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The Experimental Study on the Mechanical Properties of Fiber-Reinforced Metal Laminates Using an Innovative Heat-Solid Integrated Forming Technology

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Abstract: In the forming process of fiber-reinforced metal laminates (FMLs) product, the exploratory compound forming technology, including hot stamping of aluminum alloy and laying process of fiber prepreg which is named HFQ-FMLs was proposed to solve the puzzles such as weak rigidity, low strength and integration deformation with large difficulty, and the feasibility and mechanical properties of the innovative forming process were studied. Firstly, based on the modified metal volume fraction formula, the theoretical values of the mechanical properties of the HFQ-FMLs plates were calculated. Compared with the experimental results, the minimum error is 1%, proving that the HFQ-FMLs technology scheme is feasible. Secondly, three kinds of metal sheets with different heat treatments and specimens by HFQ-FMLs were carried out for the tensile tests, the mechanical properties distributions were demonstrated, and the influence regularity of the strain rate and rolling direction on the stress analysis was considered at the same time. As can be seen from the distribution of yield strength and tensile strength, the yield stress of metal sheets obtained by HFQ-FMLs technology along the 45° is superior to the raw material and can increase by 46% under strain rate = 0.01 s^{-1}. While, because the vacuum thermal curing treatment makes the aluminum alloy happen double aging, the metal sheet strength dropped, and the jointing strength between the metal and fiber prepreg became weak too, which made the strength limit of the new material improve weakly. Thirdly, the fractured style of the FMLs under different conditions was studied qualitatively. It is helpful to achieve the development rule of defects, optimize the craft route, and avoid deformation failure.

Keywords: FMLs; compound forming; rigidity; theoretical derivation; fracture morphology

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1. Introduction

The hybrid structure systems consisted of resin-based fiber laminates and thin aluminum alloy laminates are called fiber-reinforced metal laminates (FMLs). This new, high-efficiency, low-cost, and lightweight composite structural material combines the advantages of metals and advanced composite materials [1–4], integrating structural and functional properties. In applications, this material shows favorable properties in terms of electrical shielding, heat insulation and retention, sound attenuation, shock absorption, damping behavior [5], and impact performance [6–9] can be adjusted too. These characteristics make it a promising candidate material for new-generation aircraft components [10–13]. Among them, the glass fiber-reinforced metal laminate (GLARE) is a kind of FMLs composed of both glass fiber prepreg and aluminum alloy, and it can save 15–30% weight compared to aluminum sheets with the same volume and thickness. It has a lower density, longer service life, and maintenance during the service process than metal structures. Hence, GLARE is the most maturely developed and widely used FMLs [14–16].

For the FMLs parts used in the aerospace field, two kinds of settlements are applied mainly now. One is that the aluminum alloy was deformed first, then the glass fiber prepreg with plate shape was layered on a metal sheet, and the composite was finally dealt with vacuum thermal curing treatment. Another scheme is that the hybrid material was prepared first. It was formed using traditional forming technologies, such as the vacuum bag–autoclave forming technology, roll bending forming, shot peening forming, and the compound forming method combining the hydroforming with fiber prepreg laying processes [17]. Compared to aluminum alloy sheets, FMLs have the characteristics of high strength limit and elastic modulus along a certain direction, and it exits the uncoordinated deformation of the heterogeneous materials. All of these make the qualified FMLs deform hard using the traditional plastic forming processes, especially for big size and complex structure parts, and the large spring-back and low fracture strain are the common defects. When a large number of high-speed projectile balls impact FMLs, the shot peening technology [18–20] is a method which can gradually realize the plastic deformation of FMLs with target curvature. However, the shot peening technology and the laser peening process can only manufacture simple structures for FMLs, which limits the product types and application scope. When the single curvature parts were formed by the roll bending method, the spring back issue is caused easily by the large elastic modulus along the fiber laying direction and the high residual stress. The process is simple, has low production cost, high efficient, and is mainly used in FMLs structure parts with single curvature. The forming curvature is limited, which cannot meet the requirements of aerospace applications for large complex structure parts.

To make the FMLs parts with large-size and complex structures deform successfully and improve the rigidity of composite material, some researchers did a lot of jobs and obtained precious results. Hamza Blala [21] from the Beijing University of Aeronautics and Astronautics put up an innovative forming technology to form the FMLs with good quality. An optimized glass fiber patch geometry was designed using a circular shape with a diameter of 100 mm and an "O" shape patch with an internal and external diameter of 60 mm and 140 mm, respectively. This design scheme of the fiber shape facilitates the material flow. Complex FMLs with large sizes can be obtained with zero defects. The hybrid aluminum-fiber prepreg composite dealt with the thermal curing treatment according to the blank holder and mold. Then it became the integration with the coincident structure and performance. While because there is no essential change in the microstructure, the comprehensive mechanical properties of the FMLs were not improved, and the research of innovative forming methods by which the performance can be enhanced after manufacturing is urgent. From the point of property improvement, Reza Eslami-Farsani [22] from Toosi University of Technology researched the influence of nanoparticles on the mechanical behavior of FMLs and adhesively bonded joints between metal sheets and polymeric composites and found that there are various factors, such as surface treatment of metal sheets, type of nanoparticles, the morphology of nanoparticles will affect the properties of the FMLs. The relative reports focusing on the change of the mechanical properties according to the microstructure variation are few, and it provides a possible approach.

In this paper, an innovative compound forming technology combining the aluminum alloy hot forming with the FMLs preparation process was put up. It includes two steps. The first one is the heat forming, quick quenching process and artificial aging (HFQ) of aluminum alloy. Because of the hot environment, the plasticity of aluminum alloy was improved, and the deformation limit increased in the HFQ process. At the same time, the mechanical properties of aluminum alloy can be affected with the help of quick quenching and artificial aging treatment. The second step is that fiber/epoxy polymeric materials were laid with the metal plates obtained by the first step in certain ways, and they were dealt with vacuum thermal curing treatment. The fiber metal heterogeneous composite materials were consolidated according to the optimal heating temperature and time. Because it involves the HFQ technology and the laying technology of fiber prepregs, the whole technical route was named the HFQ-FMLs compound technology. Because the 7075-aluminium alloy is a heat-treated reinforced material, the plasticity is excellent. The deformation limit can be improved under high temperatures in the HFQ process. The tensile strength also can be enhanced according to the artificial aging treatment in the HFQ process. When the assembled FMLs are dealt with the vacuum thermal curing treatment, the metal layers will happen the second aging process, and the property of resistance to stress corrosion will be improved too. Using the innovative compound forming technology, the more complex and lighter FMLs parts with comprehensive mechanical properties will be manufactured, giving the aircraft better battery life.

To verify the practicability of the HFQ-FMLs compound technology and enlarge industrial applications, the macro mechanical parameters such as tensile stress, yield stress and module of elasticity for the new hybrid material will be analyzed and compared with the traditional materials. Hence, the standard tensile experiments and the fracture microstructure analysis are essential, as Ma [23] introduced in a review that the free vibration analysis of FMLs will promote the wide application of FMLs. They include dynamic analysis, macro mechanical and micromechanical approaches, and temperature effects.

2. HFQ-FMLs Compound Forming Process

2.1. Technological Design

For the aluminum alloys used in the aerospace field, Al–Cu–Mg alloys (2000 series), Al–Mg–Si alloys (6000 series), and Al–Zn–Mg alloys (7000 series) are all heat-treatable aluminum alloys [24–29]. Among them, the 7000 series aluminum alloys have higher strength, and their tensile strength can reach more than 500 MPa. However, these alloys have a low plastic elongation at room temperature and are easy to crack in traditional stamping, which limits the abroad application. Therefore, the 2000 series Al–Li alloy is adopted in the manufacturing process of conventional FMLs parts [30]. As the competition for military equipment is becoming increasingly fierce, higher demands for aviation equipment and materials, have been put up, such as lighter weight, higher strength, better impact resistance, and fatigue performance. To obtain structural components with high strength and complex shapes, the 7075-aluminum alloy was used in the HFQ-FMLs formation process of FMLs. Firstly, by utilizing hot stamping process routes, the thermal plasticity of the material was improved to solve the problem of small deformation limit and cracking effectively, the movement time of the die was designed for about 10 s to reduce the heat loss of the plate, and the stamping temperature is 400–420 °C in which the metal plate deforms successfully. Secondly, the aluminum alloy parts were subjected to an artificial aging treatment so that the strengthening phases in the material were uniformly precipitated to improve the strength and rigidity of the material. Finally, the thermal curing treatments were carried out to ensure sufficient adhesion between these hybrid materials and to prevent peeling during use. The innovative HFQ-FMLs compound-forming process is shown in Figure 1.

