



Quality Prediction in Long-Lap Continuous Ultrasonic Welding of Thermoplastic Composites

Acoustic behavior during continuous ultrasonic welding is simulated, and a model is proposed for predicting welding quality

BY F. YAO, Y. ZHAO, Z. LI, T. YAN, AND W. YUAN

Abstract

Continuous ultrasonic welding is an efficient and precise technology widely used for joining composite materials. However, compared to ultrasonic single-point welding, continuous ultrasonic welding exhibits lower joint quality, posing significant challenges for quality control. This study focuses on the joint quality of continuous ultrasonic welding. Based on the acoustic wave transmission principle, the acoustic behavior during continuous ultrasonic welding is simulated, and a model is proposed for predicting welding quality. Welding pressure, welding speed, and the radiation radius of welding energy are key factors influencing weld quality. The heating process of continuous ultrasonic welding is simulated using the finite element method, and the energy attenuation characteristics and heat distribution during welding are analyzed to validate the quality prediction model. Experimental verification further confirms the model's accuracy. The results demonstrate that under stable welding conditions, the model reliably predicts welding quality, offering an effective solution for quality assessment in continuous ultrasonic welding of thermoplastic composites.

Keywords

- Continuous Ultrasonic Welding
- Thermoplastic Composite
- Prediction Model
- Ultrasonic Transmission

Introduction

Thermoplastic composites have gained significant attention in welding technology research and development due to their ability to be locally re-melted and reshaped upon heating. Common welding techniques include resistance welding, induction welding, and ultrasonic welding. Among these, ultrasonic welding offers notable advantages for joining thermoplastic composites, particularly in enabling high-speed industrial welding processes (Refs. 1–4).

During ultrasonic welding, the sonotrode applies high-frequency, low-amplitude vibrations to the weld interface while maintaining a constant static pressure. Heat at the interface is primarily generated by surface friction and viscoelastic heating, enabling material bonding (Refs. 5–8). In recent years, static ultrasonic welding has emerged as a research hotspot due to its high joint strength and well-established process, resulting in significant progress in both experimental studies and numerical simulations. However, as thermoplastic composites are increasingly used in large-scale structural components, the limitations of the static welding process have become apparent, particularly in welding efficiency and joint consistency, making it challenging to meet practical engineering requirements. Consequently, continuous ultrasonic welding has emerged as a key advancement for improving welding efficiency and has gradually gained attention (Refs. 9, 10).

Continuous ultrasonic welding is an efficient and viable technology. In 2015, Senders et al. pioneered the concept of continuous ultrasonic welding in thermoplastic composites and developed an initial device for this process. Additionally, they proposed a novel method for continuously welding thermoplastic composite adhesives based on zero-current welding, successfully demonstrating the feasibility of continuous ultrasonic welding (Refs. 11, 12). Subsequently, the Villegas team compared continuous ultrasonic welding with static welding and highlighted that welding speed is the key parameter unique to continuous ultrasonic welding (Ref. 13). The German

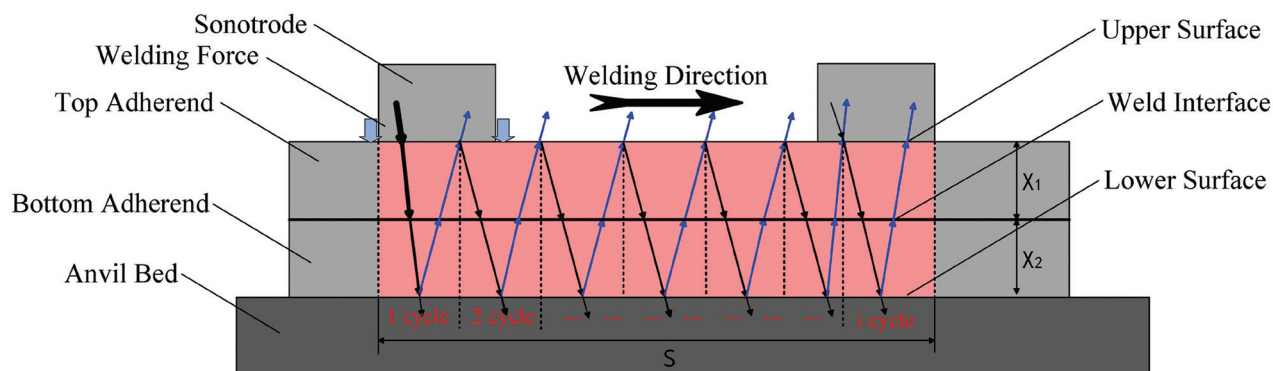


Fig.1 — Continuous ultrasonic welding acoustic wave transmission process: multiple cyclic acoustic wave transmission. To more clearly analyze the wave propagation process, the propagation path is drawn with oblique lines.

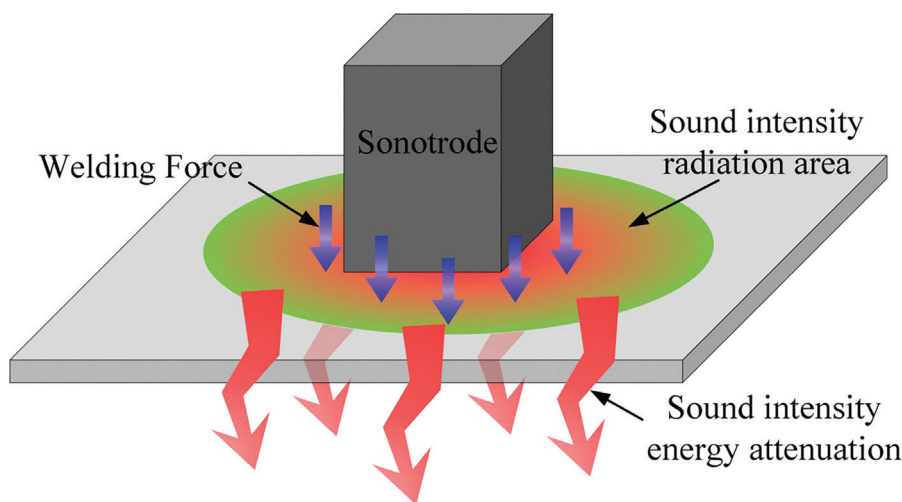


Fig. 2 — Influence factors of incident sound intensity energy.

Aerospace Center has developed a continuous ultrasonic welding robot capable of real-time monitoring of the robot's motion state, welding pressure, and sonotrode displacement. However, continuous ultrasonic welding technology is still in its early stages, and a significant gap remains between the strength of welded joints and that of single-point static welding, with the joint strength being only about two-thirds of that of single-point welded joints (Refs. 14, 15). Therefore, effectively enhancing the joint strength of continuous ultrasonic welding and optimizing welding process parameters remains a key research challenge.

Currently, research on ultrasonic welding quality prediction is primarily based on experimental methods, with relatively limited theoretical studies. Wang et al. (Ref. 16) developed a joint bonding performance model based on type II (plane) shear loading, enabling the prediction of single-point static welding quality. Paramasivam et al. (Ref. 17) applied an artificial neural network model to predict the ultrasonic welding parameters of copper-aluminum plates, successfully forecasting the yield strength and final strength of the weld. Based on the reflection and transmission characteristics of the welding material boundary, support structure, and vibration system, Khmelev et al. (Ref. 18) proposed a propagation

energy model for ultrasonic vibration in the welding zone of thermoplastic materials. Li et al. (Refs. 19–21) integrated machine learning and deep learning techniques with a wave propagation model of the welding process to predict welding quality, achieving an accuracy exceeding 99%. Görick (Ref. 22) employed a one-dimensional convolutional neural network and a fully connected neural network to predict the quality of continuous ultrasonic welding, with results indicating an overall prediction accuracy of 72%. Akay et al. (Ref. 23) developed an algorithm based on the thickness variation of the welding area before and after welding to predict continuous ultrasonic welding quality.

Although the aforementioned studies have made significant progress in predicting single-point static welding quality and have accumulated substantial experience in investigating the interaction mechanisms of welding parameters, research on continuous ultrasonic welding quality prediction still primarily relies on experimental methods. Existing studies lack systematic theoretical modeling, and the accuracy and generalizability of welding quality prediction remain limited. Therefore, developing a welding quality prediction method based on physical mechanisms

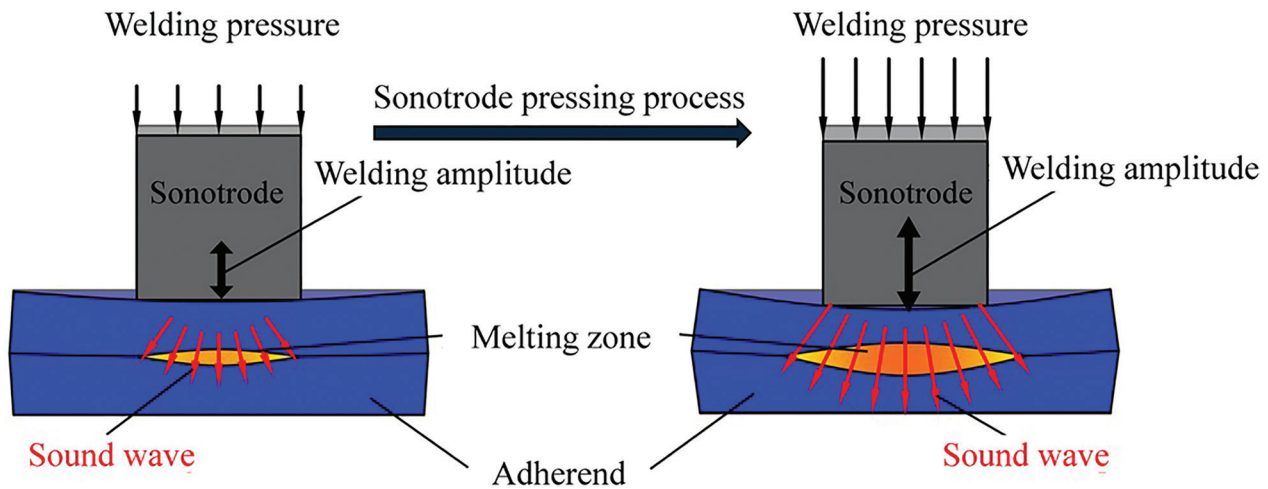


Fig. 3 — The influence of welding pressure on adherends. The length of the arrow represents the size of the value.

to achieve precise control of continuous ultrasonic welding quality has become a critical challenge in this field.

