

Non-optical-contact and clamp-free laser transmission welding of CFRP to fused silica via ethanol-assisted interfacial modification

Yuan Yao^a, Yushun Dong^a, Hong An^a, Zhanquan Yang^a, Yongfeng Qian^{a,*}, Hu Huang^{a,*}

^aKey Laboratory of CNC Equipment Reliability, Ministry of Education, School of Mechanical and Aerospace Engineering, Jilin University, Changchun 130022, China

*Corresponding authors.

E-mail addresses: qianyf@jlu.edu.cn (Yongfeng Qian); huanghu@jlu.edu.cn (Hu Huang)

Abstract

The integration of carbon fiber reinforced polymer (CFRP) and fused silica is highly desirable for multifunctional applications that demand both high specific strength and optical transparency. However, conventional laser transmission welding (LTW) of these dissimilar materials is severely constrained by their disparate thermophysical properties and the stringent requirement for precise optical contact. Here, we report a non-optical-contact, clamp-free liquid-mediated laser transmission welding (LM-LTW) approach that employs an anhydrous ethanol interlayer to enable robust joining of CFRP and fused silica. The ethanol interlayer serves as a liquid mediator, enhancing conformal contact between mating surfaces during initial assembly and effectively mitigating the heat-affected zone (HAZ) during subsequent LM-LTW process. The influence of pulse duration, spanning femtosecond, picosecond, and nanosecond regimes, on welding quality was systematically investigated. Picosecond laser irradiation yielded the optimal processing

22 window, achieving a maximum shear strength exceeding 5 MPa. The bonding mechanism
23 arises from synergistic mechanical interlocking and the formation of Si–O–C functional
24 group, driven by localized laser-induced thermal expansion and polymer softening. This
25 work establishes a robust, scalable strategy for integrating structural and optical
26 functionalities without reliance on complex clamping fixtures or demanding pre-weld
27 surface preparation.

28
29 **Keywords:** Laser transmission welding; Carbon fiber reinforced polymer; Fused silica;
30 Dissimilar joining; Interfacial modification; Non-optical-contact

1. Introduction

Carbon fiber reinforced polymer (CFRP) has been widely used in aerospace components, wind turbine blades, and automotive structures owing to its high specific strength and stiffness [1]. Fused silica, as a representative hard and brittle material, exhibits broadband optical transparency, low coefficient of thermal expansion, high hardness, and excellent chemical stability, rendering it indispensable for applications such as optical windows, lenses, and sensor encapsulation [2, 3]. Driven by the increasing demand for structural-functional integration [4], reliable joining between CFRP and fused silica has become essential in emerging fields including optical telescope assemblies (e.g., the Habitable Worlds Observatory) [5], optical inspection windows [6], and integrated sensors. Currently, such dissimilar joints are mainly realized using mechanical fastening or adhesive bonding [7]. However, mechanical fastening introduces stress concentration and undesirable structural weight [8], while adhesive bonding suffers from outgassing and material degradation under extreme environmental conditions, severely compromising dimensional stability and long-term reliability [9, 10].

Laser transmission welding (LTW) has emerged as a non-contact and high efficiency joining technique. By leveraging laser energy absorption at the interface between transparent and non-transparent materials to induce localized heat conduction, LTW offers a promising approach for dissimilar material joining [11-15]. Most research on laser joining of CFRP have focused on carbon fiber reinforced thermoplastic (CFRTP), where the thermoplastic polymer matrix enables fusion-based joining with dissimilar

materials [16-19]. In contrast, thermosetting resins exhibit an irreversibly cross-linked three-dimensional network, which fundamentally restricts their weldability. Lambiase et al. demonstrated that the concentrated laser irradiation induces the thermal degradation and the removal of the epoxy matrix from the CFRP surface, allowing the softened thermoplastic polycarbonate to infiltrate the exposed carbon fiber skeleton and form a robust mechanical interlocking joint upon cooling [20]. Nevertheless, this strategy is mainly applicable to thermoplastics with thermally induced fluidity and cannot be readily extended to high-melting-point inorganic glasses such as fused silica [21].

Beyond material constraints, traditional LTW faces significant technological bottlenecks in interfacial assembly. Standard LTW configurations rely on high numerical aperture (NA) objective lenses for tight beam focusing, yielding a depth of focus (DOF) limited to a few micrometers. This optical setup impose a stringent prerequisite for rigorous optical contact at the joining interface, typically requiring an interfacial gap smaller than $\lambda/4$ (where λ is the laser wavelength) and demanding extremely high surface flatness [22-25]. Such requirement severely limits the applicability of LTW to engineering-scale components, for which large-area surface preparation with optical quality is impractical [26]. Moreover, external mechanical clamping is commonly required to maintain intimate interfacial contact and to suppress interfacial separation caused by laser-induced recoil pressure or thermal shrinkage during cooling [27]. Consequently, achieving LTW under non-optical-contact conditions characterized by macroscopic interfacial gaps and the absence of external clamping remains a formidable

challenge in current manufacturing research [28, 29].

To overcome the stringent optical-contact requirement associated with high-NA focusing, alternative laser focusing strategies must be considered. While beam shaping techniques (e.g., Bessel beams) and temporal pulse tailoring (e.g., burst mode) offer significant advantages in focal depth and energy deposition control [26, 30-32], they often rely on specialized laser sources or complex optical setups. In contrast, standard galvanometric scanning systems equipped with F-theta lenses are widely used in industrial laser processing due to their high speed and flexibility. However, their potential for precise dissimilar material joining across relatively large interfacial gaps, particularly without external clamping, remains insufficiently explored. In addition, the fundamental mechanisms of laser-matter interaction vary drastically across nanosecond, picosecond, and femtosecond time scales [12], and the influence of these temporal regimes on the welding quality at thermoset polymer-brittle glass interfaces remains largely unknown.

To address these multifaceted challenges, this study proposes a liquid-mediated laser transmission welding (LM-LTM) method assisted by anhydrous ethanol and performed without external clamping. Long-focal-length F-theta lenses were employed to relax axial alignment tolerances while distributing laser energy over an enlarged spot, thereby reducing thermal gradients and enabling higher processing speeds compatible with industrial-scale joining [33]. Ethanol was introduced as an interfacial medium to fill interfacial gaps induced by surface roughness (S_a), thereby mitigating poor contact, suppressing HAZ and enhancing interfacial energy coupling [34-36]. To the best of our

knowledge, stable laser joining of CFRP and fused silica has not previously been achieved, particularly under non–optical-contact conditions and in the absence of mechanical clamping. Welding performance was systematically evaluated across femtosecond, picosecond, and nanosecond irradiation regimes, with the optimized process yielding a maximum shear strength exceeding 5 MPa. Through in-situ observations of the welding process, combined with the analysis of interfacial and fracture characteristics, the underlying joint formation mechanisms were comprehensively elucidated. This work establishes a practical route to integrating mechanical and optical functionalities via robust heterojunction fabrication, eliminating the need for stringent surface preparation protocols.

2. Experimental details

2.1 Materials and processing system

The thermo-physical properties of the materials employed in this investigation are summarized in Table 1. As an anisotropic composite, the thermal stability of the CFRP is governed by the glass transition and decomposition temperatures (T_g and T_d) of its epoxy matrix (WP-S5001, Wellsepoxy, China). Furthermore, the transport properties of carbon fibers, such as thermal conductivity (TC) and coefficient of thermal expansion (CTE), exhibit significant orientation dependence. Conversely, fused silica is an amorphous, optically transparent, and isotropic material characterized by high softening temperature, near-zero CTE, and moderate thermal conductivity. These attributes present a distinct

property contrast to the multi-phase CFRP. The S_a for the original CFRP and fused silica substrates were measured to be 1.44 μm and 16 nm, respectively, using the laser scanning confocal microscope (LSCM, OLS5100, Olympus, Japan).

Table 1. Thermo-physical properties of CFRP and fused silica

Material	Critical temperatures (°C)	CTE (10^{-6} K^{-1})	Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Reference
CFRP (Epoxy matrix)	425 (T_d) 134 (T_g)	49 (Glassy) 180 (Rubbery)	0.2	[37-41]
CFRP (Carbon fiber)	3900 (T_{sub})	-0.6 (L) 7.9 (T)	50 (L) 5 (T)	[37-40]
Fused silica	1600 (T_{soft})	0.56	1.38	[2, 42, 43]

Note: L and T denote the longitudinal (parallel to fibers) and transverse (perpendicular to fibers) directions, respectively. Abbreviations: T_d , decomposition temperature; T_g , glass transition temperature; T_{sub} , sublimation temperature; T_{soft} , softening point.

The experimental procedure for LM-LTW is systematically illustrated in Fig. 1(a). CFRP substrates were sectioned into dimensions of $50 \times 16 \times 2 \text{ mm}^3$ using a diamond wire sawing machine (STX-202A, Shenyang Kejing Auto-instrument, China). After a thorough cleaning with anhydrous ethanol using a swab, each specimen was dried under atmospheric environment. Subsequently, approximately 3 μL of anhydrous ethanol was dispensed onto the CFRP surface, followed by stacking the fused silica onto the CFRP substrate. The surface tension and capillary pressure generated by the confined ethanol

interlayer promote conformal contact between the two mating surfaces prior to laser irradiation.