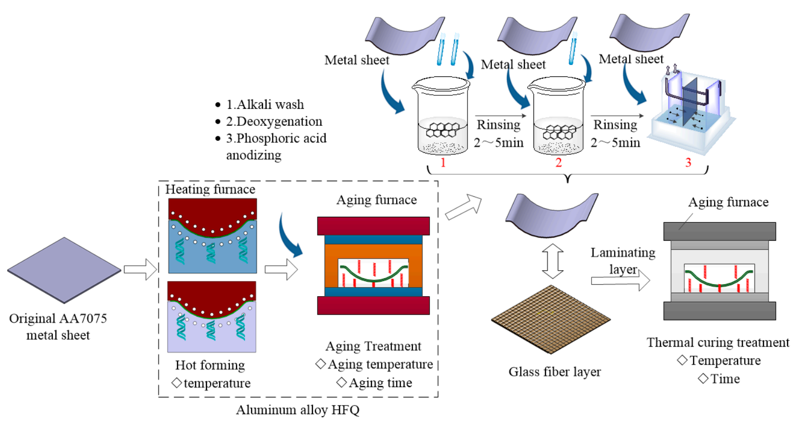


Figure 1. HFQ-FMLs compound forming process (reprinted from ref. [31]).

In the HFQ process of the aluminum alloy, the aluminum alloy was heated to 480 °C and maintained at this temperature for 5 min, which ensured that all of the alloy elements dissolved into the aluminum matrix, the grains were refined, and supersaturated solid solutions were sufficient to improve the next aging step. Artificial aging was selected for the heat treatment, the aging temperature was 130 °C, and the aging time was 16−20 h. This treatment caused the strengthening phases to diffuse out and prevented dislocation movement or lattice distortion to achieve strengthening.

2.2. Surface Chemical Treatment

Then, the obtained metal was dealt with a surface chemical treatment to ensure excellent adhesion quality between the metal and fiber composite materials [32]. The surface treatment process is shown in Figure 2.

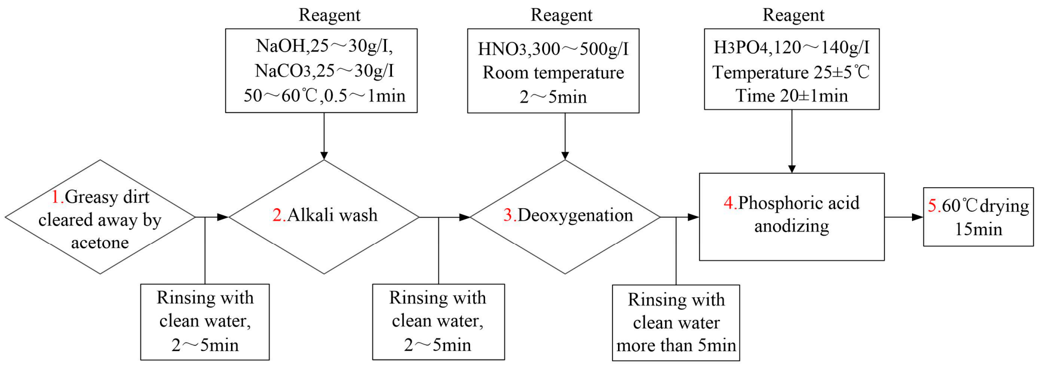
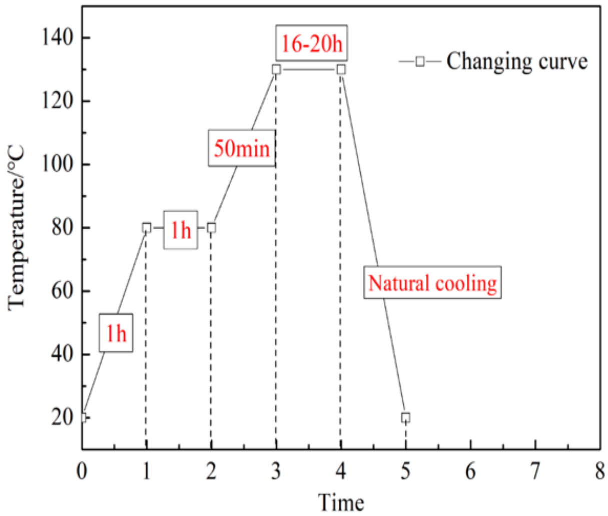


Figure 2. The surface treatment process of aluminum alloy sheets.

The surface treatment process includes four steps: acetone cleaning, alkaline cleaning, deoxidation, and phosphoric acid anodization. The process was used mainly to clean the oil stain on the sheet's surface, to change the surface state of the metal layer, and to improve the connection between the fiber and metal layers, which will reduce delamination risk [33].

2.3. Thermal Treatment Process

After the surface chemical treatment, the metal sheets and fiber composite materials (glass fiber/epoxy prepreg) were alternately laminated to assemble GLARE laminates. Then, affected by the pressure and temperature of an autoclave, the fiber prepreg was thermally cured and bonded with the metal layer, and the FMLs with complete structure and uniform mechanical properties were obtained. During the thermal curing process of the composite laminates, the aluminum alloy sheet with artificial aging treatment will undergo double-stage aging under the condition of curing temperature and time. Thus, the particles of the η' and η phases on the metal grain boundary were spheroidized. It broke the continuity of the precipitated phases at the grain boundary, improved the microstructure, reduced the sensitivity of stress corrosion and spalling corrosion, and improved the fracture toughness of the aluminum alloy sheet. Thus, aluminum alloy with better comprehensive mechanical properties was obtained [34]. Juntao Liu [35] from the University of Science and Technology Beijing researched the effect of the double aging treatment on the properties of the new 7056 aluminum alloy. It found that when the second artificial aging temperature is 150 °C, the yield stress is 650 MPa, the electrical conductivity is 21.72 MS/m, and the smaller η' phases are evenly distributed. Baohua Jiang [36] studied the influence of the double aging treatment on the mechanical performance and microstructure of the 7050-aluminum alloy. It was included that as the second aging temperature increases, the precipitated phase gradually increases, and the precipitated phase is needle-like and evenly distributed under 150 °C. Shanhong Zheng [37] from ZhengZhou University found that the second aging temperature has an obvious effect on the hardness and corrosion resistance of the 7050 aluminum alloy, and various second aging temperature was considered, such as 50 °C, 70 °C, 90 °C, 110 °C,130 °C, 150 °C respectively. Avoiding the glass fiber was destroyed at the high temperature, the temperature and time of thermal curing treatment were set to 120 °C and 1.5 h based on the empirical values and the optimization analysis. The artificial aging path of the aluminum alloy and the vacuum curing path of HFQ-FMLs composite laminates are shown in Figure 3.



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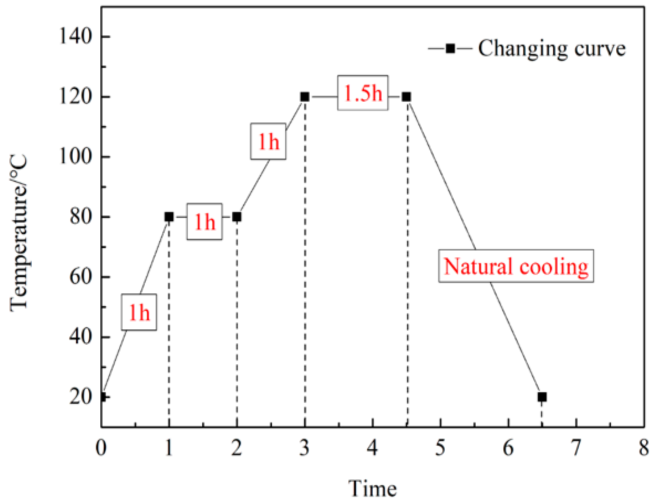


(**b**)

Figure 3. Heat treatment system: (**a**) Artificial aging path of aluminum alloy; (**b**) Vacuum curing path of HFQ-FMLs composite material.

