Effect of groove configuration on mechanical properties and fracture behavior of 6061 Al alloy and CFRTP laser joint

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Abstract
Laser surface texturing is generally a promising approach to enhance the adhesion property of a metal-thermoplastic hybrid structure, and the effect is related to groove configuration. Laser joining of a carbon fiber-reinforced thermoplastic (CFRTP) composite to a 6061 Al alloy under various groove configurations was carried out, aimed to investigate the effect of groove width and depth on interfacial morphology, mechanical properties, and fracture behavior of CFRTP/Al joints. Tensile shear force was tested, and fracture surface and interface morphology were observed by scanning electron microscopy. Besides, the numerical simulation of the temperature field was conducted to reveal the joining mechanism. The results indicate that the tensile shear strength of the CFRTP/Al joint gradually increases with the increase of groove width and reaches a peak value of 22.8 MPa when the width is 0.5 mm. As the groove width is further increased, the tensile shear strength of the CFRTP/Al joint decreases. Compared to groove width, the tensile shear strength of the CFRTP/Al joint presents a similar variation trend with the increasing groove depth on the Al alloy surface. When the groove depth reaches 0.6 mm, the maximum joint strength is 24.33 MPa. After the Al alloy is laser-textured, the surface fracture mode of the CFRTP/Al laser joint features a mixed fracture mode including a cohesive fracture and an interface fracture. This study provides a deeper understanding of the effect of groove configuration on the laser joining of the CFRTP/Al hybrid structure and potentially lays a foundation for the adjustment of a suitable groove configuration toward obtaining the desired effect.

Keywords Laser joining · CFRTP · Groove configuration · Interface morphology · Mechanical properties

1 Introduction
A carbon fiber-reinforced thermoplastic (CFRTP) composite with excellent mechanical properties, such as high specific strength, lightweight, and shock resistance, has become an alternative material in the aerospace manufacturing field [1–4]. Due to the lightweight of using CFRTP, the mixture of a metal and a CFRTP is still common, such as the Airbus H-160 helicopter hub and the Boeing 787 wing structure. A CFRTP mixed with an Al alloy can promote the material lightweight process [5, 6]. The traditional CFRTP joining methods included mechanical fastening and adhesive bonding, which have some disadvantages [7, 8]. For example, mechanical connections require perforation, causing stress concentration and increasing the weight of the joint. Adhesive bonding quality is related to surface treatment and the choice of bonding agent, but the large number of users of bonding agents will pollute the environment. To overcome the above shortcoming, laser welding [9–13], induction welding [14–17], friction stir welding [18–20], and ultrasonic welding [21–23] were adopted in the joining of CFRTP to Al alloy. Among all the joining technologies employed to date, laser welding with high efficiency and few defects was more useful to expand the application range of multi-material structures [24, 25].

However, linear expansion coefficient and heat conductivity pose a great challenge in laser joining of CFRTP to metal. The numerical simulation of the welding process plays an important role in the analysis of joint performance properties [26]. Tan et al. [27] analyzed the temperature field during laser joining of steel to carbon fiber-reinforced polymer (CFRP) process and explained the bubble formation and the mechanism of their distribution after cooling. Wang et al. [2] established a temperature field model considering heat

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transfer in the process of laser direct joining of a heterogeneous CFRT/Al alloy reactor and analyzed the improvement of joint performance through a laser direct joining experiment, proving the rationality of the proposed method. Jiao et al. [9] used the laser plastic cladding method on the metal surface to significantly improve the shear strength and fatigue resistance of CFRT/TC4 joints. Arkhurst et al. [28] studied the effect of thermal oxidation on the joining strength of carbon fiber-reinforced plastic and AZ31 Mg alloy using the laser-assisted metal and plastic joining technique. Xia et al. [29] reported the influence of laser power on the interfacial microstructure, bonding mechanism, and mechanical performance of laser-welded CFRT to steel joints and found the formation of chemical bonds during the joining process. Lambiase et al. [11, 30] claimed the laser-assisted joining between Al alloy and polyether ether ketone, and AA5053 and polyvinyl chloride (PVC), respectively. The influence of laser power on its joint performance was further analyzed.