The LM-LTW process was performed using a concentric circle scanning pattern with an outer diameter of 10 mm and an inner diameter of 9 mm, as depicted in Fig. 1(b). This ring-shaped pattern mitigates the effects of CFRP anisotropy by providing a symmetric weld path, thereby promoting uniform stress distribution along the joint. In addition, the hollow center preserves the optical transmittance of the fused silica, satisfying its functional requirement as an optical window. Along the scanning path, the pulse overlap rate (O_p) determines the continuity of energy deposition and is defined by:

$$O_p = \left(1 - \frac{v}{f \cdot d}\right) \times 100\% \quad (1)$$

where v is the scanning speed, f denotes the laser repetition frequency, and d is the focused beam diameter. In this study, v was fixed at $50 \text{ mm} \cdot \text{s}^{-1}$. f and d were set to 1087 kHz and $39 \text{ } \mu\text{m}$ for the femtosecond and picosecond lasers, and 1000 kHz and $43 \text{ } \mu\text{m}$ for the nanosecond laser, respectively. Under these conditions, O_p was maintained at approximately 99.9%. A scanning pitch (p) of $10 \text{ } \mu\text{m}$ was selected to ensure radial filling between adjacent paths. Specifically, the laser beam shifted radially at a fixed angular position after each full rotation, marked as the "Starting line" in Fig. 1(b). The inter-path overlap rate (O_l) between adjacent scanning paths is then calculated as:

$$O_l = \left(1 - \frac{p}{d}\right) \times 100\% \quad (2)$$

With these focused beam diameters, the resulting O_l was maintained at approximately 75%

for both laser sources.

To ensure a valid comparison across the various pulse duration (τ) regimes, a constant high repetition frequency of approximately 1000 kHz was used in all experiments. The resulting pulse interval of 1 μ s is significantly shorter than the thermal relaxation time of the material, leading to continuous heat accumulation [44, 45]. Consequently, the temperature field is primarily determined by cumulative energy deposition input rather than individual pulse impacts. To maintain a unified evaluation of heat input, the laser fluence (F) was adopted as the comparative metric. Defined by the measured average laser power (P), laser repetition frequency (f), and the focused beam diameter (d), it is expressed as:

$$F = \frac{4P}{\pi d^2 f} \quad (3)$$

To investigate the effect of heat input on joint formation, F was systematically varied from 0.16 to 1.26 J·cm⁻².

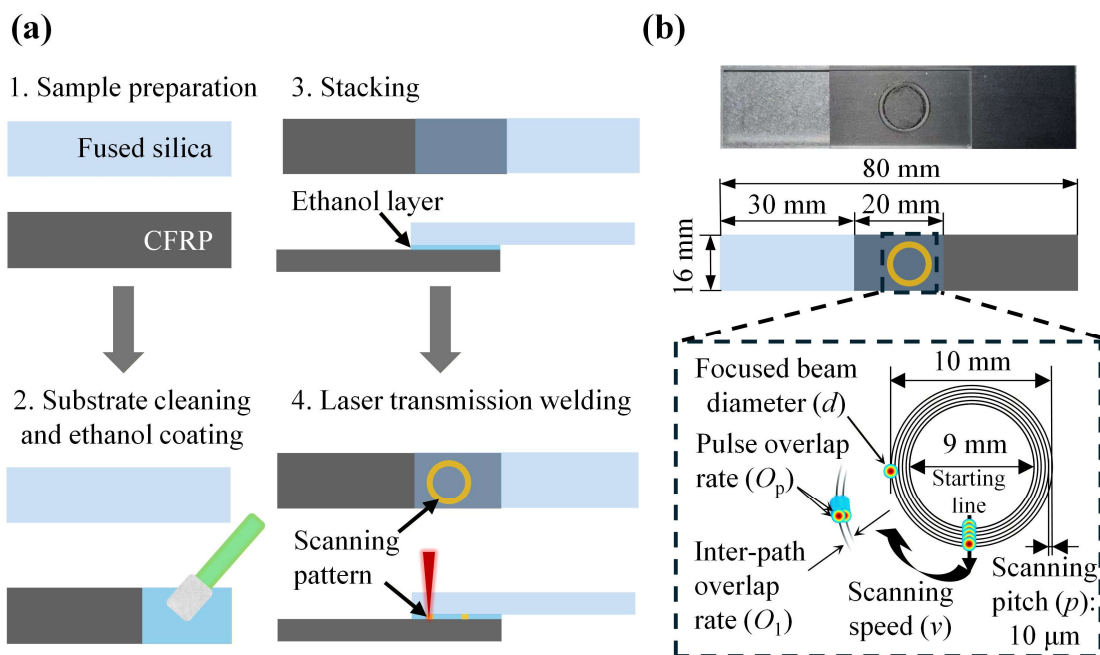


Fig. 1. Experimental workflow and setup for LM-LTW. (a) Experimental procedure: 1. Sample preparation (fused silica and CFRP), 2. Substrate cleaning and ethanol coating, 3. Stacking, 4. LM-LTW process. (b) Specimen configuration: Photograph of the welded specimen, macroscopic dimensions of the samples, and a detailed schematic of the concentric annular scanning pattern.

The laser welding systems employed in this study are schematically detailed in Fig. 2. Two distinct laser sources were employed: an ultrafast laser system (PHAROS-PH2-20W-SP, Light Conversion, USA) capable of delivering both femtosecond and picosecond pulses and a nanosecond laser system (SP-050P-A-EP-Z-F-Y, SPI Lasers, UK). Both systems utilized Gaussian beams and galvanometer scanners. The ultrafast laser operated at a central wavelength of 1030 nm and a repetition rate of 1087 kHz, with pulse durations selectable from 256 fs to 11142 fs. From this range, pulse durations of 500 fs and 10 ps were specifically selected in this study. An off-axis charge-coupled device (CCD) camera was incorporated for alignment and real-time process monitoring. In contrast, the nanosecond system operated at a wavelength of 1064 nm with a pulse duration of 10 ns and a repetition frequency of 1000 kHz. The calculated Rayleigh lengths for the nanosecond and ultrafast systems were approximately 0.86 mm and 0.97 mm, respectively corresponding to an effective DOF exceeding 1.7 mm, thereby enabling stable welding under non-optical-contact conditions without external clamping.

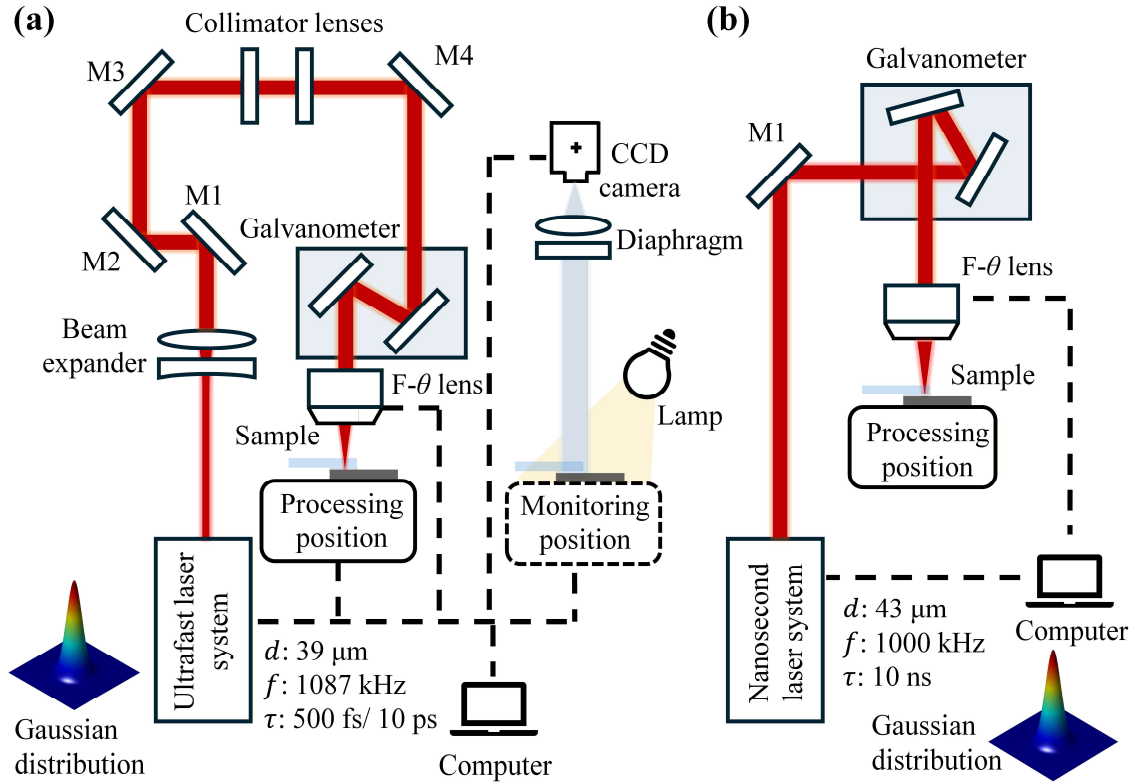


Fig. 2. (a) Schematic of the ultrafast laser processing system (fs/ps regimes) integrated with a galvanometer scanner and a CCD-based monitoring module. (b) Schematic of the nanosecond laser processing system. Key processing parameters, including d , f , and τ , were labeled, and both laser systems exhibited a Gaussian spatial beam profile.