3. Experiment Process

3.1. Materials Preparation

The designed structure of the FMLs in these tests included outer layers of 7075 aluminum alloy plates with a thickness of 1.0 mm and a middle layer of plain-weaved thermoset glass fiber/epoxy prepreg (FRP) with a thickness of 0.2 mm. The 7075 aluminum alloys were purchased from RuiShengChang Aluminum, Tianjin, China and the FRP, which the adhesive is thermosetting epoxy resin, was supplied by the Guangwei Group, Weihai, Shandong Province, China. Using the new compound forming technology HFQ-FMLs, the fiber and metal layers were jointed with adhesive after solidification treatment. The model was GLARE1-2/1-0.2, which indicated that the thickness of each aluminum alloy layer was 1.0 mm, and the number of fiber-reinforced composite layers was 1. The number of the aluminum alloy layer was 2 [38,39].

The chemical composition of 7075 aluminum alloy is shown in Table 1, the mechanical parameters of the original 7075 aluminum alloy were provided by the vender, and the mechanical properties after HFQ treatment were calculated by the experiments, which are listed in Table 2. Based on the mechanical properties of the aluminum alloy after HFQ heat treatment, the subsequent verification of the designability of the new compound forming process HFQ-FMLs can be performed. The composition and mechanical properties of the glass fiber/epoxy resin prepreg provided by the producer are shown in Table 3.

Table 1. Chemical composition of the 7075-aluminum alloy.

Chemical Composition	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Other
Ratio (%)	Bal	0.4	0.5	1.2–2.0	0.3	2.1–2.9	5.1–6.1	0.2	0.18–0.28	0.15

Table 2. Mechanical properties of the 7075 aluminum alloy.

Strain Rate/ $\dot{\varepsilon}$ / Treatment	E/GPa		σ_b/MPa		$\sigma_{0.2}$/MPa		ε_b/%	
	0.001 s^{-1}	0.01 s^{-1}	0.001 s^{-1}	0.01 s^{-1}	0.001 s^{-1}	0.01 s^{-1}	0.001 s^{-1}	0.01 s^{-1}
AA7075 raw material	57.9	100.2	247.3	267	134.4	153	13.3	31.5
AA7075 after HFQ treatment	66.3	27.7	223	204	105	99	28	22

Table 3. Characteristic parameters of glass fiber fabric prepreg WP-9621.

Model	Weaving Method	Fiber Type		Prepreg Weight /g m^{-2}	X_t/MPa	E/GPa	Compressive Strength/MPa	Interlaminar Shear Strength/MPa
		Latitude	Longitude					
WP-9011	Plain	136 tex	136 tex	204	950	42	700	50

3.2. Experiment Scheme for Mechanical Performance

Because of the influence of the fiber direction, the behavior of most FMLs is anisotropic. The metal sheet is directional due to the rolling process at the same time. At present, there are many research reports on the influence that fiber direction has on the performance of FMLs. However, there are few reports about the influence of the metal sheets' direction. Therefore, to study the influence of the anisotropy performance of aluminum alloy and strain rates on the mechanical properties and fracture evolution of FMLs laminates, the new GLARE laminates were carried out in the tensile tests in different directions and with varying rates of strain. Firstly, the aluminum alloy sheets were sampled along the directions of 0°, 45°, and 90° with the rolling direction, and the samples were long strips with a length of 175 mm and a width of 25 mm. To avoid the influence of the fiber orientation on the FMLs, the fiber orientation is fixed when the metal orientation is variable. So, when the angle between the sampling direction of the metal layer and the rolling direction is 45°, the composite laminates are stretched, and the angle between the fiber orientation and the tensile direction is 45° all the time. Secondly, the aluminum alloy samples were processed using HFQ technology. Thirdly, the aluminum alloy samples with the HFQ process were bonded with the glass fiber/epoxy resin prepreg to obtain standard tensile samples of HFQ-FMLs composite laminates in different metal directions, as shown in Figure 4. The tensile tests were carried out on a CTM 100 G universal testing machine which was manufactured by Xie Qiang Instrument Manufacturing (Shanghai) Co., Ltd. from Shanghai, China, and it is shown in Figure 5. The whole process was controlled in the form of load rates, which were converted into strain rates of 0.001 s^{-1} and 0.01 s^{-1}. To prevent the holding end of the composite material specimens from being crushed during the stretching process, the aluminum reinforcement sheets were pasted at both ends.

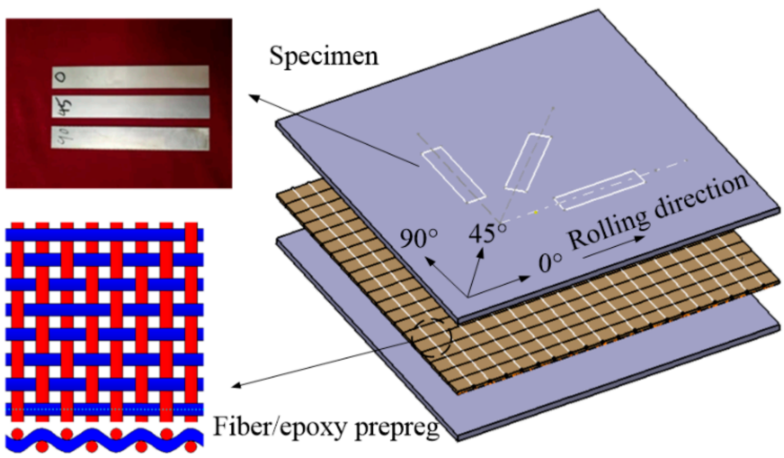


Figure 4. The sampling method of composite material.

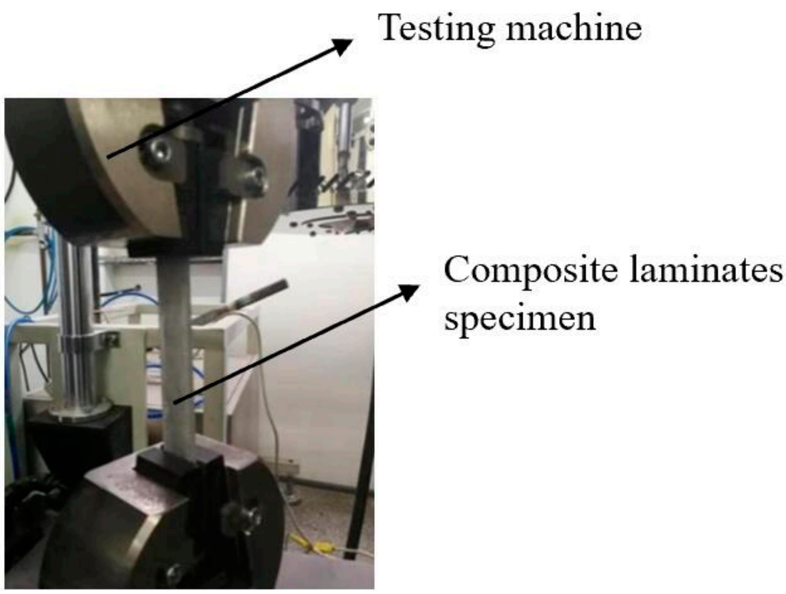


Figure 5. Tensile process of the composite laminates.

The manufacturing process of the tensile specimens is shown in Figure 6. For the surface treatment of the metal sheets, in the alkali wash process, the reagent is the mixture of NaOH and Na_2CO_3, while, In the deoxygenation process, the reagent is HNO_3, and the concentration is 300–500 g/L. In the phosphoric acid anodizing process, the reagent is H_3PO_4, and the concentration is 12–140 g/L. In the tensile procedure, the effects of the metal sheet rolling direction and strain rate on the mechanical properties of FMLs were analyzed, and the process designability and fracture development of the composite materials will be studied at the same time.