The property enhancement of a metal/CFRP joint could be realized by improving mechanical interlocking. Zhang et al. [31] investigated the laser surface engraving technology to prevent the formation of CFRP shrinkage holes, and the results show that the laser surface texture could inhibit the formation of shrinkage cavities. Heckert et al. [32] pretreated the surface of Al alloy with the laser etching technology, realized the joining between the Al alloy and a glass fiber-reinforced thermoplastic composite with the laser heat conduction technology, and found that the surface pretreatment method could improve the joint strength. Tan et al. [33] explored the effect of texture mesh depth on joint performance. Rodríguez-Vidal et al. [34] used two different laser sources to produce the metal micro-structuring and studied the effect of different groove geometries on the joint’s failure force under tensile shear tests, which demonstrated the feasibility of the laser texturing process in the enhancement of CFRT/Al alloy joints. Groove configuration, a parameter of the laser texturing morphology, affected the interfacial contact area and the final joint strength of CFRT/Al alloy joints. However, the influence of groove configuration on joint strength and fracture mode in laser joining CFRT to laser-textured Al alloy surface was not completely comprehended.

In this work, laser surface texturing was applied on the surface of the 6061 Al alloy to assist the laser joining of CFRT and 6061 Al alloy. The intention of the current study is to investigate the influence of groove configuration on the fracture mode and joining strength of the CFRT/Al alloy. Combined with the numerical simulation of temperature field, the influence mechanism of interfacial microstructure and fracture mode was revealed.

2 Experimental

2.1 Materials

The base metal used was 6061-T6 Al alloy with a solution heat-treated and artificially aged, and its nominal chemical compositions are presented in Table 1. The resin matrix of CFRT used in this study was polyether ether ketone (PEEK), and the reinforcement was T300 carbon fiber. The layer angle of composites was ±45°. The base metal was cut into the dimension of 50 mm × 25 mm × 2 mm.

2.2 Laser surface texturing

In order to improve the energy absorption rate of laser beam on the surface of the Al alloy, the surface of the Al alloy was sandblasted before the test. Then, the Al alloy sheets were treated by laser texturing before laser joining. Figure 1

Table 1 Chemical composition of the 6061-T6 Al alloy (wt%)

|       | Mg     | Fe  | Si   | Zn   | Cu   | Ti   | Mn  | Cr   | Al     |
|-------|--------|-----|------|------|------|------|-----|------|--------|
|       | 0.8–1.2 | 0.7 | 0.4–0.8 | 0.25 | 0.15–0.4 | 0.15 | 0.15 | 0.04–0.35 | Balance |

Fig. 1 Sand blast and laser fabrication on the metal surface. (a) Schematic diagram of sand blast and laser texturing process. (b) Principle of interaction between pulsed laser and Al alloy.
(a) exhibits the schematic of pulse laser beam machining to the textured Al alloy sheet surface. Based on the principle of interaction between pulse laser and Al alloy in Fig. 1(b), the pulse laser scanned the surface of metal along a specific path to remove excess materials and process the designed groove. As a result, the “raster-like” uniform and continuous Al alloy etching groove was formed. In this study, a laser fabrication area of 20 mm × 25 mm was textured on the surface of Al alloy. The groove size parameters included width, spacing, and depth. The width and spacing could be directly set in supporting software, while the depth was dependent on repeated laser processing times. Obviously, the depth increased with the increase of processing times. The pulse laser processing parameters of the groove are shown in Table 2. In order to ensure that the textured area on the Al alloy surface is the same, the spacing of the groove increases with the width of the groove. After the laser surface treatment, 6061 Al alloy samples were ultrasonically cleaned in acetone for 15 min and then in distilled water for another 15 min, and finally dried in a constant-temperature drying oven.

### 2.3 Laser direct joining

Lap joint configuration with 20 mm lap width was adopted between the laser-textured Al alloy surface and the CFRTP as shown in Fig. 2. The joining experiment of CFRTP and Al alloy was performed by laser direct joining equipment, which consisted of a KUKA 6-axis robot, an IPG YLS-10000 fiber laser, and a series of pressing clamps. Based on previous preliminary experiments, tight joining could not be achieved under lower heat input, while a large number of spatters and pore defects occurred under higher heat input. Therefore, the well-formed lap joints of the CFRTP/Al alloy could be obtained with laser power of 2000 W, joining speed of 0.015 m/s, and defocusing distance of +18 mm. In order to investigate the influence of metal surface groove configuration on the CFRTP/Al alloy joints, identical laser joining parameters were adopted in this study to avoid the effect of other factors.