This paper conducts an in-depth study of the continuous ultrasonic welding process. By examining the mechanism of acoustic wave transmission, it innovatively integrates theoretical modeling with data-driven methods to overcome the traditional reliance on experimental data and establish a welding quality prediction model. The research focuses on predicting the weld quality of long lap joints in continuous ultrasonic welding, uncovering the intrinsic relationships between key welding parameters, and systematically analyzing the principles for optimizing welding parameter selection under continuous ultrasonic welding conditions. This study provides strong theoretical support and technical guidance for the quality control of continuous ultrasonic welding in thermoplastic composites.

Model Description

Figure 1 illustrates the sound wave transmission mechanism during continuous ultrasonic welding. First, the ultrasonic transducer converts electrical energy into high-frequency mechanical vibrations, which are transmitted from the horn to the sonotrode. The sonotrode then transfers these vibrations to the welding area. At this stage, the acoustic waves propagate from the sonotrode to the upper surface of the adherend and into the top adherend. As the sound waves travel through the top adherend, their energy gradually attenuates. Upon reaching the welding interface, vibration-induced friction occurs between the top and bottom adherends, generating heat. At this interface, acoustic energy is not significantly dissipated, allowing the waves to continue into the bottom adherend. As the waves propagate through the bottom adherend, they further attenuate and partially reflect at the lower surface, resulting in additional energy loss. During continuous ultrasonic welding, the acoustic waves continuously reflect and transmit within the adherend as the sonotrode moves.

Calculation of Incident Sound Intensity Energy of Adherend

Figure 2 illustrates the factors influencing the incident sound intensity of the weldment during ultrasonic welding. The calculation of incident sound intensity primarily involves the following three aspects. First, the applied welding pressure changes the density, which in turn determines the velocity of ultrasonic wave propagation. Second, the radiation area formed by the sonotrode during the welding process influences the unwelded regions as the sonotrode moves horizontally. Finally, when the sound waves enter the adherend, they undergo reflection and transmission, leading to partial energy loss.

Effect of Welding Force

Figure 3 illustrates the compression effect of welding pressure on the adhesion during the welding process. As the acoustic wave propagates, the applied welding pressure deforms the adherend, influencing it on both micro- and macro-scales. On the microscale, welding pressure reduces the molecular spacing within the adherend, thereby enhancing intermolecular interactions and improving the efficiency of acoustic wave transmission. On the macroscale, the adherend thickness decreases. At the same time, the contact area increases, enhancing the coupling of acoustic energy at the welding interface, which in turn affects the propagation speed of the acoustic wave, as described by Equation 1.

$$c' = c_0 \sqrt{\frac{\rho}{\rho_0}} \quad (1)$$

where c' is the sound velocity in compressed medium, c_0 is the sound velocity under no pressure condition, ρ is the density of the compressed medium, and ρ_0 is the density under pressure-free conditions.

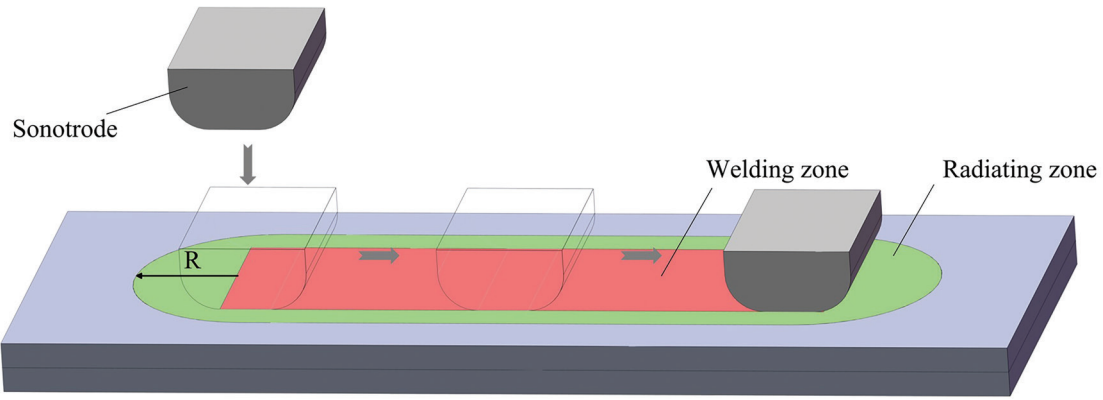


Fig. 4 – The radiative zone in continuous ultrasonic welding.

To investigate the effect of welding pressure on ultrasonic propagation velocity, the pressure coefficient α is defined based on the material's compression characteristics. This coefficient quantifies the influence of welding pressure on ultrasonic wave propagation, as expressed in Equation 2. Furthermore, the relationship between welding pressure and ultrasonic propagation velocity is elucidated by analyzing the material's deformation and stress response under varying pressure conditions, as presented in Equation 3.

$$\alpha = \frac{\partial c'}{\partial P} \quad (2)$$

$$\begin{aligned} c' &= c_0 \sqrt{\frac{\rho}{\rho_0}} \\ &= c_0 \sqrt{1 + \alpha P} \end{aligned} \quad (3)$$

where P is the welding pressure and α is the pressure coefficient.

At this moment, under the influence of welding pressure, the sound intensity energy beneath the sonotrode I_0 is given by Equation 4:

$$I_0 = 2\pi^2 f^2 A_0^2 \rho_0 c_0 \sqrt{1 + \alpha P} \quad (4)$$

where f is the welding frequency and A_0 is the welding amplitude.

Sound Intensity Radiation

During continuous ultrasonic welding, as the sonotrode moves horizontally relative to the adherend, energy from the welding radiation area propagates toward the sonotrode, influencing the temperature distribution in the non-contact region between the sonotrode's bottom surface and the adherend's surface. This energy transfer

gradually raises the adherend's temperature along the sonotrode travel direction, altering its thermodynamic state and affecting the energy distribution and transfer mechanism during welding, as shown in Fig. 4. The size of the welding energy radiation area is a key factor influencing welding quality.

In continuous ultrasonic welding, variations in welding speed may influence the size of the welding energy radiation area. Therefore, gaining an in-depth understanding of how welding speed affects the radiation area is crucial for optimizing the ultrasonic welding process and enhancing the reliability of the welding quality prediction model. From the perspective of ultrasonic welding mechanisms, changes in welding speed can alter the sound field distribution, particularly in the direction of the sonotrode's movement. While these changes may impact the sound intensity distribution within the welding area, their direct effect on the radiation radius is relatively minor. Although welding speed plays a role in the welding process, the welding energy radiation radius is primarily determined by the geometry of the sonotrode, vibration frequency, and welding power.

Based on the Huygens-Fresnel principle, the energy radiation radius in the ultrasonic welding process is analyzed. The calculation of the radiation radius comprehensively considers welding power, sound field intensity, the inhomogeneity factor of the medium, and the scattering effect factor of the sound field, which is expressed as:

$$R = \sqrt{\frac{P_w}{4\pi I_0} \times \frac{1}{f(\rho) \cdot g(\theta)}} \quad (5)$$

where P_w is the welder power, $g(\theta)$ is the scattering effect factor of the sound field, and $f(\rho)$ is the inhomogeneity factor of the medium.

The energy field during continuous ultrasonic welding is simulated using Abaqus software, and the dissipation energy in the radiation zone is computed. Based on the energy attenuation law, the attenuation curve $p(x)$ is fitted using the least squares method:

$$p(x) = p_1 \cdot x^n + p_2 \cdot x^{n-1} + \dots + p_n \quad (6)$$

where p_n is the polynomial coefficients of fitting and x is the distance from the sound source.

Based on the welding energy radiation radius derived from Equation 5 and the energy attenuation curve of the radiation zone from Equation 6, the sound intensity energy I_f in the radiation zone can be determined, expressed as:

$$I_f = \frac{1}{2} \int_0^{\sqrt{\frac{P}{4\pi I_0} \cdot \frac{1}{f(\rho) \cdot g(\theta)}}} \left(p_1 \cdot x^n + p_2 \cdot x^{n-1} + \dots + p_n \right) ds \quad (7)$$

Calculation of Internal Sound Intensity Energy of Adherend

When analyzing the propagation of sound waves within the adhesion, the key challenge is to determine the attenuation pattern and the number of wave cycles. This process requires selecting an appropriate attenuation model and ensuring accurate cycle estimation.