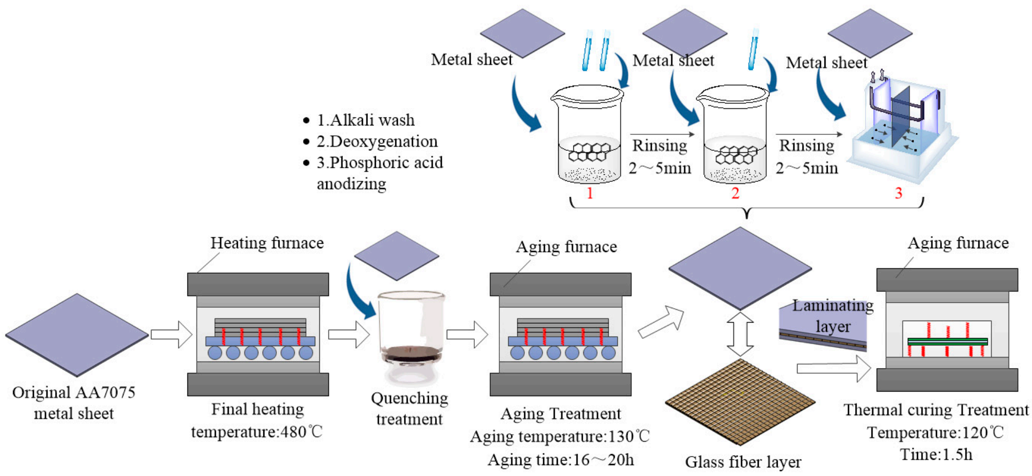


Figure 6. Preparation steps of FMLs blank using the HFQ-FMLs process.

4. Results and Discussion

4.1. Plastic Fluidity Analysis

The tensile experiment specimens were classified as the metal orientation and strain rate, sampled in each direction, and the specimens were numbered in turn. For example, #1-01 and #1-02 represent the 0° direction of the metal sheet, and the strain rate is 0.001 s^{-1} and 0.01 s^{-1}, respectively. #2-01 and #2-02 represent the 45° direction of the metal sheet, and the strain rate is 0.001 s^{-1} and 0.01 s^{-1}, respectively. At the same time, #3-01 and #3-02 represent the 90° direction of the metal sheet, and the strain rate is 0.001 s^{-1} and 0.01 s^{-1}, respectively. The specimens are labelled as the above principle and shown in Table 4.

Table 4. The principle of the specimens coding.

Parameter \ Specimen Label	#1-01	#1-02	#2-01	#2-02	#3-01	#3-02
Strain rate (s^{-1})	0.001	0.01	0.001	0.01	0.001	0.01
Metal direction (°)	0	0	45	45	90	90

To comprehensively analyze the difference in plastic fluidity and mechanical properties of the raw metal sheet, the original metal sheet, aluminum alloy dealt with solution treatment and quick quenching only, aluminum alloy plate disposed of with HFQ technology, and the HFQ–FMLs composite laminates were subjected to the unidirectional tensile test under the same conditions. These are marked as original sheets, treatment one plate, treatment two plates, and laminates. The true stress-strain curves of the four kinds of materials were obtained through data processing and fitting, and the results are shown in Figure 7. The curves are engineering stress and strain curves which can directly express the changing trend of the stress. According to the study, the strength limit and deformation limit it is helpful to make sure of the optimal forming route. Therefore, the descending part of the curve is deleted.

As can be seen from Figure 7, the true stress-strain curves of the four kinds of materials under the directions of three directions of metal sheets and two strain rates are exponential. The plastic forming capabilities of materials, such as the elongation after breakage and the tensile limit, show the sensitivity concerning the direction of the metal sheet and strain rate. When the strain rate is 0.001 s^{-1} and keep invariable, as shown in Figure 7a,c,e, the effect of metal direction on the strength limit is the most obvious for the FMLs, and the difference between the maximum value and minimum value of true stress is almost 75 MPa. While when the strain rate is 0.01 s^{-1} and keep invariable, as shown in Figure 7b,d,f, the effect of metal direction on the strength limit is the most obvious for the aluminum alloy disposed of with hot forming only, and the difference between the maximum value and minimum value of true stress is almost 125 MPa. When the metal orientation is 0° and keeps invariable shown in Figure 7a,b, the effect of strain rate on the strength limit is the most obvious for the FMLs, and the difference between the maximum value and minimum value of true stress is almost 75 MPa. When the metal orientation is 45° and keep invariable shown in Figure 7c,d, the effect of strain rate on the strength limit is the most obvious for the aluminum alloy disposed of with hot forming only, and the difference between the maximum value and minimum value of true stress is almost 125 MPa. While when the metal orientation is 90° and keep invariable shown in Figure 7e,f, the effect of strain rate on the strength limit is the most obvious for the FMLs and the aluminum alloy disposed of with hot forming only and the difference between the maximum value and minimum value of true stress is almost 50 MPa. It can be indicated that the key parameters, such as the strain rate and metal orientation, obviously influence tensile strength.

According to the fitting results of the exponential function of the curves, the distributions of the elastic modulus (E) and the strengthening coefficient (K) under different test conditions for different materials were obtained, as shown in Figure 8.