### 2.4 Tensile shear test and morphology observation

In order to obtain the mechanical strength of the produced joints, tensile shear tests of the lap joint were performed using the electronic universal testing machine UTM 5000 with a cross-head displacement rate of 1.3 mm/min. Due to no specific standard for the tensile shear test of the CFRTP/Al alloy, identical laser joining parameters were adopted in this study to avoid the effect of other factors.

Table 2  Parameters of laser surface texturing on the 6061 Al alloy surface

| Test number | Number of reprocessing | Groove width (mm) |
|-------------|------------------------|-------------------|
| No. 1       | 40                     | 0.3               |
| No. 2       | 40                     | 0.5               |
| No. 3       | 40                     | 0.7               |
| No. 4       | 55                     | 0.3               |
| No. 5       | 70                     | 0.3               |

Fig. 2  Laser direct joining of CFRTP and Al alloy. (a) Schematic diagram of the joining process. (b) Connection mechanism. (c) Flowing and filling of melted resin at the interface.
Al alloy lap joint up to now, we mainly refer to ASTM D 1002–01 and its supplementary ASTM D 3163–01 to design the single-lap joint structure and conduct the tensile shear test [35]. The schematic illustration of the tensile shear test and the dimension of the test sample are shown in Fig. 3.

The samples were cut perpendicularly to the traveling direction for interfacial characterization and tensile shear test. The cross-sections of the interfaces between CFRTP and 6061 Al alloy were mechanically ground, polished, and then etched with a solution consisting of 2.5% HCl + 1% HF + 95% H2O, and the interfacial microstructure between CFRTP and 6061 Al alloy was evaluated by SEM.

3 Finite element simulation

A 3D transient numerical model for the laser joining of CFRTP/Al was created based on the above experimental process. The temperature field was simulated using the MSC Marc commercial calculation software.

For the purpose of simplifying the simulated process and improving operation efficiency, the flow behavior of molten resin and the chemical reaction that occurred at the interface are ignored during the simulated process. The transient heat transfer equation is expressed as follows:

\[
\rho c \frac{dT}{dt} = \frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) + Q(x,y,z,t)
\]  

(1)

where \( Q \) refers to the heat caused by the laser and \( \rho \) represents the density of the materials. \( c \) means the specific heat of the materials and \( K \) means the thermal conductivity. The Al alloy is regarded as an isotropic material. Nevertheless, the CFRTP is assumed as an anisotropic material.

The selection of the heat source model directly affects the accuracy of laser joining process simulation. To ensure that the mathematical model closely reflects reality, the heat distribution generated by laser reaching the Al alloy surface is treated as “Gaussian surface heat source + exponential rotating parabolic body heat source” as described in Formula 2. The hybrid heat source can be realized by conducting a user subroutine for secondary development. On one hand, the Gaussian surface heat source represents the heating effect of plasma on the connector in the laser joining process, and the expression is shown in Formula 3. On the other hand, the exponential rotating parabolic body heat source represents the penetrating effect of the laser beam on the Al alloy surface in the process of laser thermal conductivity [36], and the expression is shown in Formula 4.

\[
Q \times \eta = Q_s + Q_v
\]  

(2)

\[
q_s(x,y) = \frac{\alpha Q_s}{\pi r_s^2} \exp \left[ -\alpha \left( x^2 + y^2 \right) \right]
\]  

(3)

\[
q_v(x,y,z) = \frac{27Q_v}{2\pi Hr_s^2} \exp \left( -\frac{3z}{H} \right) \exp \left[ -\frac{3H(x^2 + y^2)}{(H - z)r_s^2} \right]
\]  

(4)

where \( q_s \) and \( q_v \) represent the heat flux distribution of the Gauss surface heat source and the exponentially rotating parabola body heat source, respectively. \( Q_s \) and \( Q_v \) represent the effective power input of the Gauss surface heat source and the exponentially rotating parabola body heat source, respectively. \( Q \) is the total power input during the laser joining process and \( \eta \) is the thermal efficiency coefficient of the heat source. \( \alpha \) is the energy concentration coefficient of the surface heat source, \( r_s \) is the radius of the opening at the top of the heat source of the exponential rotating parabola, and \( H \) is the height of the heat source of the exponential rotating parabola. The shape of the parabolic body of rotation is determined by \( r_s \) and \( H \).