Sound Intensity Energy Transmission Attenuation

As sound waves propagate into the material, amplitude damping causes a portion of the sound intensity energy within the adhesion to convert into heat, leading to a gradual decrease in wave energy. To quantitatively describe the effect of amplitude damping on acoustic wave propagation, the Kelvin-Voigt model is employed to characterize the attenuation mechanism. The detailed derivation of this expression is provided in Appendix A. Within a single decay cycle, the residual energy I_x can be expressed as:

$$I_x = I_z \cdot \frac{1}{\sqrt{1 + \left(\frac{x}{\lambda}\right)^2}} \quad (8)$$

where λ is the viscous damping coefficient.

Calculation of Acoustic Wave Cycle

During continuous ultrasonic welding, sound waves undergo multiple reflections and transmissions within the adhesion. To minimize calculation errors and more accurately describe the attenuation behavior of sound waves over multiple cycles, this study introduces a multicycle sound intensity attenuation model for analysis. The number of acoustic cycles is determined using the cycle accuracy ε :

$$i = \log_{\gamma_1 \beta_2 \beta_1 \beta_2 \dots \varepsilon} \quad (0 \leq \varepsilon \leq 1) \quad (9)$$

where γ_1 is the transmission coefficient of plate and sonotrode, β_1 is the reflection coefficient of plate and sonotrode, and β_2 is the reflection coefficient of plate and base.

After determining the number of sound wave cycles i , the internal sound intensity energy I_i of the adhesion after i cycles can be calculated using Equations 4, 8, and 9:

$$\begin{aligned} I_{Li} &= I_z \cdot \frac{1}{\sqrt{1 + \left(\frac{x_1}{\lambda}\right)^2}} + I_z \\ &\cdot \frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} + \beta_1 I_z \cdot \frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \\ &\cdot \frac{1}{\sqrt{1 + \left(\frac{x_2}{\lambda}\right)^2}} \\ &+ \beta_2 I_z \cdot \left(\frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \right)^{2i-2} + \dots + \beta_1^{i-1} \beta_2^{i-1} I_z \\ &\cdot \left(\frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \right)^{2i-2} \cdot \frac{1}{\sqrt{1 + \left(\frac{x_1}{\lambda}\right)^2}} + \beta_1^{i-1} \beta_2^{i-1} I_z \\ &\cdot \left(\frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \right)^{2i-1} + \beta_1^i \beta_2^{i-1} I_z \\ &\cdot \left(\frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \right)^{2i-1} \cdot \frac{1}{\sqrt{1 + \left(\frac{x_2}{\lambda}\right)^2}} + \beta_1^i \beta_2^{i-1} I_z \\ &\cdot \left(\frac{1}{\sqrt{1 + \left(\frac{x_1 + x_2}{\lambda}\right)^2}} \right)^{2i} \quad (i \geq 2) \end{aligned} \quad (10)$$

where i is the cycle index, x_1 is the thickness of top adhesive layer, and x_2 is the thickness of the bottom adhesive layer.

Welding Quality Prediction

After determining the internal sound intensity energy I_i of the adhesion after i cycles, the energy absorption rates of the top and bottom adhesion layers can be calculated using the following formula:

$$W_{total} = \sum_{i=1}^n I_{Li} \cdot S \quad (11)$$

where S is the weld area between the top and bottom adherend to achieve fusion.

Assume the effective thickness of the melted layer is h , and the mass of the melted region is ($m = \rho \times S \times h$). Based on the energy requirements of the material, the energy needed to raise the material to its melting point and the energy required for melting at the melting point can be calculated as follows:

$$Q = m \cdot \int_{T_1}^{\Delta T} C_p(T) dT + \Delta H_f \quad (12)$$

where Q is the heat required for welding, ΔT is the temperature in the welding region, C_p is the temperature-dependent specific heat of the welded material, T_1 is the room temperature, and ΔH_f is the melting latent heat of materials.

To predict the quality range of continuous ultrasonic welding, this study classifies welding quality into three grades based on the melting state of the weld after welding, using the material's melting and decomposition temperatures as classification criteria. If the material temperature does not reach the melting temperature, a reliable welded joint cannot form; the welding quality is classified as "under-welded." When the material temperature reaches the melting temperature but remains below the decomposition temperature, a stable and reliable welded joint forms, defining the welding quality as "normal welding." However, if the material temperature exceeds the decomposition temperature, excessive melting occurs, potentially generating numerous pores in the welded joint and reducing welding quality. In this case, the welding quality is classified as "over-welding."

Furthermore, welding speed, a key process parameter in continuous ultrasonic welding, is incorporated into the quality prediction model to establish its relationship with welding temperature:

$$v = \frac{l}{t} = \frac{l \cdot W_{total}}{Q} \quad (13)$$

where l is the horizontal motion distance of the welding head relative to the surface of the adherend to be welded along the moving direction and t is the welding time.

As shown in Equation 14, solving this equation yields the solution for the temperature in the welding region.

$$\int_{T_1}^{\Delta T} C_p(T) dT = \frac{1}{m} \left(\frac{l \cdot W_{total}}{v} - \Delta H_f \right) \quad (14)$$

The welding level is determined based on the material temperature. T_m denotes the melting temperature of the material, and T_d denotes the decomposition temperature. When $\Delta T \leq T_m$, the material temperature does not reach the melting point, preventing the formation of a reliable joint. In this case, the welding level is classified as under-welded. When $T_m \leq \Delta T \leq T_d$, the material temperature reaches the melting point but does not exceed the decomposition temperature, allowing the formation of a reliable joint. This

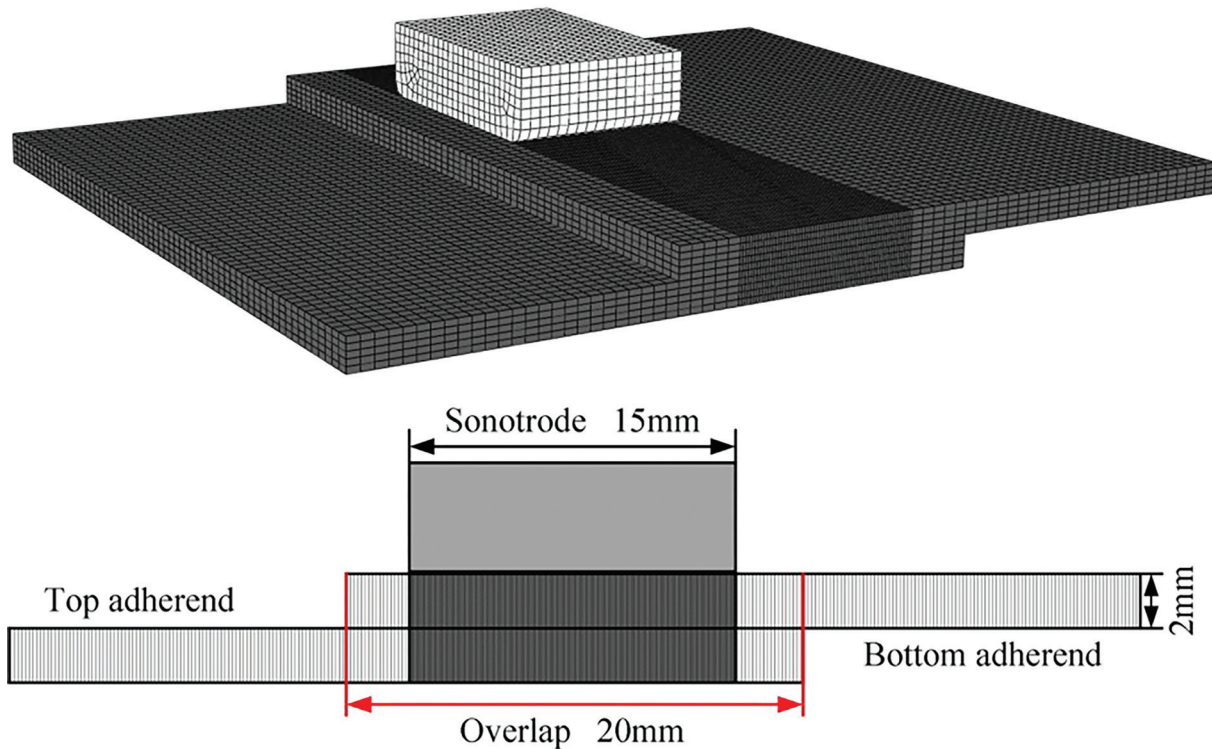


Fig. 5 — Finite element model of continuous ultrasonic welding.

condition is classified as normal welding. When $\Delta T \leq T_d$, the material temperature exceeds the decomposition temperature, causing excessive melting. Due to significant resin extrusion, numerous pores form at the joint, classifying the welding level as over-welded.

The model describes the heating mechanism in continuous ultrasonic welding by simulating the transfer and dissipation of sound wave energy between adherends, based on the law of conservation of energy. By analyzing the material’s absorption and release of acoustic energy, a conservation-based welding energy calculation is established, enabling the prediction of welding quality.