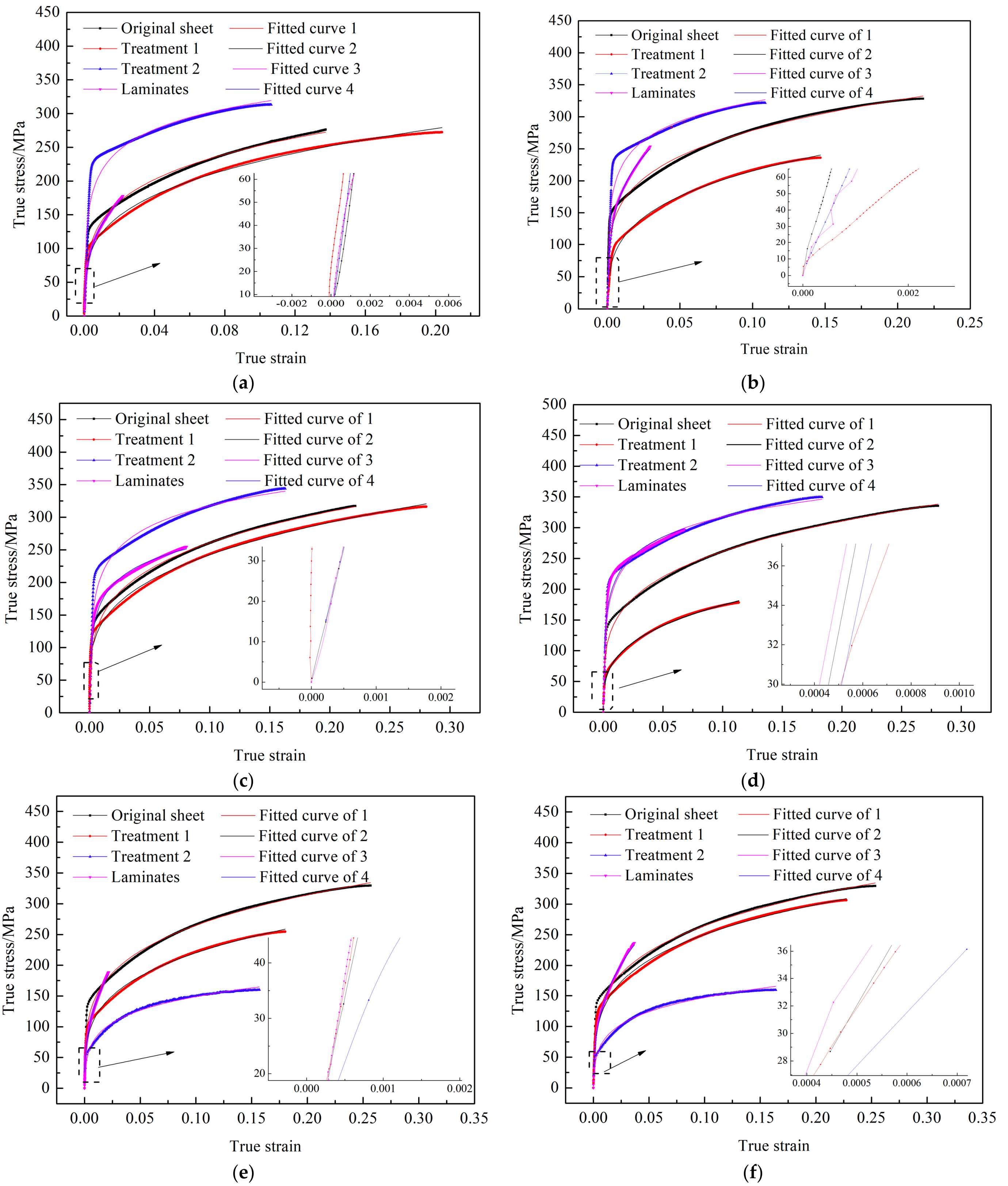
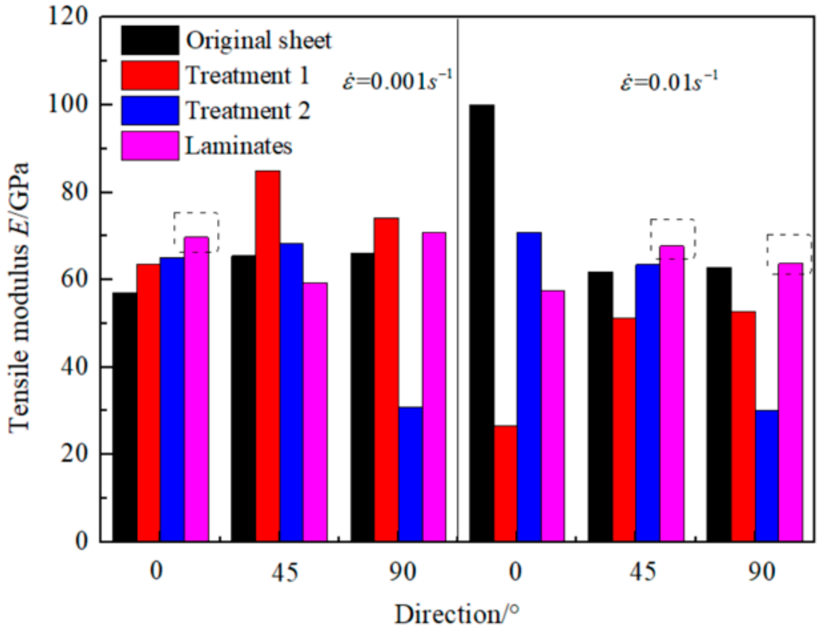


Figure 7. True stress-strain curves: (**a**) 0°, 0.001 s^{-1}; (**b**) 0°, 0. 01 s^{-1}; (**c**) 45°, 0.001 s^{-1}; (**d**) 45°, 0. 01 s^{-1}; (**e**) 90°, 0.001 s^{-1}; (**f**) 90°, 0. 01 s^{-1}.



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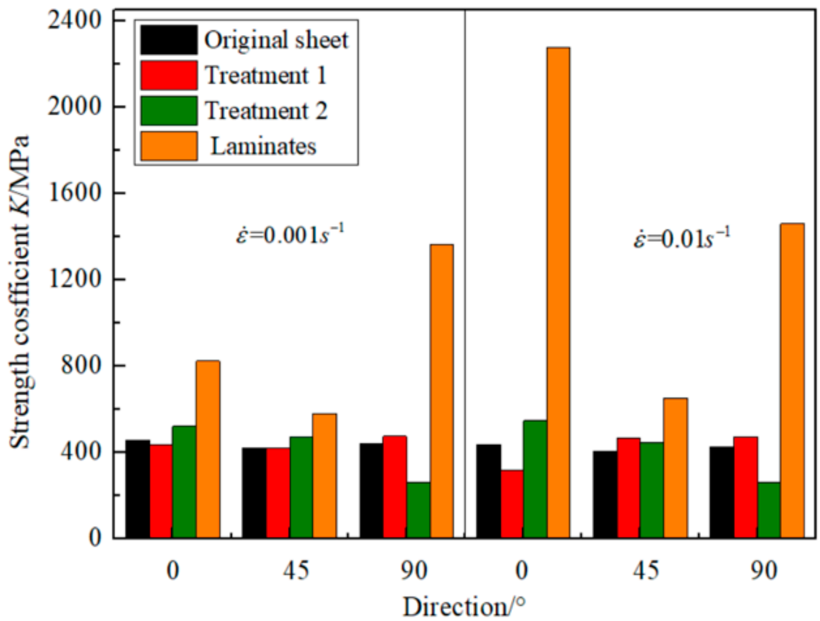


(**b**)

Figure 8. Performance parameters of elastoplastic deformation: (**a**) Tensile modulus *E*; (**b**) Strengthening coefficient *K*.

As can be seen from Figure 8a, in the elastic deformation stage, at the low strain rate, the HFQ-FMLs composite laminates have the best rigidity along the 0° direction, which are better than those of the other three kinds of metal sheet. Under high strain rate conditions, the HFQ-FMLs composite laminates samples have the best rigidity and impact resistance along the 45° and 90°, and the results for these samples are superior to those of metal sheets in the other three states. These observations indicate that the metal sheet direction is critical to fully achieve the elastic deformation resistance for HFQ-FMLs composite laminates under the conditions of different deformation loads. When the strain rate is 0.001 s^{-1}, the direction of the metal sheet of the HFQ-FMLs composite laminates should be 0°; when the strain rate is 0.01 s^{-1}, the direction of metal sheet of the HFQ-FMLs composite laminates should be 45° and 90°.

Figure 8b shows that the distribution of *K* characterizes the plastic deformation stiffness, and the HFQ-FMLs composite laminates have obvious advantages under different strain rate conditions. This is because the longitudinal tensile limit of the glass fiber/epoxy composite material is higher than that of the metal layer. When the outer metal yields and enters the plastic deformation stage, the "bridging effect" of the two kinds of materials delays the time to reach the tensile limit of the composite laminates. As the strain rate increases, the direction of the composite laminates that have superior stiffness changes from 90° to 0°, and this indicates that the plastic deformation ability of the composites is higher along the 0° and 90° directions.

The distributions of yield strength (σ_s) and tensile strength (σ_b) are shown in Table 5.

Table 5. Statistical results of yield strength and tensile strength.

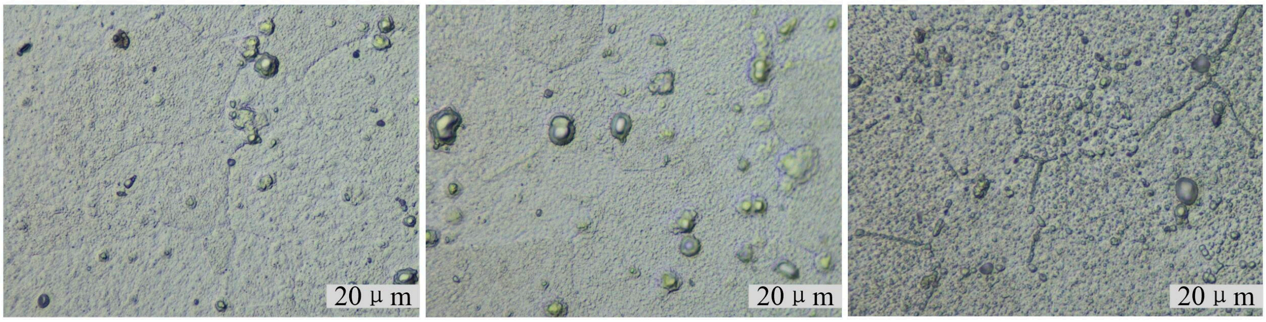
Specimen \ Index/Direction, Strain Rate (s^{-1})	σ_s/MPa						σ_b/MPa					
	0°		45°		90°		0°		45°		90°	
	0.001	0.01	0.001	0.01	0.001	0.01	0.001	0.01	0.001	0.01	0.001	0.01
Original sheet	135.6	153	140.4	142.9	140.7	143.7	276.2	328.3	317.4	335.5	329.4	329.4
Treatment 1	106	100.8	124.4	66.1	103.5	125.5	272.3	236.1	316.3	178.2	254.6	306.4
Treatment 2	230.3	236.3	216.6	216.1	62.7	57.9	313.1	326.1	343.9	349.7	160.1	159.4
Laminates	92.3	146.5	154.5	207.3	91.2	103.1	177.9	253.9	255	297	188.8	236.6