A 3D heat source model consistent with the actual size was established. The laser joining area was a rectangular area of 20 mm × 25 mm. The meshes of the single lap structure geometric entity model were divided, and the element type was hexahedron. In the region close to the laser-heated area, the energy transfer is intense and the temperature changes greatly. Therefore, to ensure solution accuracy, a finer mesh is used in the laser-heated area. At the same time, the coarse mesh is used in other areas to reduce the computation time. The accurate thermal and physical parameters of materials directly affect the accuracy of simulation results. As the carbon fiber is laid along ±45°, the thermal conductivity of CFRTP is anisotropic. In this study, the thickness direction along the CFRTP is defined as the Z direction. Based on PEEK and T300 thermophysical property parameters, the thermophysical property parameters of the CFRTP sheet were obtained, as shown in Table 3.

To improve the efficiency of solving the temperature field in the laser joining process, the finite element model was simplified appropriately by ignoring the factors that have little influence on the simulation results under the premise of ensuring the accuracy of the calculation. The following assumptions and simplifications were made for the simulation:

![Fig. 3 Illustration of the tensile shear sample (mm)](image)
In the simulation process, the room temperature is considered to be 20 °C, and the initial temperature of the laser joining process is room temperature.

The 6061 Al alloy is isotropic, and its material thermo-physical properties are independent of spatial lattice and lattice position.

The complex physical and chemical changes of carbon fibers in thermoplastic composites under laser irradiation are ignored.

It is approximately considered that the thermophysical property parameters of CFRTP do not change in the whole joining temperature range.

The shape of the grooves is all simplified to rectangles.

The boundary condition is the heat exchange with the environment medium during heating and cooling. In the process of laser joining, the heat exchange mode is divided into the heat radiation of the joint and the heat convection between the joint and the air, among which heat convection is the main way of energy loss. In the simulation process, the heat exchange method in the connection process is simplified, and the heat radiation of the joint is converted into the equivalent convective heat transfer coefficient.

4 Results and discussion

4.1 Groove configuration fabricated on Al alloy surface

The purpose of fabricating a groove on an Al alloy surface is to improve the adhesion between CFRTP and Al alloy during the laser joining process. The depth and width of the groove have an important influence on the joining effect and mechanical properties of CFRTP/Al laser joints. In the laser surface texturing process, the high energy pulse laser beam repeatedly scans the Al alloy plate and finally forms the surface groove of the Al alloy, as shown in Fig. 4. The groove with a length of 25 mm is arranged in parallel along the width direction of the sample, and the spacing between the groove is relatively uniform. The groove depth and width are controlled by processing times, which indicates that the depth and width increase with the number of processing repetitions. As expected, a groove configuration with various widths and depths is achieved by laser surface texturing.

At the same time, groove shape is found to vary with the number of processing repetitions.

The optical micrographs of the groove structure are shown in Fig. 5. When the pulse laser scanning is repeated 40, 55, and 70 times, the depth of the groove on the Al alloy surface is 0.5, 0.6, and 0.7 mm, respectively. As shown in Fig. 5(a), the phenomenon of mechanical interlocking at the interface is not observed when the Al alloy is untreated. After laser texturing the Al alloy, the melted resin can fill in the textured groove as shown in Fig. 5(b)–(f). When the groove width of the Al alloy surface is small, the groove

Table 3 Thermophysical properties of CFRTP

| Material | Density (g/cm³) | Thermal conductivity (W/(m K)) | Heat capacity (J/(kg K)) |
|----------|----------------|--------------------------------|-------------------------|
| CFRTP    | 1.53           | $K_x = 5.4, K_y = 5.4, K_z = 0.5$ | 1088                    |