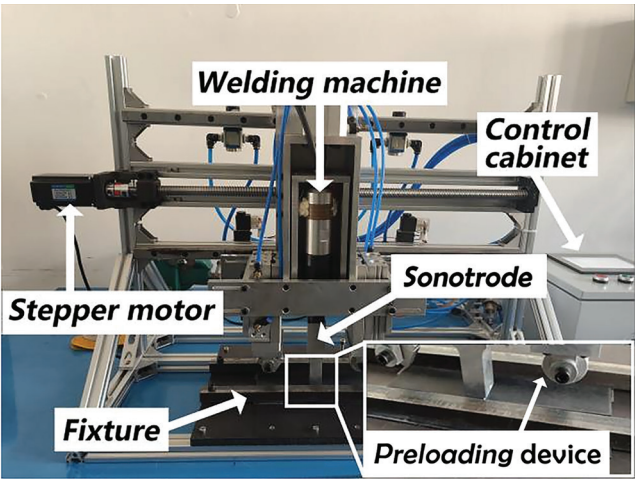


Fig. 6 – Machine for continuous ultrasonic welding.

Materials and Methods

Finite Element Analysis

Based on the heat generation mechanism of ultrasonic welding, the continuous ultrasonic welding process was simulated using Abaqus finite element software. However, in the explicit dynamic-temperature-displacement coupling analysis, the direct calculation of heat generation in viscoelastic materials as a welding heat source is not feasible. To address this, the heat generation value in the continuous welding prediction model was calculated using a VDFLUX subroutine and incorporated into the finite element model as a heat source, enhancing the simulation’s accuracy and physical consistency.

Using CF/PA66 as the research subject, with a carbon fiber mass fraction of 30%, the material properties are shown in Table 1.

The relationship between the spring stiffness, G_i , and the relaxation modulus, K_i , is determined using Equation 15, which defines the material’s relaxation and creep behavior. The viscoelastic properties of the material are characterized by fitting the Prony series, and the dissipated energy during the continuous ultrasonic welding process is subsequently calculated.

$$G_i = \frac{K_i \tau_i}{1 + \tau_i^2} \tag{15}$$

where G_i is the elastic modulus of a certain order, τ_i is the time constant of a certain order, and K_i is the certain order of spring stiffness.

After defining the material properties, the finite element model is established, as shown in Fig. 5. The model is meshed using quadrilateral solid elements (C3D8), with a mesh size

Table 1 – Material Properties of CF-PA66 Used in the Simulation

Properties	Symbol	Unit	Value
Density	ρ	$\text{kg}\cdot\text{m}^{-3}$	1270
Young's Modulus	E	MPa	3840
Poisson Ratio	ν	—	0.28
Thermal Conductivity	k	$\text{W}\cdot\text{m}^{-1}\cdot^{\circ}\text{C}^{-1}$	0.24
Specific Heat	C	$\text{J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$	1250
Thermal Expansion	α	$^{\circ}\text{C}^{-1}$	0.0001
Glass Transition Temperature	T_g	$^{\circ}\text{C}$	147
Melting Temperature	T_m	$^{\circ}\text{C}$	220

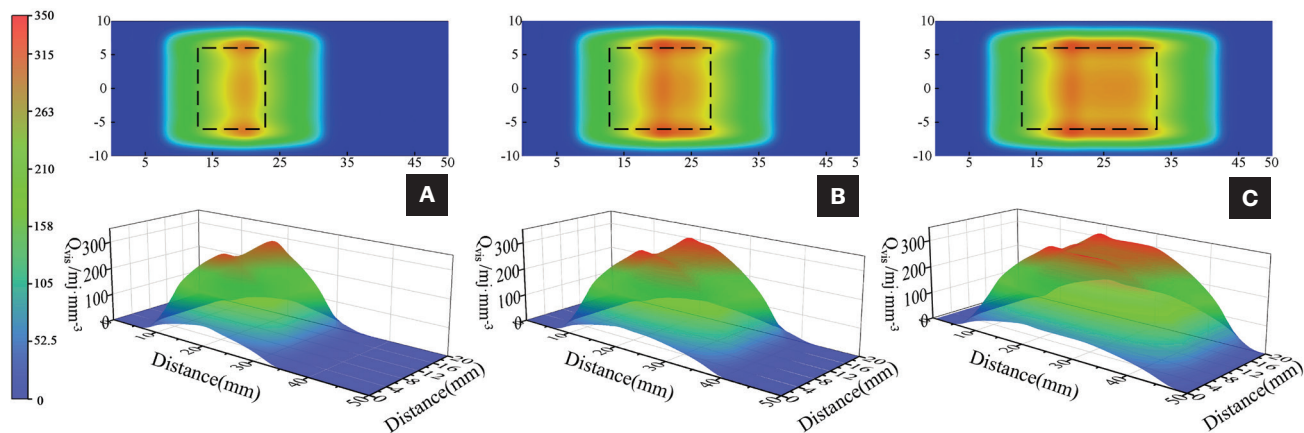


Fig. 7 – Energy distribution of the welding interface at the speed of 20 mm/s: A – Welding distance 5 mm; B – welding distance 10 mm; C – welding distance 15 mm.

of 1 mm in the overlapping region and 4 mm in the remaining areas. The contact area of the sonotrode is 12×15 mm, the adherend dimensions are $60 \times 70 \times 2$ mm, the lap area is 70×20 mm, and the lower contact area of the sonotrode is 20×12 mm.

The adherend is modeled using temperature-displacement coupling elements, with both ends fixed. A sinusoidal vibration with a vertical frequency of 20 kHz and an amplitude of $80 \mu\text{m}$ is applied to the sonotrode, along with a uniform horizontal motion. The friction coefficient is set to 0.4 between the top and bottom adherends and 0.2 between the sonotrode, base, and adherend (Ref. 24). The ambient temperature is assumed to be uniform at 25°C . The energy input for the continuous ultrasonic welding process is incorporated into the heat source via the VDFLUX subroutine to solve the temperature field during welding.

Experiments

The material used in this study was an injection-molded short carbon fiber reinforced polyamide 66 (PA66) composite plate, with a carbon fiber mass fraction of 30%. The carbon fibers had an average length of approximately 2 mm and a diameter of about $7 \mu\text{m}$. The dimensions of the specimens used in this study were $60 \text{ mm} \times 70 \text{ mm} \times 2 \text{ mm}$. The CF-PA66 composites were kindly provided by Koreda Plastic Products Co., Ltd.

The welding equipment used in this experiment is a continuous ultrasonic welding device independently developed by our research group, as shown in Fig. 6. The system consists of three main components: the acoustic system, the transmission mechanism, and the control system. The acoustic system includes an ultrasonic generator, a transducer, a horn, and a sonotrode. The transmission mechanism comprises a linear guide rail and an ultra-thin cylinder, while the control system consists of a touchscreen and a PLC. The pneumatic feeding device, transducer, horn, and sonotrode are all mounted on the same horizontally moving platform, which is driven by a stepper motor to ensure precise relative motion between the welding machine and the adherend. The specific parameters of the device are listed in Table 2.

Table 2 – Continuous Ultrasonic Welding Machine Parameters

Properties	Unit	Value
Maximum Welding Pressure	MPa	3
Maximum Amplitude	μm	80
Maximum Output Power	W	2000
Frequency	Hz	20,000
Maximum Welding Speed	$\text{mm} \cdot \text{s}^{-1}$	50
Sonotrode Section Size	mm^2	12×15
Maximum Welding Length	mm	600

Results and Discussions

Simulation Verification of Continuous Ultrasonic Welding Process

To investigate the attenuation characteristics of the radiation area in continuous ultrasonic welding, a continuous ultrasonic welding prediction model was used, assuming a uniformly distributed sound intensity in the radiation area. The energy field of continuous ultrasonic welding was simulated using Abaqus software. The welding speed was set to 20 mm/s, and the welding distance was 20 mm. Figure 7 presents

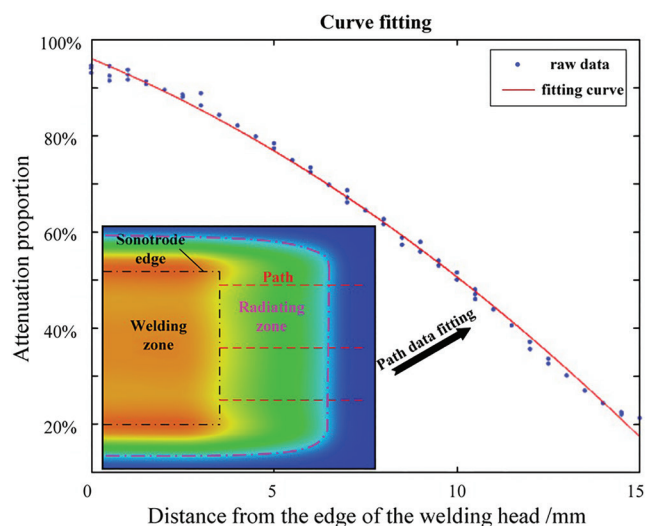


Fig. 8 — Radiation area attenuation curve fitting.