2.2 Measurement and characterization methods

Post-weld interface morphologies and three-dimensional (3D) topographies of the joint were examined through the transparent quartz glass substrate using a laser scanning confocal microscope (LSCM, OLS5100, Olympus, Japan). Surface roughness was quantified as the areal arithmetic mean height (S_a) measured by LSCM. Cross-sectional and fracture morphologies of the weld joints were characterized by a scanning electron microscope (SEM, JSM-IT200, JEOL, Japan). Elemental distributions on the fracture surfaces were analyzed using energy-dispersive X-ray spectroscopy (EDS, EX-

74600U4L2Q, JEOL, Japan) integrated into the SEM. Interfacial chemical states on the CFRP-side fracture surfaces were evaluated using X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi, Thermo Scientific, UK). In addition, the interfacial optical emission during the LM-LTW process was recorded using a high-speed camera (VEO 410L, Vision Research, USA) at a frame rate of 3000 fps with an exposure time of 330 μ s. The recorded images were post-processed using the Physics pseudo-color lookup table (LUT) in Fiji software, where the color scale represents the frame-integrated optical emission intensity. Mechanical performance of the joints was evaluated by shear testing using a universal testing machine (UTM, AG-X Plus, Shimadzu, Japan).

3. Results and discussion

3.1 In-situ observation and as-welded morphology

Fig. 3 shows representative high-speed images of the optical emission observed during LM-LTW under three laser fluences ($F = 0.31, 0.63, \text{ and } 1.10 \text{ J}\cdot\text{cm}^{-2}$) and three pulse durations (500 fs, 10 ps, and 10 ns). The high-speed camera was operated at a frame rate of 3000 fps, synchronized with a laser repetition frequency of approximately 1000 kHz. This indicates that approximately 333 pulses interacted with the target within each imaging cycle. The color scale represents the frame-integrated optical intensity on the microsecond timescale. To properly visualize the internal modification dynamics during nanosecond irradiation, the intensity scale is specifically calibrated. Consequently, the high-intensity luminous zone above the surface appears saturated in these images.

As illustrated in Fig. 3(a-f), a distinct luminous zone is observed at the interface between the fused silica and the CFRP. With increasing F , both the intensity and the apparent size of this interfacial luminous zone increase markedly. A comparative analysis between the femtosecond and picosecond regimes further reveals that longer pulse durations produce a more pronounced and spatially extended emission region. This spatial expansion is most evident under nanosecond irradiation, as depicted in Fig. 3(g-i). In addition to the interfacial luminous zone, a bright feature is visible near the air-side surface of the fused silica above the joint region. This phenomenon is attributed to Fresnel reflection of the incident laser beam at the air-silica interface. The persistent localization of the luminous zone near the joint interface is consistent with preferential absorption on the CFRP side, which is further supported by the substantially higher optical absorption of the CFRP constituents relative to the laser-transparent fused silica [46]. This localized energy deposition leads to matrix pyrolysis at the interface, which in turn induces material redistribution. These interfacial phenomena, along with the resulting morphological changes on both the CFRP side and the fused silica side, are further validated by the LSCM and cross-sectional observations presented in the following sections.

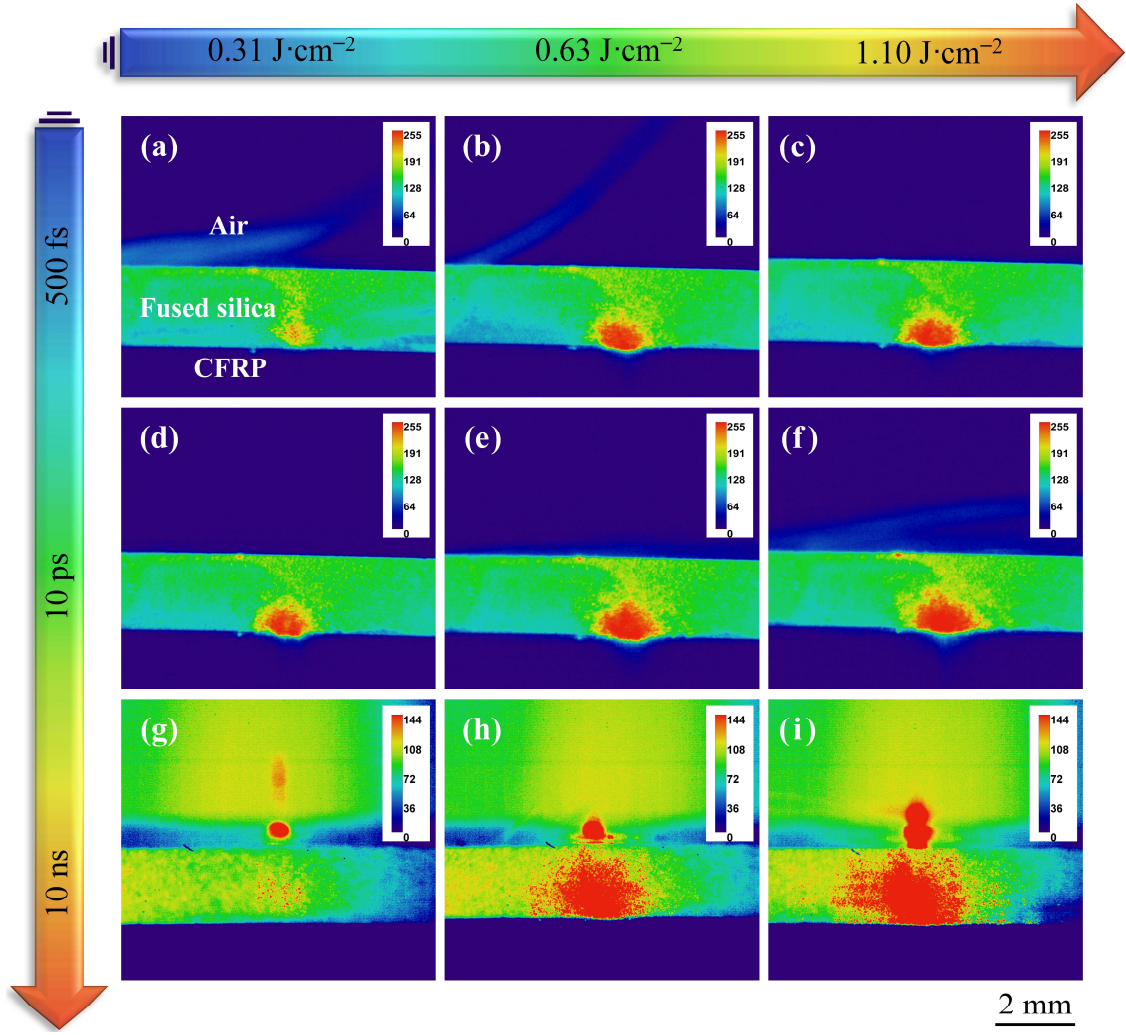


Fig. 3. High-speed camera imaging results of interfacial radiation behavior during LM-LTW. Rows correspond to τ (500 fs, 10 ps, and 10 ns), and columns correspond to F (0.31, 0.63, and 1.10 J·cm⁻²).

Fig. 4 presents LSCM images of the as-welded CFRP surface observed through the transparent fused silica layer following the LM-LTW. With increasing laser fluence, pronounced changes in surface morphology are observed across the weld region. At a relatively low laser fluence of 0.16 J·cm⁻², the weld region exhibits a non-uniform grayscale contrast, indicating limited interfacial bonding quality. In contrast, at intermediate power densities of 0.31 J·cm⁻² and 0.47 J·cm⁻², the confocal images display

a more homogeneous interfacial feature distribution across the weld track, suggesting a more uniform energy deposition and a correspondingly superior interfacial bonding quality. Furthermore, an increase in laser fluence drives the inward expansion of the HAZ toward the geometric center of the weld trajectory. Within the high-temperature irradiated zone, the fundamental cross-linked molecular architecture of the thermosetting epoxy matrix prevents conventional melting and solidification phenomena. In fact, these materials undergo thermal degradation rather than melting upon overheating. In the adjacent HAZ, where the local temperature is expected to reside between T_g and T_d , the epoxy matrix transitions into a high-elastic rubbery state. Driven by significant thermal expansion and localized pressure, this softened resin is forced to deform and bridge the interfacial micro-gap. It is hypothesized that this viscoelastic flow acts as an in-situ 'sealing ring' that effectively suppresses the lateral free expansion of the laser-induced plasma. This confinement is expected to facilitate the generation of high-pressure shockwaves, potentially forcing the resin to conform tightly to surface asperities of the fused silica, as shown in Fig. 4(f). The resulting robust joint is therefore attributed to the synergy of localized ablation, the plasma confinement induced by the softened resin, and the enhanced wetting facilitated by the ethanol interlayer. Based on the planar 2D view shown in Fig. 4(c), where black regions correspond to resin, more pronounced resin accumulation is observed in the central region (inner side of the weld seam) than in the periphery (outer side). This distribution is attributed to the scanning path, which moves from the inside to the outside.