Fig. 4 Groove feature fabricated by laser texturing. (a) Macroscopic morphology. (b) No. 1. (c) No. 2. (d) No. 3. (e) No. 4. (f) No. 5
presents a “triangle” shape, as described in Fig. 5 (b), (e), and (f). This phenomenon is related to the degree of laser texturing on the Al alloy surface. In the process of laser texturing, with the increase of textured depth, the molten Al alloy forms a “recasting zone” at the bottom of the groove. At the same time, the heat at the bottom of the groove diffuses faster, resulting in less molten Al alloy, thus forming a “triangle” shape. Compared with Fig. 5 (a) and (e), the groove depth of 0.7 mm indicates a larger width at the bottom of the groove in Fig. 5(f) due to increased texture scanning and larger heat input. In addition, it can be seen from Fig. 5 (b), (c), and (d) that with the increase of textured groove width, the groove shape gradually tends to be a “rectangular” shape.

4.2 Mechanical properties of CFRTP/Al laser joints

Figure 6 shows the tested shear strength of the CFRTP/Al laser joint under various CFRTP/Al laser joint groove configurations on the Al alloy surface. The shear strength of specimens without laser texturing is 18.51 MPa. As expected, the shear strength of the CFRTP/Al laser joint is obviously increased when the Al alloy surface was laser-textured. As for the groove depth, the shear strength gradually increases as the laser-textured groove depth increases from 0.5 to 0.6 mm. The maximum shear strength of 24.33 MPa is attained at the laser-textured groove depth of 0.6 mm. Then, the shear strength decreases to 21.66 MPa at the laser-textured groove depth of 0.7 mm as the laser-textured groove depth further increases. As for the groove width, the shear strength is found to increase as the width of the groove increases from 0.3 to 0.5 mm. The maximum shear strength is 22.8 MPa at the laser-textured groove width of 0.5 mm. With further increase of the laser-textured groove width, the shear strength decreases to 21.73 MPa at the groove width of 0.7 mm. In short, with increasing groove depth or width, the tensile shear strength of CFRTP/Al laser joints first increases and then decreases.

The SEM results of the fracture surface of the CFRTP/Al laser joint with various groove configurations are exhibited in Fig. 7 to analyze the failure mechanism. For all studied cases, the residual resins adhered on the CFRTP surface can be detected and the original CFRTP substrate morphology can be observed. It is noted that the residual amounts of resins on the fracture surface indicate the adhesion ability with various groove configurations, which is related to the shear strength of the CFRTP/Al laser joint. As shown in Fig. 7 (a) and (b), the failure occurs at the interface of the CFRTP/Al laser joint; i.e., a large number of residual resins remain on the groove of the Al alloy. This suggests that the fracture mode of laser joints under the case of No. 1 is mixed failure including interface failure and cohesive failure under...
Fig. 7 Fracture surface morphology of laser joints. (a), (e), (g), and (i) are the fracture morphologies of sample Nos. 1–5, respectively; (b), (d), (f), (h), and (j) are the corresponding enlarged images.
the action of tensile shear force. However, the raised resins adhered on the CFRTP surface are observed in the case of Nos. 2 and 3 in Fig. 7(c)–(f). This phenomenon reveals that the failure occurs at the interface and interior of the CFRTP/Al laser joint during the tensile shear test, which suggests that the fracture mode of the CFRTP/Al laser joint is also mixed failure, but the cohesive fracture of the CFRTP/Al laser joint accounts for a large proportion. When the width of the groove is large, it is not easy to crack in the root region with the tensile stress and shear stress. At this time, the crack initiation location appears in the middle of the filled resins, and the proportion of the cohesive fracture of the tensile specimen increases accordingly. Hence, the shear strength of the CFRTP/Al laser joint rises with the increase of groove width and resin filling amount, which is consistent with the tensile shear test results in Fig. 6. As the groove width further increases, the melted resins fill into the micro-textures ineffectually and decrease the actual joining area between the resins and the Al alloy. Therefore, the shear strength of No. 3 is lower than that of No. 2.

