity than the single-web one.

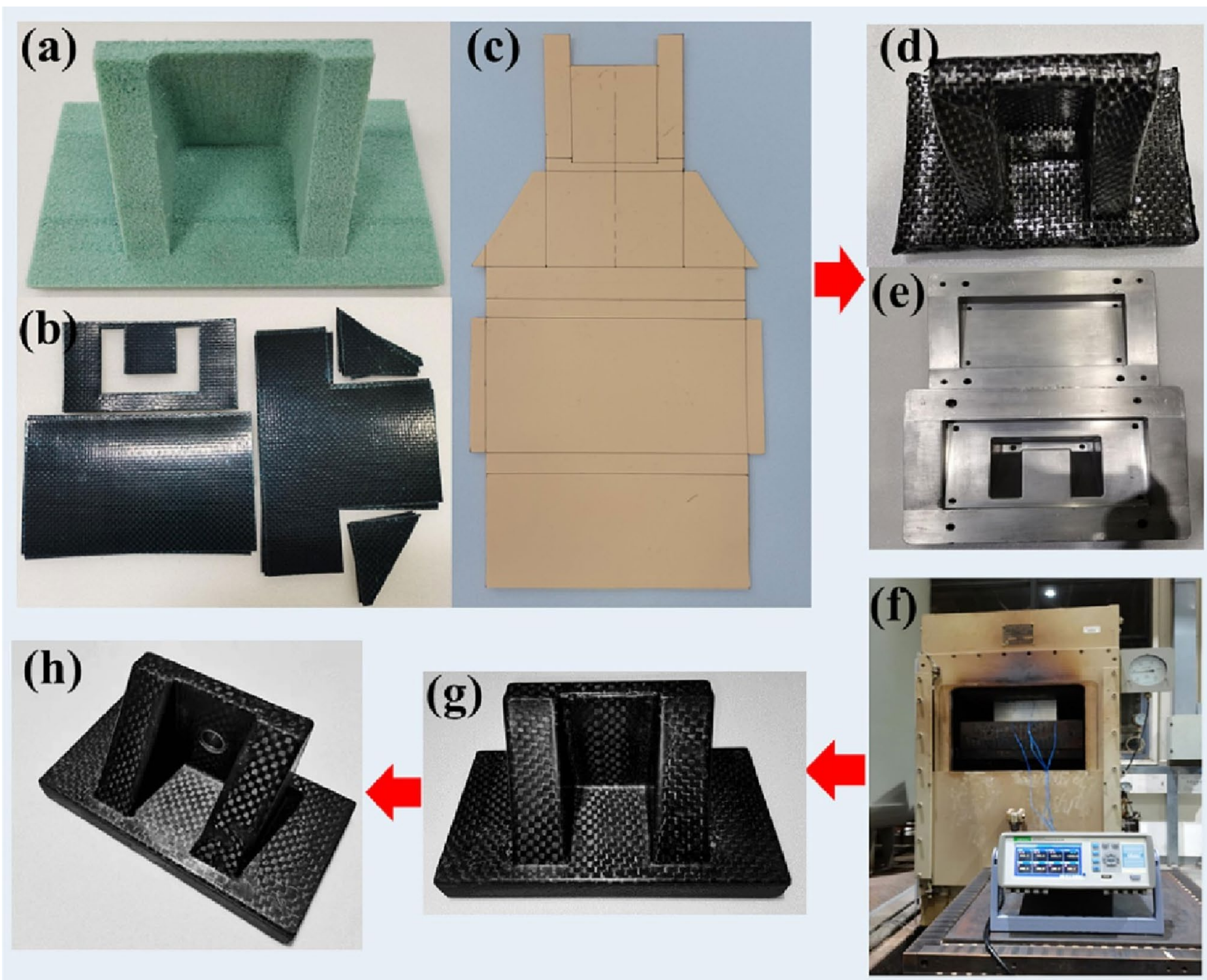


Fig. 18 Schematic diagram of the preparation process of the lifting lug: lightweight core carved from polyethylene terephthalate (PET) foam (**a**), CF-reinforced PMC prepreg (**b**), thermal expansion epoxy foam prepreg (**c**), prefabricated sample of the lifting lug (**d**), mold (**e**), schematic diagram of sample preparation for TEMP technology (**f**), lifting lug sample after molding (**g**), and lifting lug for mounting steel sleeve (**h**) (reproduced with permission from [40])

5 Conclusions and outlook

Through the review on the research and development of processing and molding methods for different materials in the automobile industry in recent years by the scientific research community and the industrial community, it can be seen that a major trend in the automobile body manufacturing is the reasonable combination of different materials and different processes. In this process, not only the overall construction of the body and the manufacturing of parts are required to be coordinated, but also different processing methods and techniques need to be selected according to different materials. For the simultaneous use of multiple materials, there are only a few cases where different materials can be processed simultaneously. More often, what needs to be considered is the connection between the parts made of different materials. It is believed that with the continuous development of new materials and the continuous improvement of their properties, as well as the improvement of traditional processing and molding methods and the research and development of new methods, the industry can adapt to the current transformation from fuel vehicles to hybrid vehicles and then to electric vehicles, and provide them with the necessary technical support. It is also expected that the basic strategies to achieve the energy conservation and emission reduction through the multi-materials and lightweight as discussed in this review can contribute some theoretical guidance and practical basis to the further development of the automobile industry.

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Declarations

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