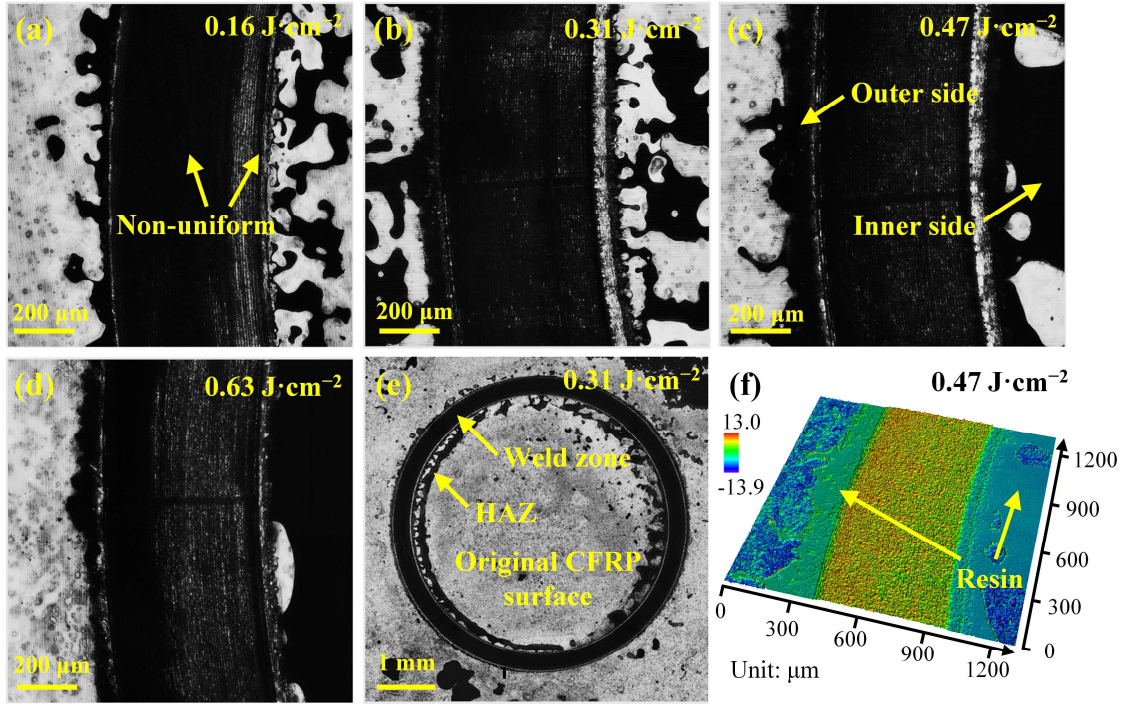


Fig. 4. Confocal microscope images of the as-welded CFRP surface, acquired through the transparent fused silica layer after LM-LTW at $\tau = 10$ ps and prior to mechanical separation. (a-d) Planar 2D confocal images obtained at fluences of 0.16, 0.31, 0.47, and 0.63 $\text{J}\cdot\text{cm}^{-2}$, respectively. In the planar 2D view shown in Fig. 4(c), the black regions correspond to the resin, highlighting the difference in resin distribution between inner and outer sides of the weld seam. (e) Full-ring confocal microscope image of the weld seam, revealing the radial non-uniformity induced by the scanning strategy. (f) 3D topographic reconstruction of the region shown in Fig. 4(c), where the colour scale represents the relative surface height variation.

Fig. 5 presents the cross-sectional morphologies of the fused silica/CFRP welded joints obtained at different F , corresponding to single-pulse energies of 3.7 μJ , 5.5 μJ , and 7.4 μJ , respectively. It is observed that despite the complete absence of external clamping and initial optical contact, intimate interfacial contact is achieved across all parameters,

with no apparent gaps or voids visible in the cross-sections. As the energy input increases, the epoxy matrix on the CFRP side undergoes significant pyrolysis, leading to a significant volumetric enlargement of the weld profile. The cross-sectional SEM images reveal a distinct teardrop-shaped modification zone extending into the fused silica. This morphology is consistent with the hydrodynamic behavior of a laser-induced melt pool [26]. Such structural evolution indicates that the glass interface underwent localized melting and flow driven by the expanding plasma/vapor. However, it is noteworthy that the penetration depth of the exposed carbon fiber layer (along the depth direction, perpendicular to the interface) does not increase proportionally with the applied laser energy, despite substantial expansion in the lateral direction (parallel to the weld seam). This phenomenon is primarily attributed to the significant thermal conductivity anisotropy of the CFRP (Table 1). Since the longitudinal thermal conductivity of carbon fiber is substantially higher than its transverse and through-thickness counterpart, the absorbed laser energy tends to diffuse rapidly along the fiber axis rather than penetrating deeply. This preferential heat conduction promotes significant lateral widening of the HAZ while restricting vertical heat transfer. Moreover, the ablation threshold of the resin is lower than that of the carbon fiber [47]. Once the superficial resin matrix is pyrolyzed and evacuated, the newly exposed, highly refractory carbon fiber network functions as a robust thermal shield. This protective barrier effectively impedes further energy coupling into the sub-surface resin layers. Consequently, the resin removal is largely confined to the immediate surface domain, resulting in a relatively stable exposure depth despite the

increased energy input.

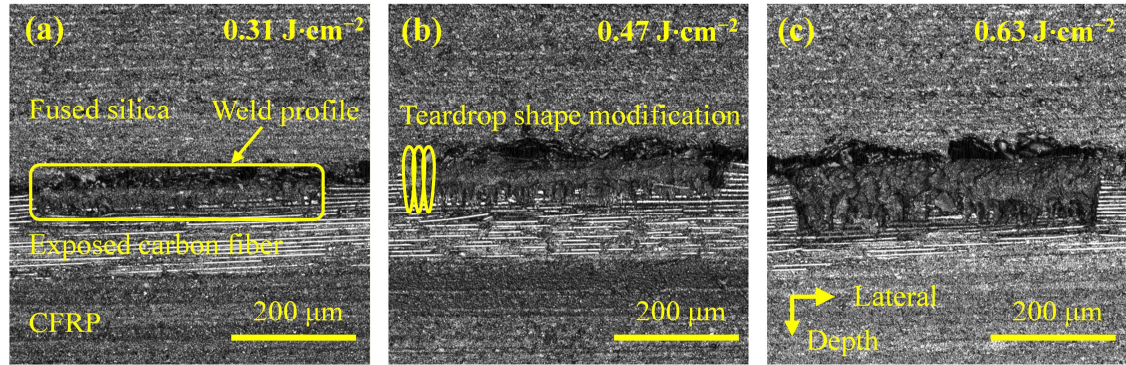


Fig. 5. Cross-sectional morphologies of the fused silica/CFRP joints obtained at $\tau = 10$ ps under different F : (a) $0.31 \text{ J} \cdot \text{cm}^{-2}$, (b) $0.47 \text{ J} \cdot \text{cm}^{-2}$, and (c) $0.63 \text{ J} \cdot \text{cm}^{-2}$.

3.2 Shear strength and process window

Shear strength was evaluated using the configuration shown in Fig. 6(a), in which the CFRP specimen was fixed in the lower clamp and a vertical load was applied by the upper indenter to impose shear at the welded joint. Fig. 6(b) summarizes the bonding outcomes ($\checkmark$ successful, $\square$ weak, $\times$ failed) and the corresponding shear strength as a function of laser fluence and pulse duration. Specifically, "failed" refers to processing conditions under which no effective bonding is achieved, and the two materials remain separate. "Weak" denotes conditions where temporary adhesion occurs, but the joint cannot withstand the initial loading of the shear test; consequently, no valid shear strength-displacement curve can be obtained. "Successful" indicates that a robust joint is formed, and a reliable shear strength-displacement curve is established, enabling determination of the shear strength.

Compared with the nanosecond case, picosecond and femtosecond pulses exhibit a broader window of successful bonding and generally higher-strength responses. This

difference can be attributed to distinct laser-matter interaction regimes governing each
 temporal domain. For nanosecond laser welding, the relatively long pulse duration at
 1000 kHz leads to a larger HAZ and a restricted usable parameter range. This limitation
 is primarily driven by the less concentrated energy distribution, as evidenced by the
 spatially extended emission observed in Fig. 3(g–i). Such delocalized energy input makes
 the process highly sensitive to thermal fluctuations. Insufficient energy input fails to
 bridge the interface through thermal conduction, while slightly higher energy input
 potentially causes macroscopic carbonization of the CFRP. In contrast, femtosecond and
 picosecond pulses facilitate a more stable and concentrated energy deposition. This precise
 energy confinement minimizes collateral thermal damage and significantly widens the
 processing window, which is particularly crucial for sustaining structural integrity in the
 absence of external clamping forces.