Figure 7 (g) and (h) exhibit the SEM morphology of a typical fracture surface on the Al alloy side under the condition of laser-textured Al alloy surface with a 0.6-mm groove depth. A large number of melted resins are found to be filled into the textured groove. At the same time, the failure site occurs in the root of filled resins, indicating that the joint strength between the resins and the groove wall is large. This phenomenon implies that the fracture mode of the tensile specimen features mixed fracture and cohesive fracture accounts for a large proportion, which also further promotes the interlocking of melted resins to the textured groove of the Al alloy substrate. When the groove depth increases to 0.7 mm, the fracture mode is also characterized by the mixed fracture between the resins and the Al alloy surface. But there is still a small amount of cohesive fracture of the resin layer observed in local areas, and some carbon fibers are exposed, as indicated in Fig. 7 (i) and (j). The above results suggest that joint strength correlates with the fracture mode of the CFRTP/Al laser joint at the joining region.

4.3 Simulation of interface temperature field

Figure 8 shows the comparison between the experimental results and the simulation results of the temperature field in laser joining of the CFRTP to the Al alloy. The left side shows the actual macroscopic morphology of the weld cross-section on the Al alloy surface of the laser joint, and the right side shows the simulation results of the temperature field under the same process parameters. The experimental dotted line was drawn along the isotherm of melting temperature. It can be observed that the predicted weld profile is well consistent with the experimental results, which indicates that the thermal representation in the model is reasonably accurate. Besides, the heat source model is suitable for the structure of the CFRTP/Al lap laser joining process of finite element simulation.

Figure 9 depicts the calculated temperature field at the cross-section of the CFRTP/Al laser joint as a function of groove width and depth. The phenomenon of the different temperature profiles in the CFRTP/Al laser joint is discovered owing to varying groove configurations during the joining process. Within the bonded region of resins, it can be seen that the interfacial temperature of the CFRTP/Al laser joint lies between its melting point (343 °C) and gasification temperature (520 °C). When the interfacial temperature is in the range of 340–460 °C, the resins can close attachment to the Al alloy since they are melted at 340 °C and vaporized at 460 °C or higher. As shown in Fig. 9 (b), (c), and (e), when the Al alloy surface is textured by pulse laser, the temperature of the groove fusion zone and the interface fusion zone is below the decomposition temperature of the resins, and its decomposition does not occur in this zone. Thus, resins filled in the groove are completely melted in the laser joining process. However, when the groove depth is 0.7 mm in Fig. 9(f), it is found that the temperature of the groove bottom in the groove fusion zone is higher than the resin decomposition temperature. In this case, resin decomposition occurs, and the defects such as gaps and bubbles are easily formed in the groove, which can deteriorate the joint strength. When the groove width increases from 0.4 to 0.7 mm in Fig. 9(d), the temperature at the bottom of the groove is higher than the resin decomposition temperature due to the accumulation of heat in the area below the molten pool. As a result, the resins tend to decompose, forming bubbles and other defects, which is not conducive to forming good joints.

The thermal cycle curves of the groove bottom under the condition of various groove configurations are presented in Fig. 10. Overall, the peak temperature tends to surpass the melting temperature of resins for various groove configurations. It should be also noted that the maximum temperature of sample Nos. 1, 2, and 4 is all lower than the decomposition temperature of the resins. Thus, the molten resins filled in the groove do not decompose during the laser joining process, theoretically reducing the possibility of forming bubbles, gaps, and other microscopic defects at the interface. However, the maximum temperature of sample Nos. 3 and 5.
is higher than the decomposition temperature of the resins. So, the partially melted resin in the groove is decomposed into CO$_2$ and other gases due to the high temperature, tending to produce non-fusion defects at the interface. This may reduce the bonding area of the molten resins and the Al alloy surface. Macroscopically, the shear strength of the CFRTP/Al laser joint is deteriorated.