Vertical comparison of the data in Table 5 shows that the yield strength (σ_s) and tensile strength (σ_b) of the sheets in four different states are significantly different under different strain rates and different directions of the sheets. Taking the yield strength as an example, strain rate has a minimal effect on yield strength for the first three materials, and the yield strength value is very close along the same direction of the metal sheet under different strain rate conditions. The maximum difference is 46.8% under the condition of the treatment of one plate along the 45° direction, and the minimum difference is nearly 0 under the treatment of two plates along the 45° direction. However, the strain rate significantly influences the yield strength of the HFQ-FMLs composite laminates, and the yield strength along the 45° direction of the metal sheet is the largest. In the same way, taking the tensile strength as an example, the strain rate significantly influences the tensile strength of the HFQ-FMLs composite laminates, and the tensile strength along the 45° direction of the metal sheet is the largest.

All these show that the HFQ-FMLs composite laminates are significantly sensitive to strain rate. When the metal sheet is sampled at 45° along the rolling direction, the mechanical properties of the composite laminates are more prominent. The yield stress value and the tensile stress value are all the maximum, thus revealing that the performance of the FMLs is affected by not only the direction of the fiber layup but also the anisotropy of the metal sheet.

The differences in the mechanical properties of the aluminum alloy samples after two heat treatment processes were analyzed and combined with the microstructure observation, so the non-deformed areas of the original material and the specimens with two kinds of heat treatments were sampled and observed. The results are shown in Figure 9.

In Figure 9a, the original microstructure is mainly the α (Al) solid solution, and many black impurity phases are distributed on the microstructure. In Figure 9b, it is the quenched microstructure which is consisted of α (Al) matrix. It is embedded with many black impurity phases and a small number of precipitated phases distributed as gray bulk. As can be seen in Figure 9c, which dealt with artificial treatment after quick quenching, the microstructure is a mixture of α (Al) matrix, many grain boundaries and lots of intragranular precipitation phases, lots of precipitation phases hinder the dislocation movement, and the macroscopic mechanical properties can be improved, this is the key to significantly improve the strength of aluminum alloy after artificial aging.



(**a**) (**b**) (**c**)

Figure 9. Distributions of microstructure at various stages: (**a**) Original microstructure; (**b**) Quenched microstructure; (**c**) Microstructure after artificial aging.

4.2. Designability of the HFQ-FMLs Composite Laminates

Given the above-mentioned mechanical properties of fiber laminate, aluminum alloy laminate with HFQ treatment, and HFQ-FMLs composite laminates, a mathematical model was used to predict and compare their tensile properties to verify the designability of the HFQ-FMLs composite laminates. The metal volume fraction (*MVF*) formula proposed by M.S.pma [40] was used as the theoretical foundation. The *MVF* value is defined as:

$$MVF = \frac{\sum_{1}^{p} t_{al}}{t_{lam}} \tag{1}$$

Among them, the t_{al} is the thickness of the single-layer aluminum alloy sheet, mm; t_{lam} is the thickness of FMLs, mm; p is the number of aluminum alloy sheets.

In the above formula, when $MVF = 1$, the HFQ-FMLs composite laminates are pure aluminum alloy sheets, and the performance is that of aluminum alloy. When $MVF = 0$, the HFQ-FMLs composite laminates are pure glass fiber/epoxy resin prepreg. Using *MVF*, the tensile property prediction of the HFQ-FMLs composite laminates is as follows:

$$E_{lam} = MVF \times E_{met} + (1 - MVF) \times E_{FRP} \tag{2}$$

$$\sigma_{0.2,lam} = \left[MVF + (1 - MVF) \times \frac{E_{FRP}}{E_{met}} \right] \times \sigma_{0.2,met} \tag{3}$$

$$\sigma_{t,lam} = MVF \times \sigma_{t,met} + (1 - MVF) \times \sigma_{t,FRP} \tag{4}$$

where E is the tensile modulus, MPa; $\sigma_{0.2}$ is the tensile yield strength, MPa; σ_{t} is the ultimate tensile strength, MPa; *lam* represents the laminates, *met* represents the aluminum alloy, and *FRP* represents the fibre-reinforced composite material.

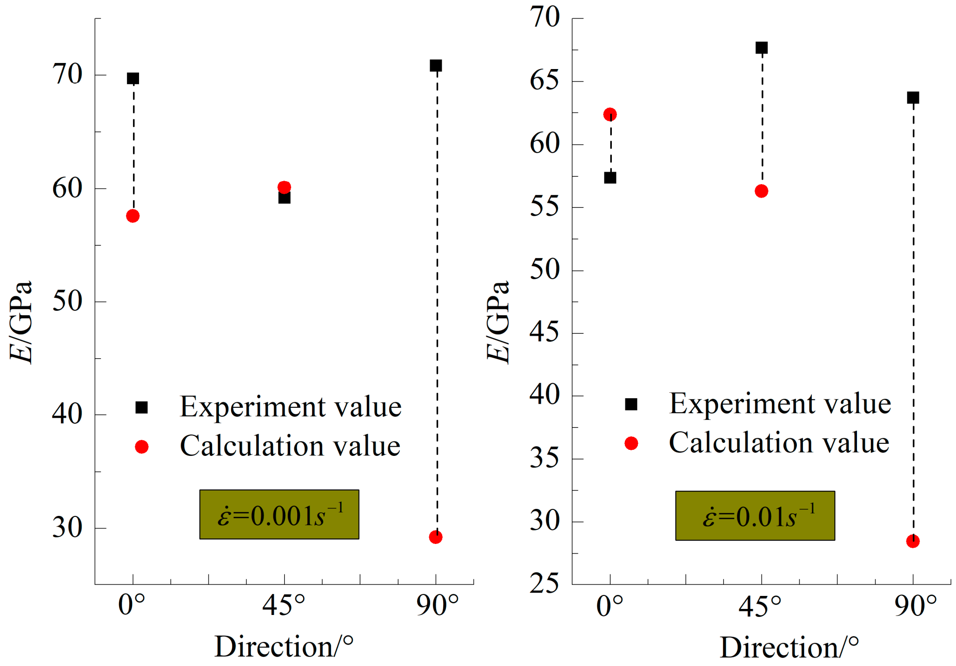
Because the *MVF* theory is for composite laminates laying unidirectional, the glass fiber in this paper is plain weave, and it can be regarded as a transverse and longitudinal orthogonal layer. The *MVF* theory needs to be improved and revised. Referring to the research method of Hongyi Ma [41], the *MVF* theory was modified because of the unidirectional layer theory. Thus, the *MVF* formula of the orthogonal bidirectional layer was obtained.