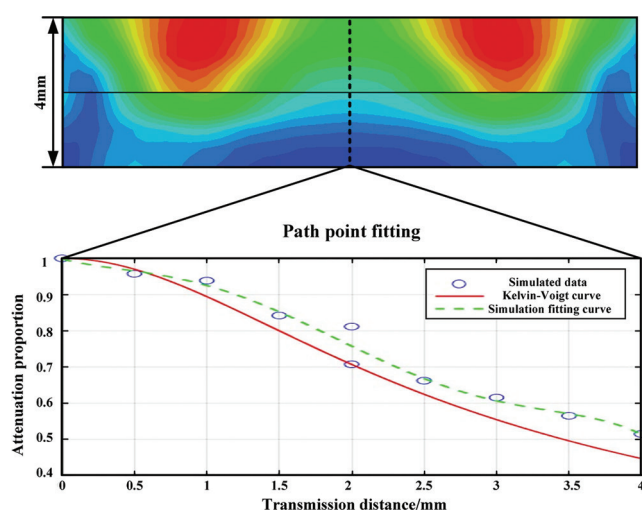


Fig. 9 — Kelvin-Voigt model and simulation data curve comparison diagram.

the energy distribution at the contact interface between the sonotrode and the top adherend at a welding speed of 20 mm/s. Taking the center of the sonotrode as the reference point, three welding stages with welding distances of 10 mm, 15 mm, and 20 mm were analyzed. It should be noted that the energy intensity is not strictly radially symmetric with respect to the sonotrode center. The black dotted box in the figure highlights the region of movement for the sonotrode. Due to the influence of the “hammering effect” (Ref. 25), energy distribution in both the initial and final welding stages is unstable. Therefore, only the energy distribution in the steady-state stage of welding was selected to fit the attenuation curve of the attenuation region.

Figure 8 illustrates the path division of the radiation area under a welding speed of 20 mm/s and a welding distance of 10 mm. Three equidistant paths from the center to the

edge of the sonotrode were selected. Based on this path data, the attenuation curve was fitted using the nonlinear least squares method. To enhance the fitting accuracy, the residual sum of squares between the observed data and the fitting function was minimized, ensuring a precise estimation of the attenuation curve. The results indicate that the fitting function effectively characterizes the attenuation behavior of the radiation area. Furthermore, using the fitted equation, the distribution of sound intensity energy within the radiation area can be further determined when the welding radiation radius is specified.

In the continuous ultrasonic welding model, the Kelvin-Voigt model is employed to simulate the attenuation process of acoustic wave transmission. To validate the model’s accuracy, Abaqus was used to simulate the ultrasonic static single-point welding process. The calculation accuracy was enhanced by refining the density of the vertical mesh, and the dissipation energy data along the plate’s thickness direction were extracted. The obtained dissipation energy data were then fitted and compared with the prediction curve of the Kelvin-Voigt model. The results indicate that the Kelvin-Voigt model effectively captures the attenuation behavior of acoustic wave transmission, demonstrating high consistency with the simulation data and verifying its effectiveness in describing acoustic wave energy dissipation, as shown in Figure 9.

To verify the accuracy of the continuous ultrasonic welding quality prediction model, the deviation between the heat generation during welding and the model’s predicted results was analyzed. Based on the prediction model, the applicable welding speed range for the material was determined, and the temperature field of continuous ultrasonic welding was simulated. During the simulation, the VDFLUX subroutine was used to calculate the viscoelastic energy generated during the welding process, and temperature field contour plots were generated at different welding speeds. Within the temperature range of 220°C to 360°C, samples were selected at 20°C intervals for analysis, and the prediction model was used to calculate the temperature distribution of eight groups at varying welding speeds. Figure 10 presents the temperature distribution at the welding interface for different welding speeds, with temperature data extracted from the welding midpoint for comparative analysis. The results indicate that as the welding speed decreases, the material’s peak temperature increases gradually, resulting in greater heat accumulation. Furthermore, under different welding speed conditions, the radiation area remains relatively stable throughout the welding process, suggesting that welding speed has a limited impact on the radiation area.

Table 3 presents a comparison of the predicted and simulated temperature rises at different welding speeds. The results show that, as the welding speed increases, the discrepancy between the predicted and simulated values gradually grows, although the overall error remains within the range of 1.28–10.18%.

This phenomenon can be interpreted in the context of the heating mechanisms involved in ultrasonic welding. In the initial stage of welding, when intimate contact across the overlap has not yet been fully established, the dominant heat source is interfacial frictional dissipation between the

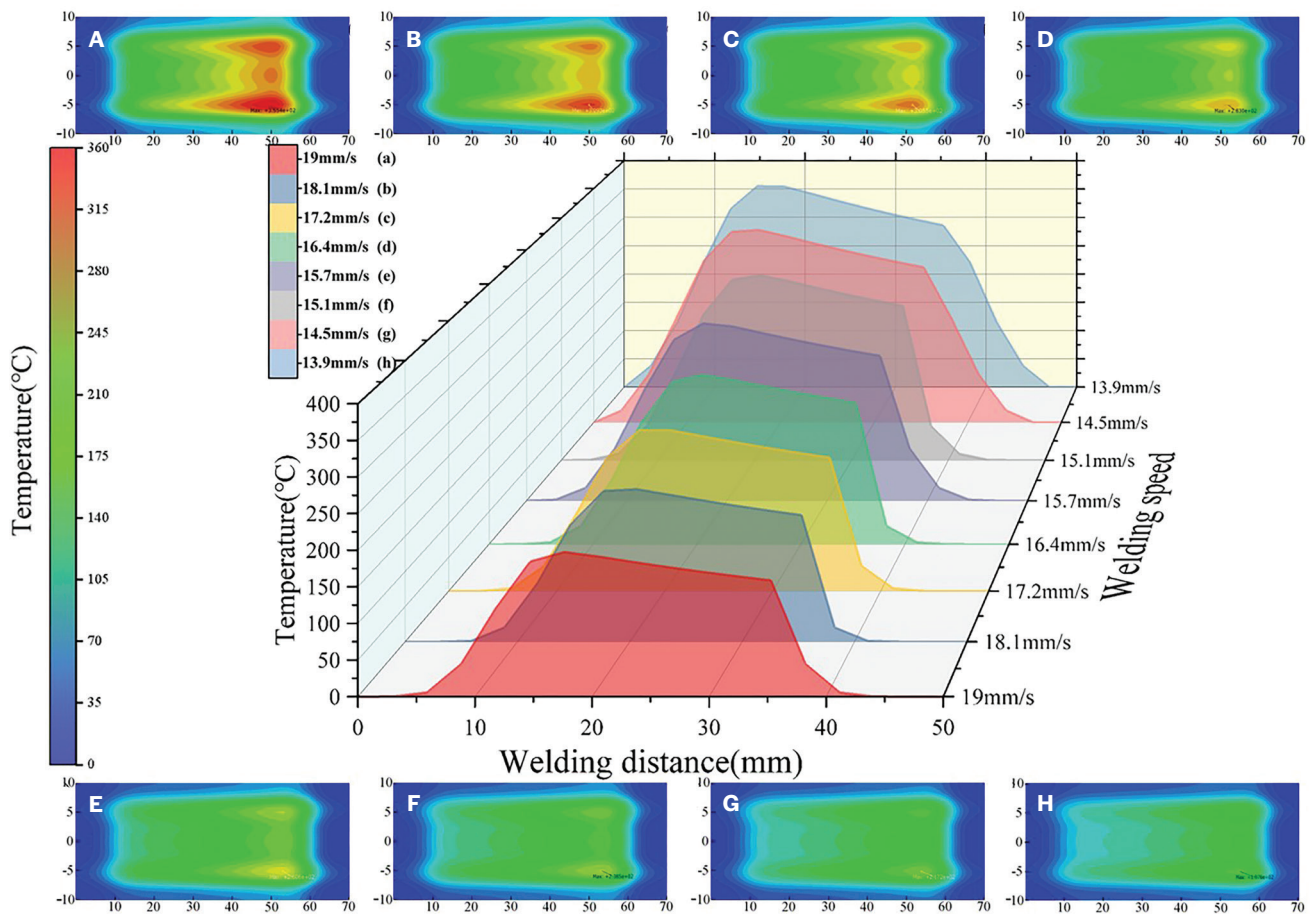


Fig. 10 – Temperature distribution of the welding interface at different welding speeds. In the figure, the size units are in mm.

Table 3 – Continuous Ultrasonic Welding Simulation and Model Prediction Errors				
No.	Welding Speed	Prediction Results	Simulation Result	Error Rates
1	13.9 mm/s	360°C	355.4°C	1.28%
2	14.5 mm/s	340°C	329.3°C	3.15%
3	15.1 mm/s	320°C	305.5°C	4.53%
4	15.7 mm/s	300°C	283°C	5.67%
5	16.4 mm/s	280°C	260.6°C	7.46%
6	17.2 mm/s	260°C	238.5°C	8.27%
7	18.1 mm/s	240°C	217.2°C	9.5%
8	19 mm/s	220°C	197.6°C	10.18%

adherends. The corresponding frictional power density at the weld interface can be expressed as

$$Q_{fric} = e \frac{\omega}{\pi} \mu |\sigma_{yy}(x) u^*(x)| \quad (16)$$

where μ is the friction coefficient, ω is the angular frequency, $\sigma_{yy}(x)$ is the normal stress amplitude, $u^*(x)$ is the relative sliding amplitude, and e is the hammering coefficient that accounts for the intermittent contact between the sonotrode and the composite (Ref. 8). As welding progresses and intimate contact is gradually achieved, the relative sliding at the interface diminishes, and the dominant heat source shifts towards bulk viscoelastic dissipation within the adherends. For a linear viscoelastic solid under harmonic loading, the associated volumetric viscoelastic power density can be written as

$$Q_{vis} = \frac{\omega \varepsilon_0^2 E''}{2} \quad (17)$$

where E'' is the loss modulus and ε_0 is the cyclic strain amplitude.