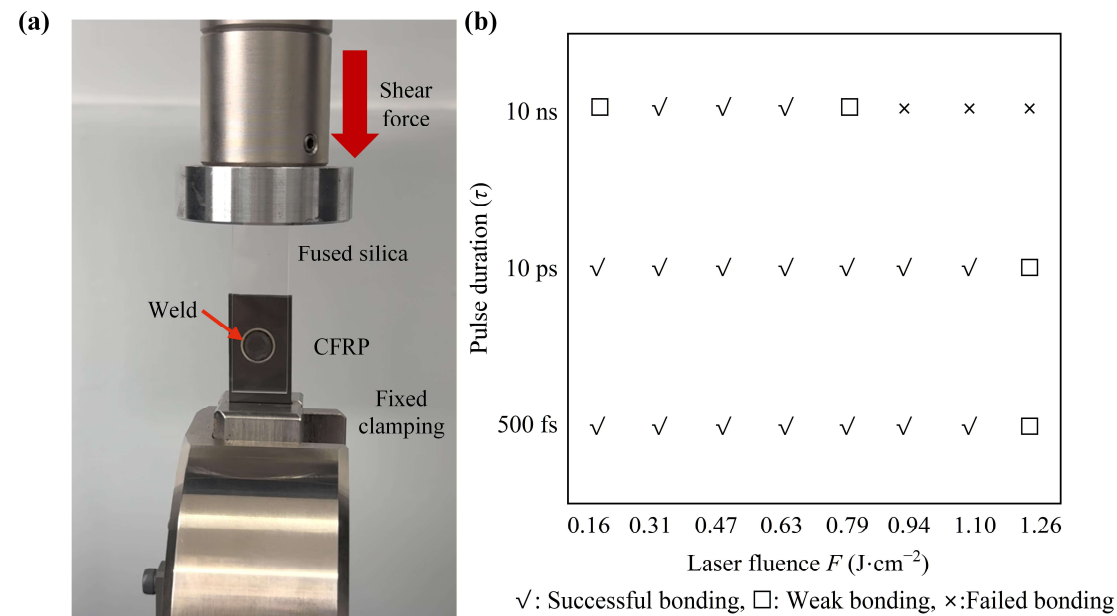


Fig. 6. Laser welding process window and joint performance evaluation. (a) Experimental

setup for the shear test, (b) Mapping diagram of the process window and shear strength distribution under varying pulse durations and laser fluence.

As shown in Fig. 7(a–c), the shear strength of the CFRP–fused silica joints are significantly influenced by both laser pulse duration and laser fluence. Under femtosecond laser irradiation (Fig. 7(a)), the shear strength of heterogeneous joints remains relatively stable even at higher laser fluences. In contrast, the picosecond laser regime (Fig. 7(b)) exhibits an overall decreasing trend, wherein the highest average shear strength of 3.50 MPa is achieved at a relatively low fluence of $0.16 \text{ J}\cdot\text{cm}^{-2}$. Notably, despite this trend, a maximum individual joint strength of 5.04 MPa is successfully recorded under a specific fluence of $0.31 \text{ J}\cdot\text{cm}^{-2}$. The nanosecond laser (Fig. 7(c)) shows a notably narrower processing window, with effective bonding only within a restricted range. Although noticeable data scatters suggest a need for further optimization of process repeatability, these robust macroscopic strength values demonstrate the significant potential of this proposed welding strategy. Fig. 7(d) presents a representative shear strength-displacement curve obtained under the 10 ps condition at $0.63 \text{ J}\cdot\text{cm}^{-2}$. The curve exhibits a linear elastic loading stage followed by an abrupt drop in force, with no evident plastic deformation plateau. This behavior indicates a typical brittle failure mode, confirming that the measured values primarily reflect the interfacial bonding strength of CFRP and fused silica under the clamp-free conditions.

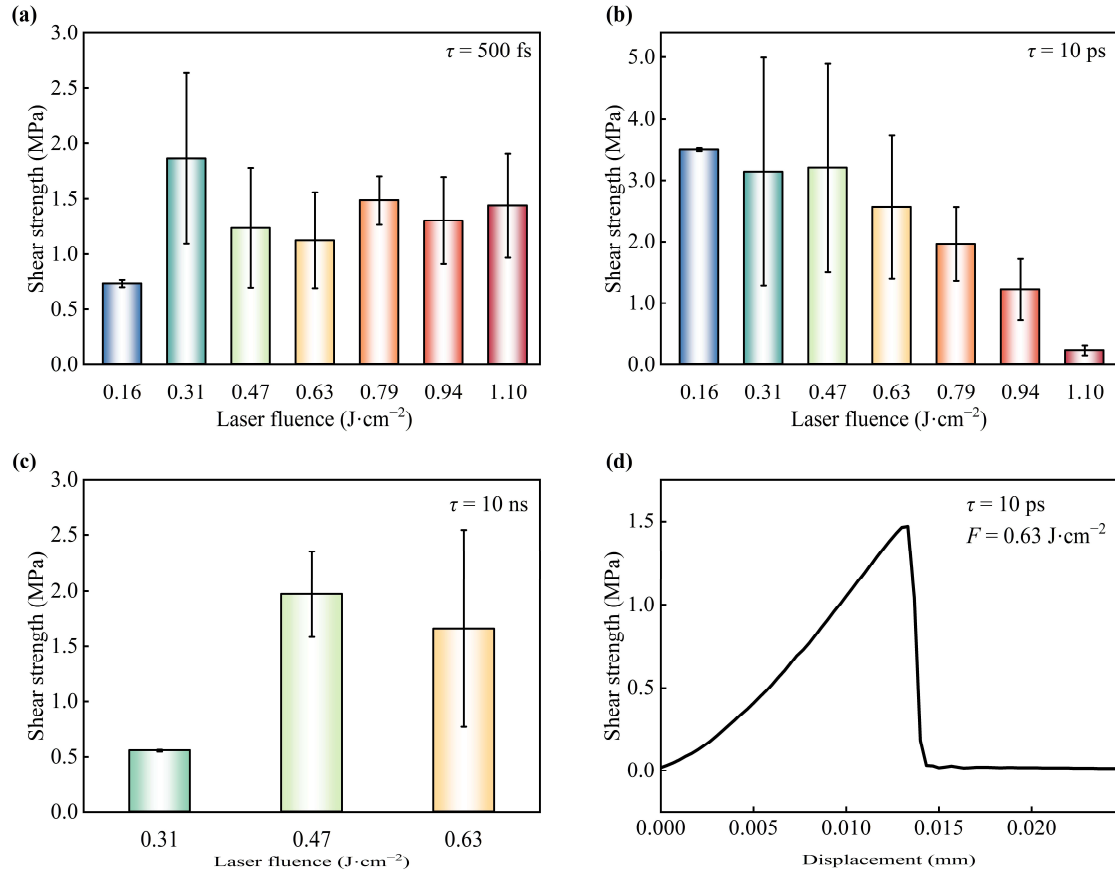


Fig. 7. Shear strength result of laser-welded CFRP/fused silica joints. (a–c) Shear strength versus F for τ of (a) 500 fs, (b) 10 ps, and (c) 10 ns. (d) Representative shear strength–displacement curve indicating brittle failure.

3.3 Fracture morphology

To gain deeper insight into the interfacial bonding mechanisms and failure behavior, fracture surfaces of both CFRP and fused silica sides were examined. Fig. 8 presents representative SEM morphologies and corresponding 3D topographies of the CFRP and fused silica surfaces after separation, obtained with a pulse duration of 10 ps at three F (0.31, 0.63, and $1.10 \text{ J}\cdot\text{cm}^{-2}$). Under all conditions, a distinct HAZ surrounds the direct laser ablation region on the CFRP side, where the epoxy matrix is degraded, and carbon fibers become exposed. This phenomenon occurs because the T_d of the epoxy matrix is

significantly lower than the T_{soft} of the fused silica. Consequently, the resin degrades to expose the fibers before the fused silica can soften and encapsulate them.

As the F increases, the resultant surface morphology evolves markedly, and the surface roughness gradually increases. At relatively low F , the scanning tracks remain clearly distinguishable and fine. Furthermore, powdery fused silica particles are relatively uniformly distributed across the interface. The corresponding areal S_a measures $1.81\text{ }\mu\text{m}$ on the CFRP side and $1.55\text{ }\mu\text{m}$ on the fused silica. At intermediate F , the dispersed fused silica particles coalesce into clusters, accompanied by an increase in S_a to $3.98\text{ }\mu\text{m}$ for CFRP and $2.91\text{ }\mu\text{m}$ for fused silica. At relatively higher F , the scanned region is dominated by coarse, resolidified fused silica structures that form pronounced ridges and grooves. The surface roughness increases substantially, reaching S_a values of $8.21\text{ }\mu\text{m}$ on the CFRP and $4.57\text{ }\mu\text{m}$ on the fused silica. The presence of these coarse re-solidified structures suggests a loss of interfacial uniformity, which acts as potential defect sites that compromise the mechanical integrity of the joint.

In addition, a depression at the welding initiation region (the inner portion of the weld ring) becomes increasingly prominent at higher F . This localized defect is attributed to the initial lack of thermal accumulation because laser energy input primarily causes material ablation rather than effective melting and interfacial bonding during the early irradiation stage [48]. As the scanning process proceeds, the gradual heat accumulation eventually reaches the threshold required for fused silica melting, which enables stable joint formation. The presence of residual resin on both fracture surfaces further confirms

that the redistribution and solidification of the polymer are essential for creating the joint [49].