$$E_{lam} = MVF \times E_{met} + \frac{1}{2}(1 - MVF) \times E_{FRP} \tag{5}$$

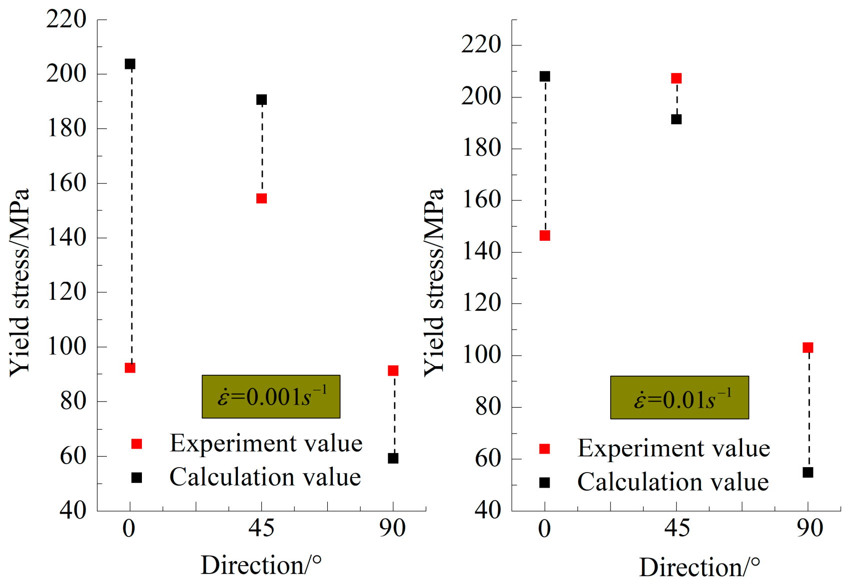
$$\sigma_{0.2,lam} = \left[MVF + \frac{1}{2}(1 - MVF) \times \frac{E_{FRP}}{E_{met}} \right] \times \sigma_{0.2,met} \tag{6}$$

$$\sigma_{t,lam} = MVF \times \sigma_{t,met} + \frac{1}{2}(1 - MVF) \times \sigma_{t,FRP} \tag{7}$$

Using the above modified *MVF* formula, the mechanical properties of aluminum alloy laminates and glass fiber prepreg were brought in, and the theoretical calculation values of tensile modulus, tensile yield strength, and ultimate tensile strength of the HFQ-FMLs composite laminates were obtained. The calculation results are compared with the experimental values shown in Figure 10.

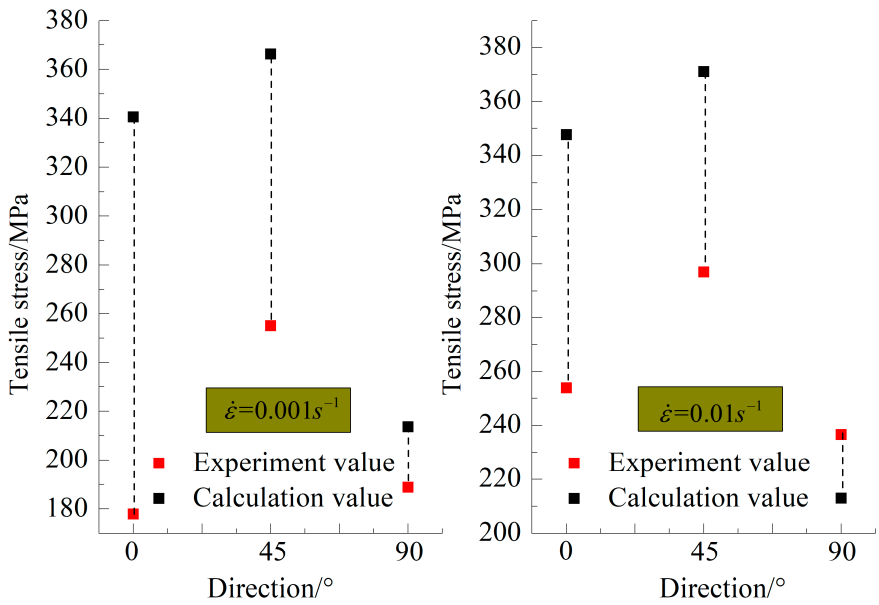


(**a**)



(**b**)

Figure 10. *Cont*.



(**c**)

Figure 10. Comparison of theoretical calculations and experimental values of mechanical properties of the HFQ-FMLs composite laminates: (**a**) Tensile modulus; (**b**) Yield stress; (**c**) Tensile stress.

For the modulus of elasticity, yield stress and tensile stress, it was shown in Figure 10 that there exist different deviation degrees between the experimental results and calculations, and it is indicated that the influence of alloy orientation on the FMLs obtained by the HFQ-FMLs technology is random and there is no regular. The strain rate has little effect on the error level between the experimental and calculated values of the tensile properties of the HFQ-FMLs composite laminates. Instead, the direction of the metal sheet has a significant effect on the error level. When the strain rate is 0.001 s^{-1}, the deviation between the experiment value and calculation value of tensile modulus is minimum along the 45°. It is almost 0, and the maximum error values exited along the 90°. When the strain rate is 0.01 s^{-1}, the deviation between the experiment value and calculation value of yield stress is not more than 10% along the 45°, and the maximum error values exited along the 90° too. At the same time, the deviation between the experiment value and calculation value of tensile stress is not more than 20% along the 90°, while the maximum error values exited along the 0° and 45°, respectively. Therefore, the theoretical predictions of the tensile properties of HFQ-FMLs composite laminates are directional and can be designed along certain directions of the metal sheet. The tensile modulus of HFQ-FMLs composite laminates can be theoretically predicted along the 0° and 45° directions, the tensile yield strength can be theoretically predicted along the 45° and 90° directions and the ultimate tensile strength can be theoretically predicted along the 90° direction. This comprehensively shows that the anisotropy of the metal sheet is an essential factor influencing the performance difference of the FMLs.

4.3. Fracture Development of the HFQ-FMLs Composite Laminates

After the tensile experiments for all the specimens, the observations of the enlarged image of the morphology were shown in Figure 11.