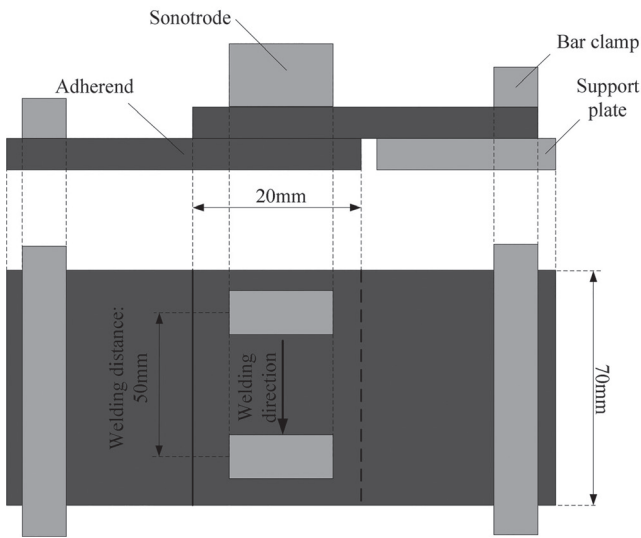


Fig. 11 – Schematic of the continuous ultrasonic welding sample used in this study.

These relations indicate that, in the initial stage, the larger local stress and relative sliding near the overlap edges cause frictional dissipation to be mainly confined to the regions close to the edges, whereas the subsequent viscoelastic dissipation is distributed within the bulk of the adherends (Ref. 26). In the present study, however, these equations are introduced solely to clarify the physical origin of heat generation during welding; the temperature prediction is still based on the total acoustic energy dissipated in the weld region obtained from the conservation-of-energy model, without explicitly separating the frictional and viscoelastic contributions. The edge-localized frictional heating tends to be overrepresented by the overall averaged energy used in the model. As a result, the predicted temperatures are slightly higher than the simulated values at high welding speeds, while the overall agreement between them remains satisfactory.

Experimental Design

To validate the model experimentally and correspond to the simulation results, continuous ultrasonic welding experiments were conducted at different welding speeds based on the welding parameters used in the finite element analysis. The experimental adherend dimensions were 70 × 60 × 2 mm, with a lap area of 70 × 20 mm and a welding distance of 50 mm. The welding pressure was set to 2 MPa, and the welding amplitude was 80 μ m. The adherend lapping method is illustrated in Fig. 11.

In this experiment, a K-type thermocouple (GG-K-36, with a temperature range of 0–480°C) was used to measure the temperature in the welding overlap area. The total diameter of the sleeve thermocouple was 0.4 mm, while the thermocouple wire itself had a diameter of 0.12 mm. Notably, the sleeve was partially peeled off, allowing only the bare thermocouple wires to be placed directly on the welding interface. During temperature acquisition, a guide rail temperature transmitter (SBWZ-Pt100) recorded temperature data at a sampling frequency of four times per second, with high-frequency fluctuations filtered to minimize measurement errors. To prevent stress concentration in the measurement area – caused by thermocouple insertion, which could result in localized high-temperature readings – a square groove (0.3 mm × 0.3 mm) was machined in the central region of the lower plate. The thermocouple was placed within this groove, ensuring it remained sandwiched

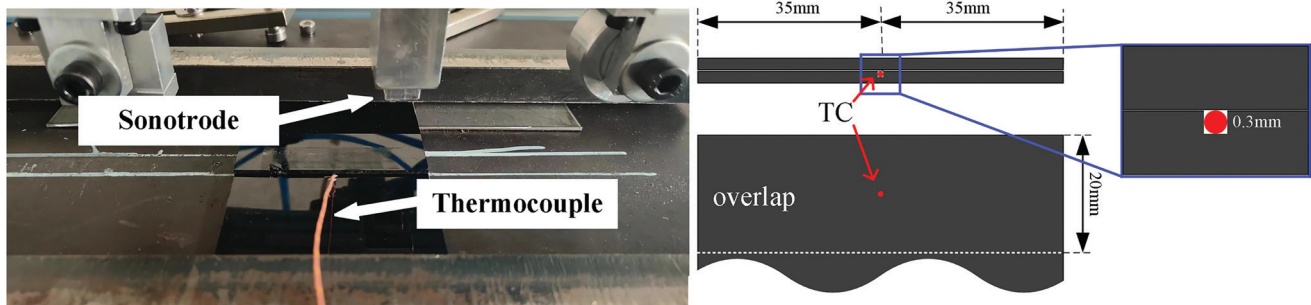


Fig. 12 – Schematic side and top view of the temperature measurement configurations used in this study on adherends.

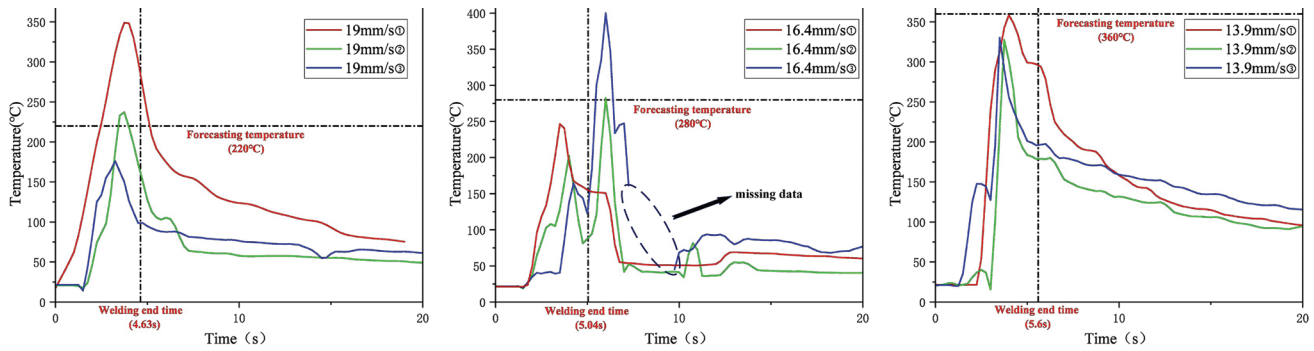


Fig. 13 — Temperature evolution law and interface morphology at the weld interface during the continuous welding process.

Table 4 — The Maximum Experimental Temperature and Predicted Temperature Error

No.	Welding speed	Prediction results	Experimental result	Error rates
1	19 mm/s		355.4°C	61.5%
2	19 mm/s	220°C	246.4°C	12%
3	19 mm/s		171.4°C	22.3%
1	16.4 mm/s		277.1°C	1%
2	16.4 mm/s	280°C	282.3°C	0.8%
3	16.4 mm/s		400°C	42.8%
1	13.9 mm/s		358.6°C	0.3%
2	13.9 mm/s	360°C	330.4°C	8%
3	13.9 mm/s		335.5°C	6.8%

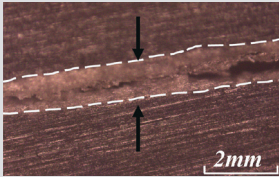
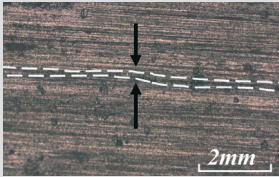
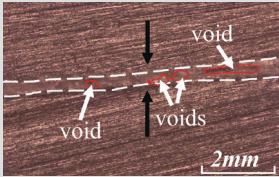
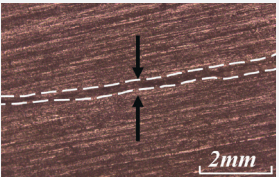
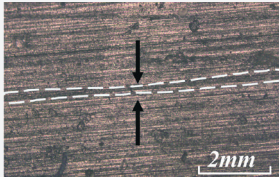
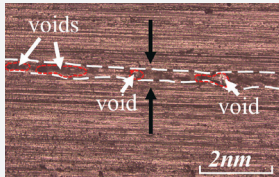
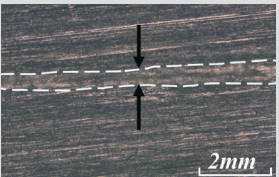
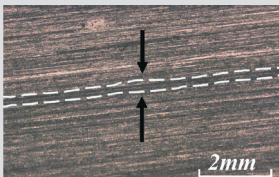
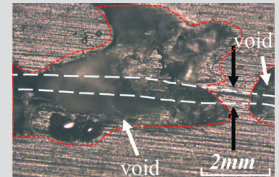
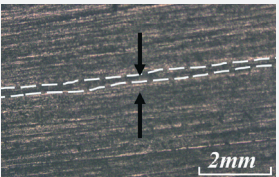
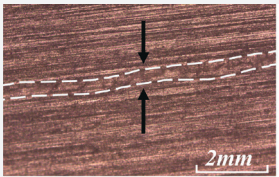
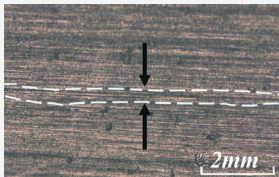
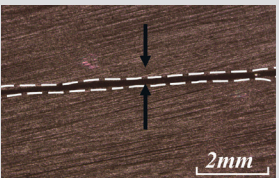
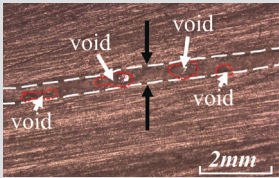
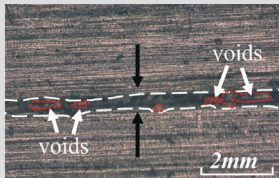
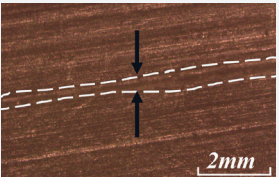
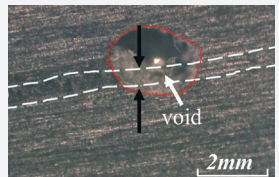
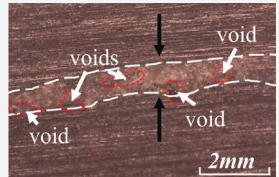
between the two adherends for accurate measurement. The test arrangement is illustrated in Fig. 12.