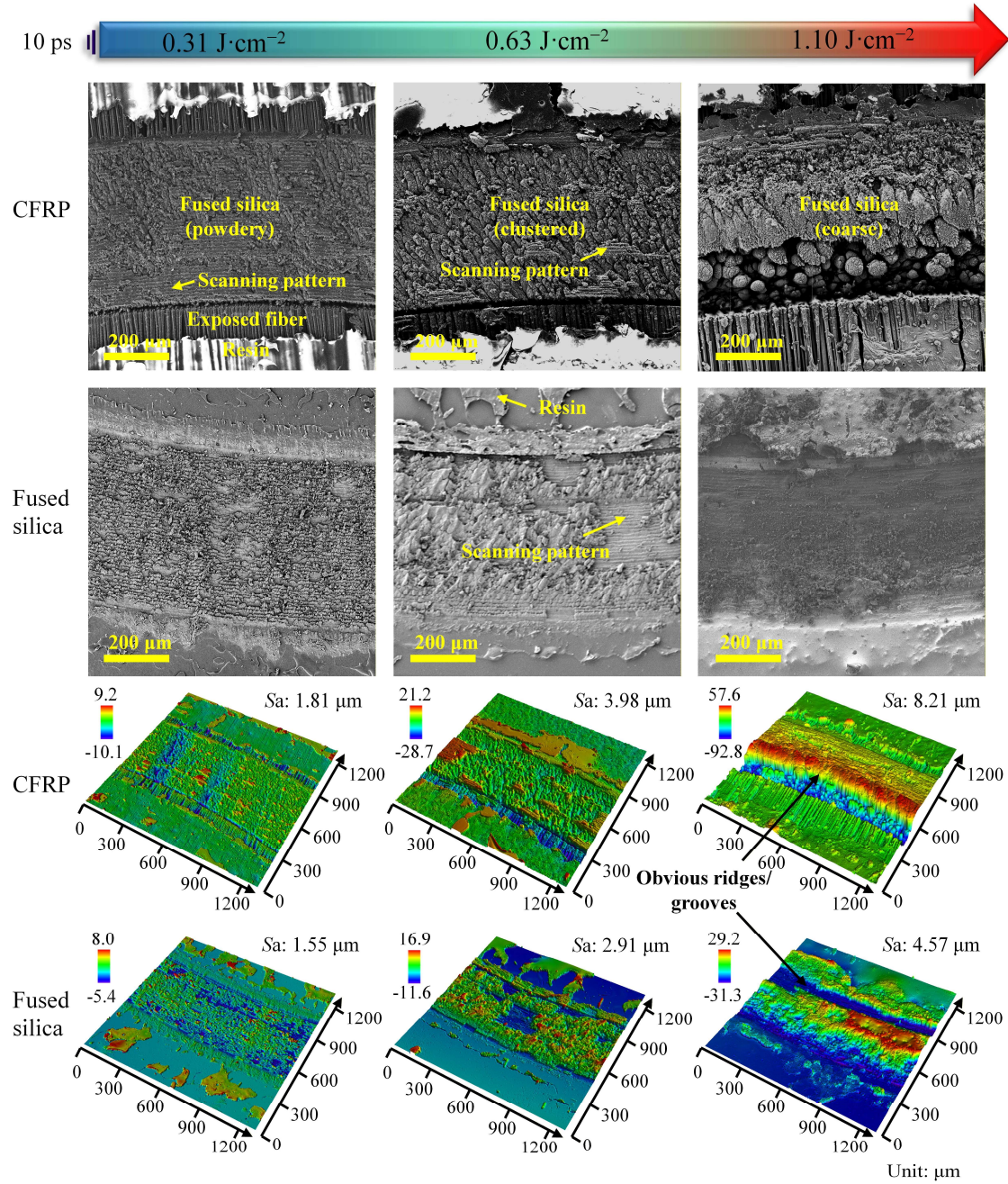


Fig. 8. Representative SEM morphologies and 3D topography of the CFRP and fused silica fracture surfaces. The joints were welded at $\tau = 10$ ps with F values of 0.31, 0.63, and 1.10 J·cm⁻².

Fig. 9 shows the fracture morphologies and corresponding three-dimensional topographies of CFRP and fused silica surfaces welded at a constant fluence of $0.47 \text{ J} \cdot \text{cm}^{-2}$ using three different pulse durations. To exclude the influence of macroscopic bonding strength and isolate the effect of pulse duration on interface evolution, the samples from the three pulse duration conditions (each comprising both CFRP and fused silica) were deliberately selected with nearly identical shear strengths: 2.21 MPa for 500 fs, 2.39 MPa for 10 ps, and 2.13 MPa for 10 ns. Because the macroscopic bonding strength is maintained at a highly comparable level, any structural variation in the fracture morphologies can be primarily attributed to the distinct energy deposition and heat conduction mechanisms governed by the laser pulse duration.

For the ultrafast regimes (500 fs and 10 ps), the laser scanning tracks are visible on the mating fracture surfaces of both the CFRP and fused silica. These tracks are marked by distinct initiation features labeled as an ablation groove at scanning initiation points and an initial ablation groove at the inner region of the weld ring, respectively. The laser scanning tracks are partially covered by resolidified fused silica, indicating that despite the ultrashort pulse duration, the high repetition rate induces sufficient heat accumulation to melt the fused silica at the interface. Morphologically, the two ultrafast regimes exhibit striking consistency in interfacial features and resolidification behavior, with the primary distinction being a modest increase in HAZ extent under picosecond irradiation ($230 \text{ } \mu\text{m}$) relative to femtosecond irradiation ($160 \text{ } \mu\text{m}$). This similarity is corroborated by quantitative surface roughness analysis of the fracture surfaces, which yields nearly

identical S_a values for the 500 fs ($2.36\text{ }\mu\text{m}$ for CFRP and $1.63\text{ }\mu\text{m}$ for fused silica) and 10 ps ($2.48\text{ }\mu\text{m}$ for CFRP and $1.67\text{ }\mu\text{m}$ for fused silica) conditions.

In contrast, fracture surfaces generated with 10 ns pulses exhibit fundamentally distinct morphological characteristics. The laser scanning tracks are no longer visible. Instead, the interface is dominated by coarse resolidified fused silica particles, resulting in markedly increased surface roughness ($S_a = 6.45\text{ }\mu\text{m}$ for CFRP and $3.05\text{ }\mu\text{m}$ for fused silica). Concurrently, a significantly larger HAZ ($412\text{ }\mu\text{m}$) and a widened ablation groove are observed. These features arise from enhanced thermal diffusion during nanosecond laser irradiation, where prolonged energy deposition facilitates substantial heat conduction. This leads to delocalized heating, extensive melting, and coarser resolidification textures. Notably, despite these pronounced morphological and roughness disparities, the CFRP fracture surface across all pulse durations remains consistently covered by transferred fused silica. This indicates that joint formation universally relies on heat-accumulation-induced softening of the fused silica followed by its solidification onto the CFRP substrate, irrespective of the specific pulse duration.