### 4.4 Failure analysis of CFRTP/6061 Al alloy laser joints

In the laser joining of CFRTP to Al alloy, the melted resins at the interface fill into the micro-textures on the Al alloy surface under the compression of external pressure, where mechanical interlocking is achieved to fasten two joining components. The interface bonding between Al alloy and CFRTP largely depends on the van der Waals force and mechanical bonding force. In general, the mechanical bonding force is featured by the interlocking force that is formed after cooling and curing of molten resins filling the textured structure on the Al alloy surface, which is dominant at the interface. Based on the above results, for the 6061 Al alloy and CFRTP laser joint, the fracture mode of lap tensile specimens mainly includes interface fracture, cohesive fracture, and mixed fracture. When the cohesive fracture of the CFRTP/Al laser joint accounts for a larger proportion, it is indicated that the shear strength of the joint presents a higher value.

It can be seen from Fig. 11 that two kinds of interface morphology are observed at the resin/Al joint in the groove. One is the serrated recasting interface and the other is a relatively smooth interface. It should be known that the recasting material layer not only increases the contact surface area between the resins and the Al alloy but also enhances the wettability and the mechanical anchoring effect between the resins and the Al alloy [37, 38]. As a result, the serrated recasting interface tends to improve the shear strength of the CFRTP/Al laser joint, resulting in the formation of cohesive fracture. In comparison, the smooth interface enables mostly interfaced fracture due to weak binding force.

Figure 12 shows the fracture mode of the CFRTP/Al laser joint under tensile shear load. When the material is pulled at both ends, in addition to the tensile shear force parallel to the CFRTP surface, the resin root filled into the groove structure should bear a higher bending moment. Therefore, the root of the resin is subject to large shear and tensile stresses at the same time, and it is easy to crack at the root of the resin first [39]. Specifically, when the bonding force between the inner wall of the Al alloy groove
and the resin is large, the resin is easy to fracture from the root. A lot of resins remain in the groove structure of the Al alloy, presenting the form of a cohesive fracture. When the inner wall of the Al alloy groove is relatively smooth and the recast material is less, it is easier for the resin to peel off the inner wall of the Al alloy groove and produce an interface fracture. As shown in Fig. 7, for various groove configurations, the fracture mode of the CFRTP/Al laser joint has the feature of a mixed fracture including cohesive fracture and interface fracture. It is worth noting that the fracture mode of the CFRTP/Al laser joint converts from interface fracture to cohesive fracture, which can contribute to the improvement of joint strength. Therefore, it is suggested that the values of groove width and depth should be set in an appropriate range for the popularization and application of laser surface texturing according to our experiences.

5 Conclusion

In order to improve the CFRTP/6061 Al alloy laser joint quality, a feasible way of laser surface texturing was proposed to assist the laser joining between CFRTP and 6061 Al alloy. The mechanical properties, the failure mechanism, and the temperature field simulation on the CFRTP/Al alloy laser joint were investigated. Some conclusions were obtained as follows:

1. A groove pattern was textured on Al alloy substrates by the pulse laser texturing system, and the textured Al alloy sheets and CFRTP substrates were joined by the laser joining process. Pores and defects are not detected inside the CFRTP because joining temperature can be effectively controlled between melting point and gasification temperature.

2. In the process of laser joining, the resins can completely fill the groove when the groove configuration is optimized. Compared with the non-textured Al alloy and CFRTP laser joint, the groove configuration on the Al alloy surface can effectively improve the shear strength of CFRTP/Al laser joints, and the shear strength increased by a maximum of 31.4%. With increasing groove depth or width, the shear strength of CFRTP/Al laser joints first increases and then decreases. The maximum joint strength of 24.33 MPa is attained at the laser-textured groove depth of 0.6 mm and width of 0.3 mm.

3. The temperature field simulation results indicate that groove configuration plays a significant role in the interfacial temperature of the CFRTP/Al laser joint, which is closely related with resin decomposition. When resin decomposition appears in the groove fusion zone, the defects such as gaps and bubbles are easily emerged in the groove, deteriorating the joint strength. Therefore, in order to completely fill into the textured groove of the Al alloy surface, the interfacial tempera-
tecture of the CFRTP/Al laser joint is optimized in the range of 340–460°C.

(4) The surface fracture mode of the CFRTP/Al laser joint is mixed fracture including cohesive fracture and interface fracture regardless of groove configuration. It is suggested that the fracture mode of the CFRTP/Al laser joint converts from interface fracture to cohesive fracture, which can contribute to the improvement of joint strength.

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Declarations

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