At three different welding levels, specific welding speeds were selected for three repeated experiments to monitor temperature variations at the measurement points. The welded joints were then cut into shear lap adherends, approximately 20 mm in width, within the temperature measurement area. A CX40M metallographic microscope was used to examine the weld morphology and assess whether the welding level aligned with the predicted results, as shown in Fig. 13. The measured temperature data were compared with the predicted values, and Table 4 presents the error between the highest recorded temperature and the predicted temperature for each experimental group. The results indicate that the experimental temperature measurements were generally consistent with the model's predictions. However, due to the complexity of heat transfer during welding and uncertainties in the experimental environment, some discrepancies remained. After

excluding the data from the third experiment, which had a welding speed of 16.4 mm/s, the overall error across the three experimental sets was 11.75%.

Table 5 presents the microstructure of the welds on both sides of the thermocouple temperature measurement area at three different welding speeds. The results indicate that the weld morphology aligns well with the welding conditions reflected by the thermocouple temperature measurements. Excluding special influencing factors, the welding quality at different speeds can be analyzed based on the weld morphology. At a welding speed of 19 mm/s, incomplete fusion is observed in the weld, resulting in a welding quality that falls between under-welding and normal welding. The thermocouple temperature data show that the temperature is close to the material's melting point, confirming that the welding quality corresponds to under-welding or normal welding, consistent with experimental results. When the welding speed is reduced to 16.4 mm/s, the weld exhibits good fusion without unwelded regions, indicating normal

Table 5 – The Weld Morphology on Both Sides of Thermocouple Temperature Measurement Area

No.	Adherend	19 mm/s	16.4 mm/s	13.9 mm/s
1	Left side			
	Right side			
2	Left side			
	Right side			
3	Left side			
	Right side			

* The white dashed line delineates the material welding zone, while the black arrows indicate the weld seam. The red dashed line circumscribes the porosity region, with the white arrows pointing to the porosities.

welding. The thermocouple data show that the interface temperature is between the material’s melting and decomposition temperatures, verifying that the welding quality meets the normal welding standard, in agreement with experimental observations. Further reducing the welding speed to 13.9 mm/s results in increased porosity in the weld, indicating over-welding, with the welding quality transitioning from normal welding to over-welding. At this speed, the thermocouple data show that the interface temperature approaches the material’s decomposition temperature, confirming an over-welded condition, consistent with experimental findings.

Conclusion

In this study, a predictive model is proposed for assessing the quality of continuous ultrasonic welding, incorporating key factors such as welding pressure, welding energy radiation area, and energy attenuation. For CF/PA66 composites, the model’s accuracy was validated through finite element simulations and orthogonal experiments conducted at different welding speeds. Comparative analysis between the predicted and experimental results demonstrates a high degree of agreement, confirming the reliability of the

proposed model. The main conclusions of this study are summarized as follows:

The quality prediction model proposed in this paper can effectively characterize the energy transfer and attenuation laws in the process of continuous ultrasonic welding, showing high prediction accuracy at different welding speeds. The comparison between simulation and experimental results shows that the model can accurately predict the welding quality within a reasonable range. The simulation error ranges from 1.28% to 10.18%, and the experimental comprehensive error is 11.75%, which verifies the reliability and applicability of the model.

Through an in-depth analysis of the welding temperature field distribution and the variation in welding energy, the ultrasonic welding process was optimized using finite element simulations and experimental validation. The simulation-based evaluation of different welding parameters not only reduces experimental costs but also enhances research efficiency, providing a robust theoretical foundation for optimizing the ultrasonic welding process and ensuring quality control.

Welding speed significantly influences welding quality. At a high speed of 19 mm/s, the weld is prone to a lack of fusion, leading to under-welding or normal welding. At a medium speed of 16.4 mm/s, the weld exhibits good fusion quality without noticeable defects. However, at a lower speed of 13.9 mm/s, pores easily form within the weld, resulting in over-welding. These findings highlight the importance of precise welding speed control in optimizing welding quality.

Appendix A: Energy Decay Derivation Based on the Kelvin–Voigt Model

The acoustic reflection coefficient (β) and transmission coefficient (γ) at the interface are given by the following equations:

$$\beta = \left(\frac{\rho_0 c_0 - \rho_1 c_1}{\rho_0 c_0 + \rho_1 c_1} \right)^2 \quad (\text{A1})$$

$$\gamma = \frac{4\rho_0 c_0 \rho_1 c_1}{(\rho_0 c_0 + \rho_1 c_1)^2} \quad (\text{A2})$$

where c_i is the sound velocity of the incident medium, c_0 is the sound velocity under no pressure conditions, ρ_0 is the density under pressure-free conditions, and ρ_1 is the injected medium density.

As the sound wave propagates from the upper surface into the interior of the material, the total energy I_z entering the top adhesion layer can be expressed as:

$$I_z = (I_f + I_0)\gamma \quad (\text{A3})$$

where I_f is the sound intensity energy and I_0 is the sound intensity energy beneath the sonotrode.

During the transmission of sound waves into the material, the viscoelastic properties of the adherend medium cause the propagation to be affected by amplitude damping. This damping effect causes a gradual conversion of part of the acoustic energy into heat, leading to a progressive attenuation of the sound intensity. The effect of amplitude damping is particularly pronounced in high-frequency ultrasonic transmission, where it plays a critical role in the efficiency of energy transfer and the distribution of the acoustic field. Based on the Kelvin–Voigt model, the viscoelastic wave equation can be employed to describe this process, and the constitutive relation between stress σ and strain ε is given as:

$$\sigma(t) = E \cdot \varepsilon(t) + \eta \cdot \frac{d\varepsilon(t)}{dt} \quad (\text{A4})$$

where η is the viscous damping coefficient and E is the elasticity modulus.

The ultrasonic wave propagates along the thickness direction of the adherend (defined as the x -direction). The attenuation of sound intensity $I(x)$ with distance results from the combined effects of geometric diffusion and viscous dissipation. Considering the one-dimensional wave equation and introducing a viscous damping term, the following expression can be obtained:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \cdot \frac{\partial^2 u}{\partial x^2} + \frac{\eta}{\rho} \cdot \frac{\partial^3 u}{\partial x^2 \partial t} \quad (\text{A5})$$

where u is displacement.

Under the assumption of a uniformly distributed sound intensity, the wavefront can be represented as a plane wave, and the sound field analysis can therefore be simplified using plane wave theory:

$$u(x, t) = U(x)e^{j\omega t} \quad (\text{A6})$$

where ω is angular frequency.

By simultaneously solving Equations A5 and A6, the following expression is obtained:

$$-\omega^2 U = c^2 \cdot \frac{d^2 U}{dx^2} + j\omega \cdot \frac{\eta}{\rho} \cdot \frac{d^2 U}{dx^2} \quad (\text{A7})$$

By substituting the wave number $k = \omega/c$ and introducing the elastic modulus E , the expression can be reformulated as follows:

$$k(\omega) = \frac{\omega}{c} \sqrt{1 + \frac{j\omega\eta}{E}} \quad (\text{A8})$$

Assuming that the acoustic signal is represented in the frequency domain as $U_0(\omega)$, its time-domain field can be expressed by the inverse Fourier transform as:

$$u(x, t) = \int_{-\infty}^{+\infty} U_0(\omega) \cdot e^{j\omega t} \cdot e^{-jk(\omega)x} d\omega \quad (\text{A9})$$

Accordingly, the amplitude distribution at the contact position between the sonotrode and the adherend can be expressed as:

$$U_0(\omega) = U_{00} \cdot \exp \left[-\frac{(\omega - \omega_0)^2}{2\Delta\omega^2} \right] \quad (\text{A10})$$

where U_{00} is the maximum amplitude of the spectrum, ω_0 is the center frequency of the spectrum, and $\Delta\omega$ is the spectral bandwidth.

In ultrasonic welding, when an acoustic wave with a Gaussian envelope propagates through the material, its time-domain waveform gradually broadens due to dispersion effects or nonlinear effects. By applying the method of the stationary phase in Fourier integrals, it can be demonstrated that the time-domain envelope remains Gaussian, while its width broadens with propagation distance. The result can be expressed as:

$$A(x, t) = \exp \left[-\frac{(t - k'_\omega x)^2}{2\sigma^2(x)} \right] \quad (\text{A11})$$

where k'_ω is the dispersion parameter.

The broadening factor $\sigma(x)$ is given by:

$$\sigma(x) = \sigma_0 \sqrt{1 + \left(\frac{x}{\lambda}\right)^2} \quad (\text{A12})$$

where σ_0 is the near-field envelope width, λ is the viscous damping coefficient, and x is the propagation distance of the acoustic wave.