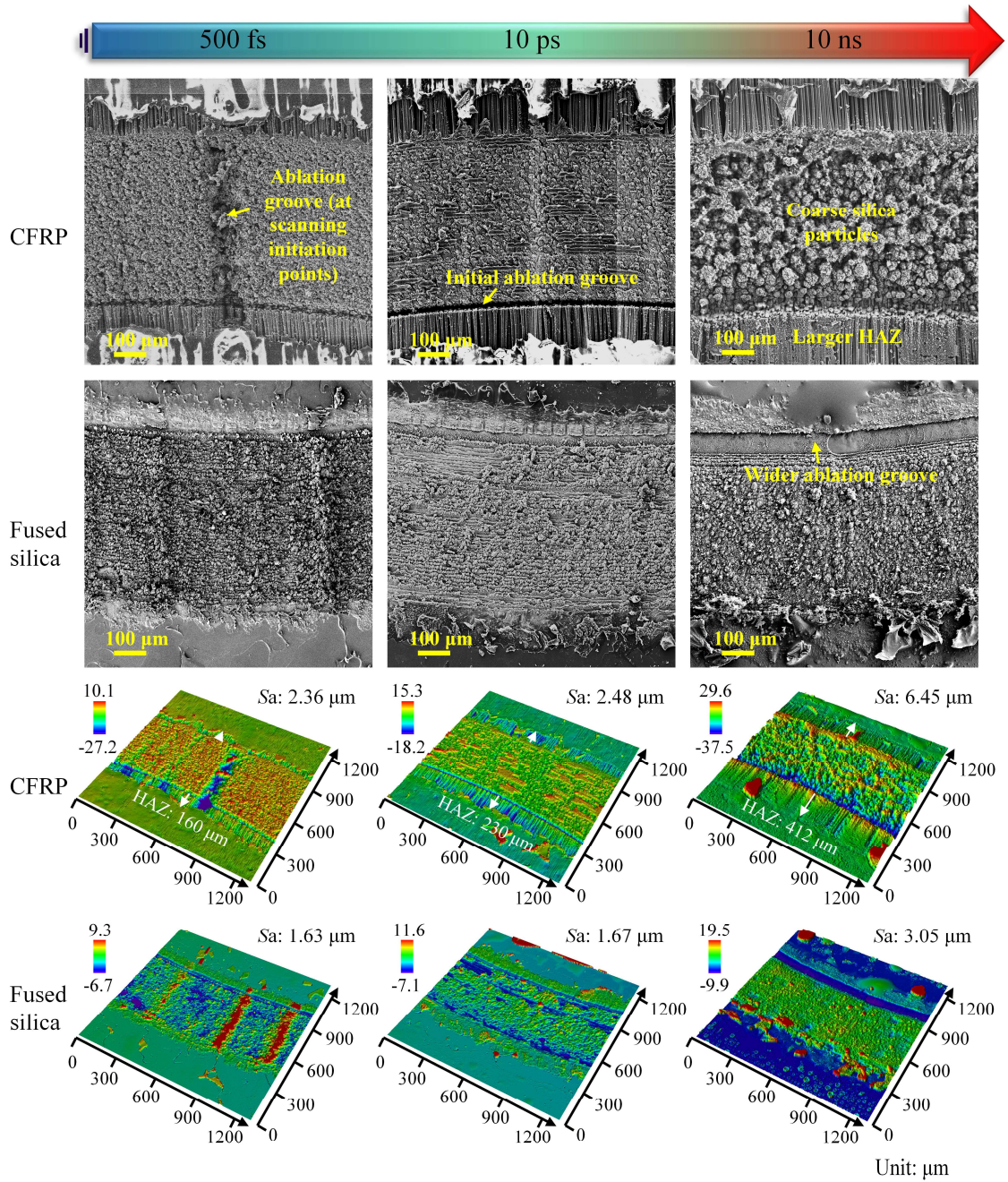


Fig. 9. Representative SEM morphologies and 3D topography of the CFRP and fused silica fracture surfaces. The joints were welded at a constant F of $0.47 \text{ J}\cdot\text{cm}^{-2}$ with different τ (500 fs, 10 ps, and 10 ns).

To elucidate the bonding mechanisms governing the CFRP-fused silica joints, the fracture morphologies and macroscopic elemental distributions on the CFRP side were

examined by SEM and EDS. Fig. 10(a-d) and (e-h) shows two representative fracture modes, respectively. In Fig. 10(a-d), the CFRP fracture surface is extensively covered by silicon (Si) signal, as represented by the blue signal distribution. This elemental distribution suggests that the fracture path propagates primarily within the fused silica substrate. This cohesive failure of the fused silica implies that the interfacial bonding strength was likely higher than the mechanical strength of the fused silica substrate in its laser-modified state. The observation of glass transfer represents compelling evidence for the formation of a bond that is stronger than one of the parent materials.

In contrast, the morphology of CFRP fracture surface in Fig. 10(e-h) is dominated by carbon (C) signals, characterized by distinct exposed and torn carbon fibers. This morphology signifies a shift in the failure mode to the CFRP substrate side. The presence of fiber tearing and pull-out indicates that the interfacial bonding is robust enough to effectively transfer loads, exceeding the interlaminar shear and tensile strength of the CFRP substrate. Consequently, this fiber-tearing mode typically corresponds to higher shear strength values reported in Fig. 7. Such direct interfacial interaction, characterized by the intimate element distribution, suggests the potential formation of synergistic physical and chemical bonding within the laser scanning region.

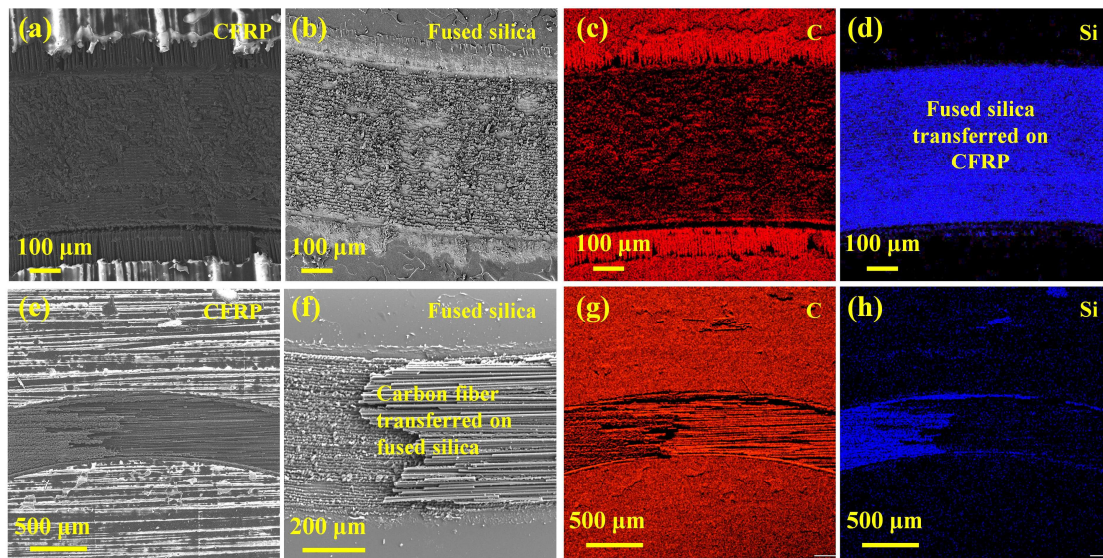


Fig. 10. SEM morphologies of the mating fracture surfaces (both CFRP and fused silica sides) and the corresponding EDS elemental mappings acquired from the CFRP side: (a-d) cohesive failure within the fused silica layer (10 ps, $0.31 \text{ J}\cdot\text{cm}^{-2}$), showing (a) SEM morphology of the CFRP side, (b) SEM morphology of the corresponding fused silica side, and (c, d) EDS mappings of elements C and Si on the CFRP side; (e-h) cohesive failure within the CFRP substrate characterized by fiber tearing (10 ps, $0.16 \text{ J}\cdot\text{cm}^{-2}$), comprising (e) SEM morphology of the CFRP side, (f) SEM morphology of the corresponding fused silica side, and (g, h) EDS mappings of elements C and Si on the CFRP side.

3.4 Physicochemical bonding mechanism

To gain insight into the interfacial bonding mechanisms, high-resolution XPS was performed on the fracture surface of the CFRP side. The high-resolution Si 2p spectrum provides direct spectral evidence supporting interfacial chemical reactions. As shown in Fig. 11(c), the spectrum can be deconvoluted into two components: a peak at 103.3 eV

assigned to SiO_2 (attributed to fused silica residues) and a prominent peak at 102.2 eV. According to the literature, this lower binding energy peak is characteristic of Si–O–C covalent linkages, indicating that Si atoms originating from the fused silica chemically reacted with carbon species derived from the CFRP [50, 51].

This assignment is further supported by the C 1s and O 1s spectra. In the C 1s spectrum in Fig. 11(a), the shoulder at 286.1 eV is dominated by intrinsic epoxy C–O bonds, but it is also energetically compatible with overlapping contributions from Si–O–C species. More specifically, the O 1s spectrum in Fig. 11(b) shows oxygen environments consistent with this interpretation. Peak deconvolution indicates contributions assignable to C=O and Si–O–C-related oxygen species, which is consistent with the presence of interfacial chemical bonding. The detection of Si–O–C covalent linkages carry significant implications for understanding the joining mechanism. These bonds represent a direct chemical bridge between the fused silica and carbonaceous species originating from the CFRP. The formation of such bonds requires both intimate contact at the atomic scale and sufficient thermal activation to overcome reaction barriers. Under the confined irradiation conditions characteristic of the present process, the combination of localized high temperatures, elevated pressures generated by confined ablation, and the reactive environment created by pyrolysis of the epoxy matrix appears to facilitate this chemical interaction. Consequently, the detected Si–O–C bonds support the conclusion that, in addition to mechanical interlocking, laser-induced chemical bonding likely contributes to the joint strength between fused silica and CFRP.

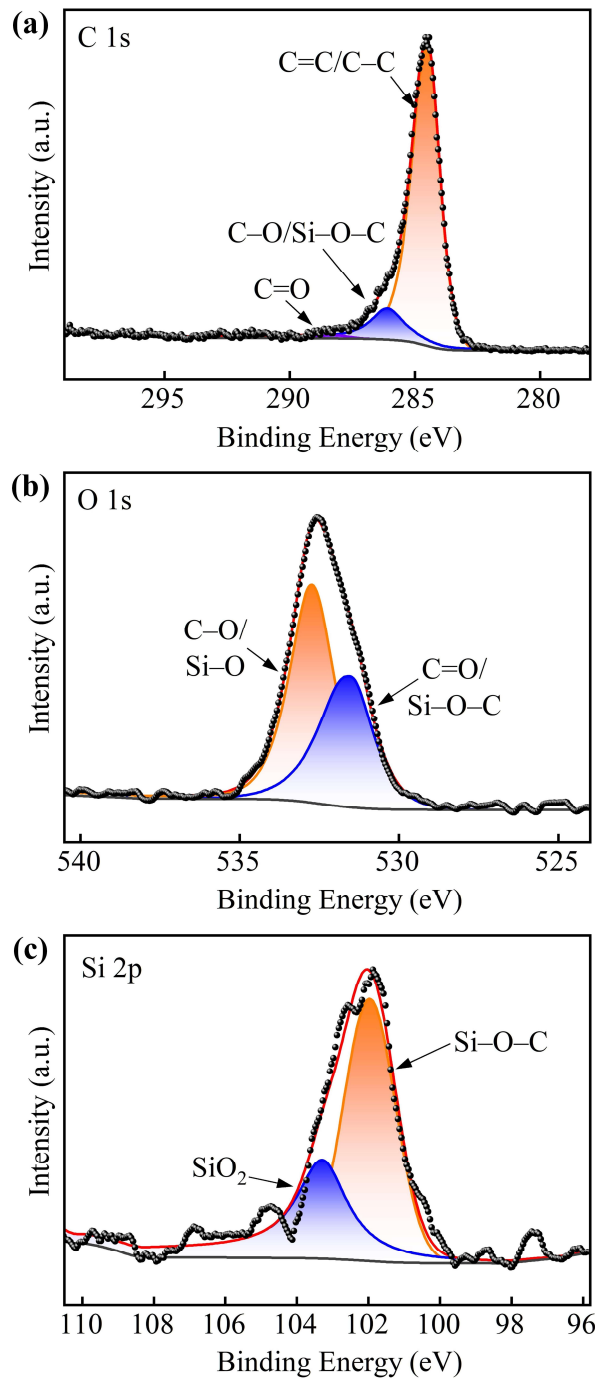


Fig. 11. High-resolution XPS spectra collected from the CFRP-side fracture surface after LM-LTW: (a) C 1s spectrum, (b) O 1s spectrum, and (c) Si 2p spectrum.