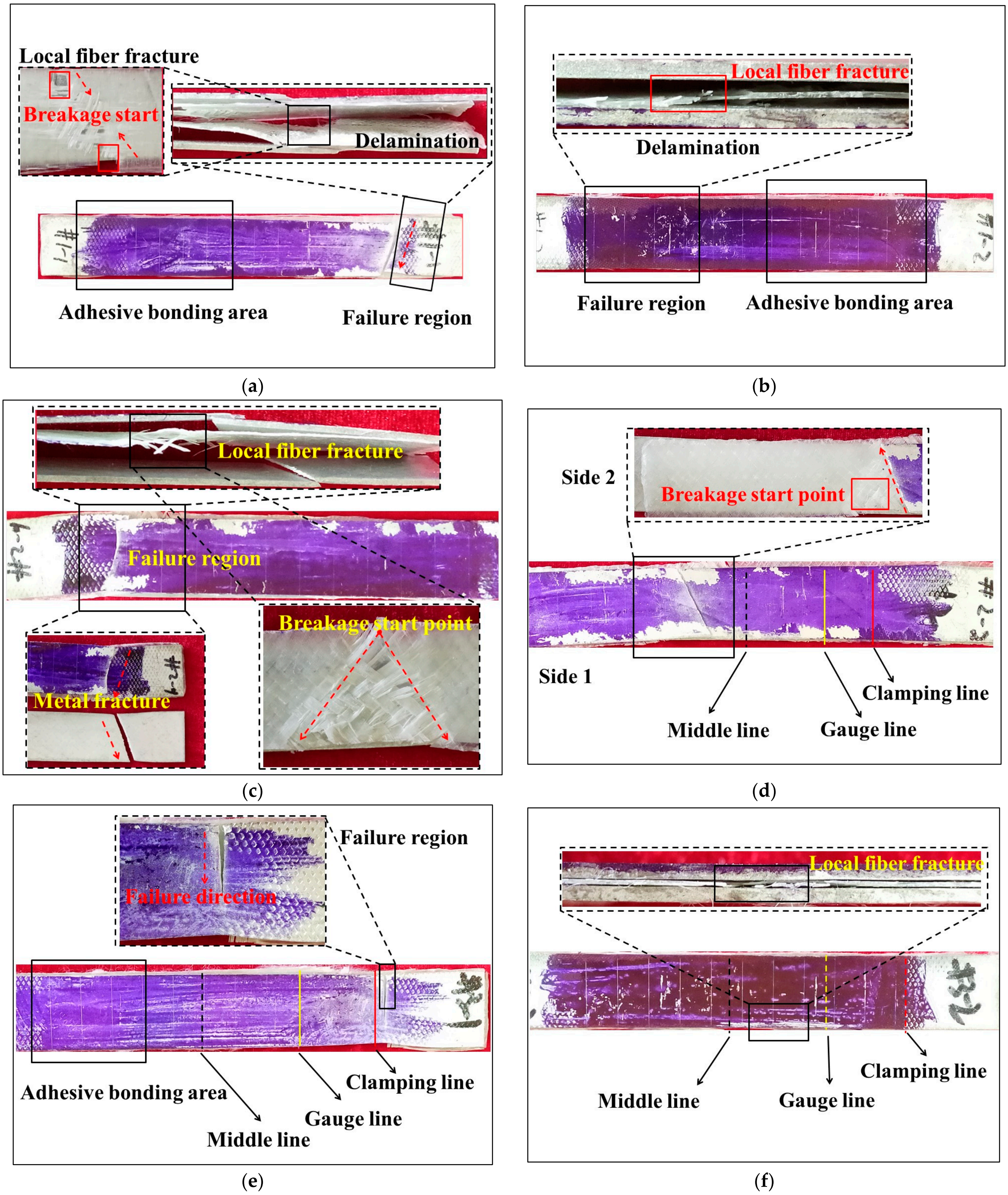


Figure 11. Analysis of the fracture defect morphology: (**a**) 0°, 0.001 s^{-1}; (**b**) 0°, 0.01 s^{-1}; (**c**) 45°, 0.001 s^{-1}; (**d**) 45°, 0.01 s^{-1}; (**e**) 90°, 0.001 s^{-1}; (**f**) 90°, 0.01 s^{-1}.

According to the fracture morphology shown in Figure 11, when the combination of the sheet direction and the strain rate was 0°/0.001 s^{-1}, 45°/0.001 s^{-1}, 45°/0.01 s^{-1}, and 90°/0.001 s^{-1} respectively, the metal plate was destroyed. Because the maximum stress in the FMLs has exceeded the strength limit of the metal, the metal happened cracks. First, the cracks extended over the prepreg, and the FMLs finally failed. Moreover, when the direction of the metal sheet was 45°, and the strain rate was 0.001 s^{-1}, the metal plate was destroyed on both sides, and this is highly consistent with the changing trend of the displacement–load curve in Figure 11. At the same time, when the directions of the metal sheet were 0° and 45°, and the strain rate was 0.001 s^{-1}, the HFQ-FMLs composite laminates happened a serious delamination phenomenon. This is because delamination is mainly governed by the interlaminar shear strength of FMLs. Delamination occurs when the induced shear stress exceeds the interlaminar shear strength of FML. When the direction of the metal sheet was 0°, and the strain rate was 0.01 s^{-1}, there was obvious delamination of the metal and fiber layers. When the direction of the metal sheet was 90°, and the strain rate was 0.01 s^{-1}, there was no obvious delamination of the metal and fiber layers. It may be affected by the joint quality between the alloy and fiber prepreg, so to obtain the FMLs with better mechanical properties, the surface treatment quality of the alloy and the cohesive state of thermosetting resin are essential. However, as can be seen from the bonding interface, the fiber layer was destroyed to a certain extent, which ultimately led to the load drop in the displacement–load curve.

The innovative HFQ-FMLs compound forming technology includes hot forming for high-strength aluminum alloy and fiber prepreg laying craft. In the HFQ forming process, the deformation limit of aluminum alloy can be improved because of the high forming temperature, and the tensile strength can also be enlarged due to the diffusion precipitation of the reinforced phase. This ensures that the FMLs will have complex shapes and big sizes. In the second step, just as in the thermal curing process of the hybrid material, the composites with entire structures and uniform mechanical properties will come true according to setup and optimize the curing temperature and time. At the same time, the aluminum alloy happened double-stage aging. The strength will descend within a small range while it shows excellent stress corrosion resistance capacity. The key scientific issue is looking for a perfect technology route by which the comprehensive metal property is promoted, and the FMLs have excellent quality and complicated structure. The research results can facilitate the wide application of materials in the aerospace field and enhance national defence and military ability. While the GLARE laminates will not obtain the complex shape, big structure size and perfect comprehensive properties at the same time using the traditional technologies, and there is no relevant report for the innovative HFQ-FMLs forming process.

5. Conclusions

(1) According to the distribution of elastoplastic mechanical properties of HFQ-FMLs composite laminates and the other sheets in three different states, the performance of FMLs is sensitive to the direction of the metal sheet and strain rate. It can be seen from the yield stress distribution that the maximum deviation is 63.3 MPa when the strain rate is 0.001 s^{-1}, the maximum deviation is 104.2 MPa when the strain rate is 0.01 s^{-1}, and the maximum value happened at the 45°, so the metal direction 45° has an essential effect on the FMLs. Along the metal direction 0° and 45°, the maximum deviation is almost 50 MPa under different strain rates. Along the metal direction 90°, the minimum deviation is nearly 12 MPa, so it can be concluded that the strain rate has little effect on the yield ability when the metal direction is 90°. The rigidity of the composite laminates is better than that of other metal sheets in three states for the following three situations: (1) a strain rate of 0.001 s^{-1} and the metal sheet direction of 0°, (2) a strain rate of 0.01 s^{-1} and the metal sheet direction of 45°, and (3) a strain rate of 0.01 s^{-1} and the metal sheet direction of 90°. These observations emphasize the necessity of designing the HFQ-FMLs compound process for FMLs and show that the performance of FMLs is affected by both the direction of the fiber layer and the anisotropy of metal laminates.

(2) Modified *MVF* theory was used to predict the tensile properties of the HFQ-FMLs composite laminates. A comparison of experimental and theoretical values found

that the designability of HFQ-FMLs composite laminates is directional. The tensile modulus can be predicted theoretically along the 0°, and 45° directions, the minimum deviation between the experimental and theoretical value is 0 when the strain rate is 0.001 s^{-1} along 45°, and the minimum deviation value is 5 GPa when the strain rate is 0.01 s^{-1} along 0°. The yield strength can be predicted theoretically along the 45°, and 90° directions, the minimum deviation between the experimental and theoretical value is 30 MPa when the strain rate is 0.001 s^{-1} along 90°, and the minimum deviation value is 20 MPa when the strain rate is 0.01 s^{-1} along 45°. The ultimate tensile strength can be predicted theoretically along the 90° direction, and the minimum deviation between the experimental and theoretical value is 20 MPa when the strain rate is different.

(3) According to the analyses of the displacement–load curves and fracture morphology of the HFQ-FMLs composite laminates, it is found that the direction of the metal sheet and strain rate affect the defect evolution of the composite material. This results in differences in the elongation of the composite material after fracture, and this reflects the different damage tolerances of the composite materials in different states. When the combination of the direction and strain rate of the metal sheet is 45°/0.001 s^{-1} and 45°/0.01 s^{-1}, the mechanical properties of the composite laminates are more prominent, the yield stress and the tensile stress are all the maximum, the value is 207.3 MPa and 297 MPa respectively, and the composite material has excellent damage tolerance.

(4) In this paper, the comprehensive property of GLARE laminates with complex structure can be improved greatly by optimizing the parameters, because there is a lot of influence factors and the morphological cooperative control process is very complex, the optimization process for the coupling of limit values of the mechanical properties and big size is a very challenging direction of research for the scholars. For the high strength, lightweight and complex structure, the GLARE laminates obtained by the HFQ-FMLs compound forming technology will not only be able to be used in the field of aerospace but also in the field of automobiles and ships and has a large range of market applications and promotion.

Author Contributions: Q.Z. and F.S. put up the multi-filed compound forming technology and designed the experiments; Q.Z. Designed the schemes of the tensile test of the composite laminates obtained by the HFQ-FMLs compound forming technology; Y.M. performed the metallographic, microstructure analysis; Z.S. and Y.M. calculated the experiment results and obtained the mechanical performance parameters under different conditions; F.S. and Z.S. carried out the derivation of the theoretical formula, and compared the results with the experimental data. All authors have read and agreed to the published version of the manuscript.

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