During acoustic wave propagation, according to the law of energy conservation, the local energy density of the wave is inversely related to the peak value of its envelope. As the wave propagates through the medium, if the energy diffuses spatially, the local energy density correspondingly decreases. For a Gaussian envelope, the peak amplitude A_{peak} is also inversely proportional to the broadening factor $\sigma(x)$. In other words, as the propagation distance increases, the

envelope gradually broadens, resulting in a decrease of the peak amplitude, which can be expressed as:

$$A_{peak}(x) \propto \frac{1}{\sigma(x)} \propto \frac{1}{\sqrt{1 + \left(\frac{x}{\lambda}\right)^2}} \quad (\text{A13})$$

In long-lap continuous ultrasonic welding, due to the small thickness of the adherend, the welding region is located within the near-field range of the ultrasonic wave. Let the incident sound intensity be denoted as I_z . According to the attenuation trend defined in Equation A13, the sound intensity energy I_x after propagating along the thickness direction of the adherend and undergoing attenuation can be expressed as:

$$I_x = I_z \cdot \frac{1}{\sqrt{1 + \left(\frac{x}{\lambda}\right)^2}} \quad (\text{A14})$$

Acknowledgements

We are thankful for financial support by the Science and Technology Support Program of Tianjin (25YDTPJC00640).

References

- Marcus, M., and Sancaktar, E. 2025. Strain-based heating of polymers under ultrasonic excitation: An investigation of the physical properties that affect viscoelastic heating of polymers under ultrasonic vibration. *Welding Journal* 104(1): 1-s to 16-s. DOI: 10.29391/2025.104.001
- Siddique, A., Iqbal, Z., Nawab, Y., and Shaker, K. 2023. A review of joining techniques for thermoplastic composite materials. *Journal of Thermoplastic Composite Materials* 36(8): 3417–3454. DOI: 10.1177/08927057221096662
- Stoehr, N., Baudrit, B., Haberstroh, E., Nase, M., Heidemeyer, P., and Bastian, M. 2015. Ultrasonic welding of plasticized PLA films. *Journal of Applied Polymer Science* 132(4). DOI: 10.1002/app.41351
- Zheng, Y., Xiong, R., Zhao, Z., Zhao, C., Wang, Z., Niu, W., Xue, H., Cheng, F., Liu, W., and Wei, S. 2025. Laser melting deposition of in-situ (TiB + TiC) hybrid reinforced TC4 composites: Preparation, microstructure, and room- and high-temperature corrosion behaviour. *Journal of Materials Science & Technology* 228: 137–154. DOI: 10.1016/j.jmst.2024.11.080
- Marcus, M., and Sancaktar, E. 2024. Prediction of ultrasonic welding parameters for polymer joining. *Welding Journal* 103(10): 308-s to 324-s. DOI: 10.29391/2024.103.027
- Ge, J., Catalanotti, G., Falzon, B. G., Higgins, C., McClory, C., Thiebot, J. A., Zhang, L., He, M. M., Jin, Y., and Sun, D. 2024. Process characteristics, damage mechanisms, and challenges in machining of fibre reinforced thermoplastic polymer composites: A review. *Composites Part B: Engineering* 273. DOI: 10.1016/j.compositesb.2024.111247
- Villegas, I. F. 2015. In situ monitoring of ultrasonic welding of thermoplastic composites through power and displacement data. *Journal of Thermoplastic Composite Materials* 28(1): 66–85. DOI: 10.1177/0892705712475015
- Levy, A., Le Corre, S., and Villegas, I. F. 2014. Modeling of the heating phenomena in ultrasonic welding of thermoplastic composites with flat energy directors. *Journal of Materials Processing Technology* 214(7): 1361–1371. DOI: 10.1016/j.jmatprotec.2014.02.009

9. Pu, Z., Song, J., Xu, C., and Wang, J. 2023. Research progress in ultrasonic welding of fiber-reinforced polymeric composites. *Journal of Materials Engineering* 51(7). DOI: 10.11868/j.issn.1001-4381.2022.000855
10. Montagna, L. S., Morgado, G. F. D., Lemes, A. P., Passador, F. R., and Rezende, M. C. 2023. Recycling of carbon fiber-reinforced thermoplastic and thermoset composites: A review. *Journal of Thermoplastic Composite Materials* 36(8): 3455–3480. DOI: 10.1177/08927057221108912
11. Köhler, F., Jongbloed, B., Filipe, T., Herrmann, A., Villegas, I. F., and Benedictus, R. A roadmap for developing an industrial continuous ultrasonic welding process for thermoplastic composites. Proceedings of the International Thermoplastic Composites Conference (ITHEC).
12. Senders, F., Van Beurden, M., Palardy, G., and Villegas, I. F. 2016. Zero-flow: A novel approach to continuous ultrasonic welding of CF/PPS thermoplastic composite plates. *Advanced Manufacturing: Polymer & Composites Science* 2(3–4): 83–92. DOI: 10.1080/20550340.2016.1253968
13. Jongbloed, B., Teuwen, J., Benedictus, R., and Villegas, I. F. 2020. On differences and similarities between static and continuous ultrasonic welding of thermoplastic composites. *Composites Part B: Engineering* 203. DOI: 10.1016/j.compositesb.2020.108466
14. Larsen, L., Görick, D., Engelschall, M., Fischer, F., and Kupke, M. 2020. Process data-driven advancement of robot-based continuous ultrasonic welding. Proceedings of the International Conference and Exhibition on Thermoplastic Composites.
15. Engelschall, M., Larsen, L.-C., Fischer, F., and Kupke, M. 2019. Robot-based continuous ultrasonic welding for automated production of aerospace structures. Proceedings of the SAMPE Europe Conference.
16. Wang, K., Shriver, D., Banu, M., Hu, S. J., Xiao, G., Arinez, J., and Fan, H.-T. 2017. Performance prediction for ultrasonic spot welds of short carbon fiber-reinforced composites under shear loading. *Journal of Manufacturing Science and Engineering* 139(11): 111001. DOI: 10.1115/1.4037320
17. Paramasivam, S. S. S., Paulraj, G., and Kesavan, S. 2023. Application of artificial neural network models to predict ultrasonic welding parameters for joining copper to aluminium sheet. *Materials Today: Proceedings* 72: 2410–2416. DOI: 10.1016/j.matpr.2022.09.423
18. Khmelev, V. N., Slivin, A. N., and Abramov, A. D. 2007. Model of process and calculation of energy for heat generation of a welded joint in ultrasonic welding of polymeric thermoplastic materials. *Proceedings of the 8th Siberian Russian Workshop and Tutorial on Electron Devices and Materials*: 316–322.
19. Wang, B., Li, Y., Luo, Y., Li, X., and Freiheit, T. 2021. Early event detection in a deep-learning-driven quality prediction model for ultrasonic welding. *Journal of Manufacturing Systems* 60: 325–336. DOI: 10.1016/j.jmsy.2021.06.009
20. Li, Y., Yu, B., Wang, B. C., Lee, T. H., and Banu, M. 2020. Online quality inspection of ultrasonic composite welding by combining artificial intelligence technologies with welding process signatures. *Materials & Design* 194. DOI: 10.1016/j.matdes.2020.108912
21. Li, Y., Liu, Z. W., Shen, J. Q., Lee, T. H., Banu, M., and Hu, S. J. 2019. Weld quality prediction in ultrasonic welding of carbon fiber composite based on an ultrasonic wave transmission model. *Journal of Manufacturing Science and Engineering* 141(8). DOI: 10.1115/1.4043900
22. Görick, D., Larsen, L., Engelschall, M., and Schuster, A. 2021. Quality prediction of continuous ultrasonic welded seams of high-performance thermoplastic composites by means of artificial intelligence. *Procedia Manufacturing* 55: 116–123. DOI: 10.1016/j.promfg.2021.10.017
23. Akay, E., Köhler, F., and Villegas, I. F. In situ monitoring of weld line thickness in continuous ultrasonic welding of thermoplastic composites. *Proceedings of the 20th European Conference on Composite Materials*, p. 616–623.
24. Tutunjian, S., Eroglu, O., Dannemann, M., Modler, N., and Fischer, F. 2019. A numerical analysis of an energy directing method through friction heating during the ultrasonic welding of thermoplastic composites. *Journal of Thermoplastic Composite Materials* 33(11): 1569–1587. DOI: 10.1177/0892705719833108
25. Nonhof, C., and Luiten, G. 1996. Estimates for process conditions during the ultrasonic welding of thermoplastics. *Polymer Engineering & Science* 36(9): 1177–1183
26. Yao, F., Chu, Z., Tan, C., Zhao, Y., Wei, Y., Yan, T., and Li, Z. 2025. Study on heating process and weld growth mechanism in continuous ultrasonic welding of carbon fiber reinforced thermoplastic composite. *The International Journal of Advanced Manufacturing Technology* 138(7): 3135–3149. DOI: 10.1007/s00170-025-15678-6

FULIN YAO (yaofulin@tiangong.edu.cn), **YUE ZHAO**, **ZHELIN LI**, **TINGFENG YAN**, and **WEI YUAN** are with the School of Mechanical Engineering, Tiangong University, Tianjin, China, as well as the Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology, Tianjin, China.