Based on the comprehensive experimental evidence presented above, a unified mechanistic framework governing LM-LTW of CFRP to fused silica under non-optical-

contact, clamp-free conditions is established. Prior to laser irradiation (Fig. 12(a)), interfacial wetting is enhanced by the ethanol interlayer through capillary pressure, thereby establishing a continuous medium for subsequent energy coupling. Upon laser exposure (Fig. 12(b)), the transmitted beam is preferentially absorbed by the CFRP, leading to intense localized heating and the generation of an interfacial luminous region (see Fig. 3). This rapid energy deposition triggers matrix decomposition, and a high-pressure vapor/plasma state is produced, which is strictly confined by the transparent fused silica. Analogous to the confined ablation mechanism reported for glass-metal welding [52, 53], a transient interfacial overpressure is generated by the restricted expansion of these ablation products. Concurrently, thermal conduction causes the epoxy within the HAZ to be softened into a rubbery, viscoelastic state. Driven by this transient overpressure, the softened resin and ablated materials are redistributed to conformally fill the initial interfacial gap, while the plasma bridges the gap and further enhances heat transfer and energy coupling. During the subsequent cooling stage (Fig. 12(c)), the softened resin is transformed into a glassy state, and the carbon fibers at the interface are locally encapsulated by the resolidified fused silica. Consequently, a robust joint is formed through a dual mechanism: physical interlocking is achieved via material redistribution, complemented by chemical bonding (i.e. Si–O–C) as confirmed by spectroscopic evidence.

The proposed approach achieves successful joint formation despite a relatively high initial surface roughness ($S_a = 1.44 \mu\text{m}$), indicating a tolerance for surface unevenness

beyond conventional optical-contact requirements. This tolerance is primarily attributed to the multifunctionality of the ethanol interlayer: it generates capillary pressure to bridge the gap and expel interfacial air, thereby maintaining liquid-mediated continuity and enhancing heat transfer. Additionally, ethanol replaces the air gap with a medium whose refractive index is closer to that of fused silica, which minimizes interfacial reflection and promotes stable laser energy coupling into the CFRP surface. Furthermore, the liquid ethanol layer is expected to act as a thermal buffer during rapid heating–cooling cycles, where the latent heat of evaporation helps moderate the peak temperature rise and mitigate thermal shock [35, 54]. Together, these results demonstrate that the ethanol interlayer plays a critical role in facilitating energy coupling, thermal management, and joint strength enhancement.

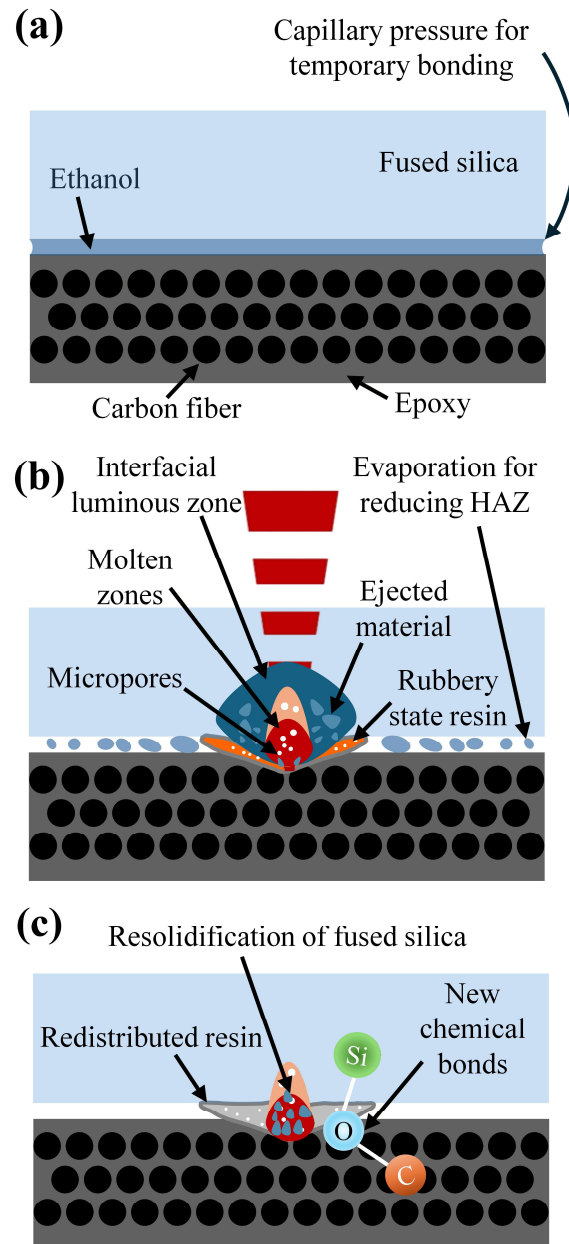


Fig. 12. Schematic illustration of the interfacial bonding mechanism during LM-LTW of CFRP and fused silica. (a) Prior to welding: the ethanol interlayer wets the interface, utilizing capillary pressure to promote conformal contact. (b) Laser irradiation stage: the laser beam transmitted through fused silica is absorbed by the CFRP, leading to localized interfacial heating, resin decomposition, and material ejection/redistribution. (c) Cooling and solidification stage: the redistributed resin and resolidified fused silica form

mechanical interlocking, while new chemical bonds are established at the interface.

4. Conclusions

In this study, a non-optical-contact, clamp-free LM-LTW approach for joining CFRP with fused silica was developed, leveraging an interfacial layer of anhydrous ethanol. The ethanol interlayer improved initial surface wetting and promoted intimate contact between the dissimilar materials, thereby obviating the need for precise optical contact or mechanical clamping. By employing a long-focal-length F-theta lens in conjunction with a concentric annular laser scanning strategy, the process accommodated macroscopic surface topography, successfully welding CFRP substrates with an initial arithmetic S_a of $1.44\text{ }\mu\text{m}$. Systematic experiments across femtosecond, picosecond, and nanosecond pulse durations revealed that picosecond pulses provided the most favorable trade-off between energy coupling and thermal confinement, resulting in a maximum shear strength exceeding 5 MPa. In contrast, the use of longer pulse durations led to excessive thermal accumulation, which induced greater surface degradation, evidenced by increased S_a values and coarser fracture features.

The bonding mechanism was found to proceed through a sequence of laser-induced physical and chemical processes. During early-stage irradiation, rapid vaporization of the ethanol interlayer absorbed excess energy and limited lateral heat diffusion, thereby suppressing expansion of HAZ. Simultaneously, localized thermal decomposition of the epoxy matrix at the CFRP surface exposed underlying carbon fibers. As the temperature

at the interface rose further, molten fused silica infiltrated the fiber-rich region, while the softened thermoset resin underwent viscoelastic flow, collectively enabling mechanical interlocking. Critically, interfacial Si–O–C covalent bonds were formed, as confirmed by XPS analysis, providing direct evidence of chemical adhesion between the inorganic and organic phases.

Future work should focus on refining spatiotemporal laser beam profiles and scanning trajectories to achieve more uniform energy deposition across complex interfaces. Concurrently, the development of coupled multiphysics models, accounting for optical absorption, phase change, and fluid dynamics of fused silica, and thermal degradation of polymer will be crucial for unraveling the transient phenomena governing joint formation in such highly dissimilar material systems.

CRedit authorship contribution statement

Yuan Yao: Writing-original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Yushun Dong:** Writing-review & editing, Investigation, Formal analysis. **Hong An:** Investigation. **Zhanquan Yang:** Formal analysis. **Yongfeng Qian:** Writing-review & editing, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Hu Huang:** Supervision, Resources, Methodology, Funding acquisition.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 52405480), the Natural Science Foundation of Jilin Province (Grant No. 20250102116JC), the National Key Research and Development Plan Project (Grant No. 2026YFE0205000), the Open Project Program of Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Ministry of Education, Changchun University of Science and Technology (CMNM-KF202505), and the Fundamental Research Funds for the Central Universities (Grant No. 2023-JCXK-02).

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