NUMERICAL CALCULATION AND ANALYSIS OF TEMPERATURE FIELD IN ULTRASONIC WELDING OF POLYPROPYLENE DIALYZER

by

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Ultrasonic plastic welding is widely used in the bonding process of medical device accessories. In this paper, a thermo-force indirect coupling finite element analysis model was established in the ultrasonic plastic welding process between the blood cap and the shell of polypropylene (PP) dialyzer. The temperature field distribution between the blood cap and the shell was simulated and analyzed by using finite element analysis software, and the influence of welding process parameters on the temperature field was studied. The results show that: by changing the ultrasonic amplitude parameters, welding time parameters, initial pressure, etc., the longer the ultrasonic welding time, the temperature of the welding area will increase. In order to ensure the quality of the dialyzer, it should be controlled within 0.8-1 seconds. The increase of ultrasonic amplitude will make the welding temperature continue to rise, and in order to avoid poor welding, the amplitude should not exceed 120 μm. The initial pressure has little effect on the temperature field.

Key words: *PP, dialyzer, ultrasonic welding, finite element analysis*

Introduction

The PP plastic, also known as polypropylene, is a white translucent non-side chain, high density linear polymer material widely used in industrial products, daily necessities and medical devices, with good comprehensive properties. In the bonding process of plastics, in order to reduce costs and improve efficiency, ultrasonic welding is used [1]. Ultrasonic plastic welding principle is generated by the generator of 20 KHz (or 15 KHz) high pressure, high frequency signal, through the transducer system, the signal into high frequency mechanical vibration, added to the plastic products workpiece, through the workpiece surface and the friction between molecules and make it transferred to the welding temperature rise, when the temperature reaches the melting point of the workpiece itself. The workpiece interface is quickly melted, and then the gap between the interfaces is filled. When the vibration stops, the workpiece is cooled and shaped under a certain pressure at the same time, and qualified plastic welding is achieved [2]. The ultrasonic welding machine and welding principle are shown in fig. 1.

As early as the 1980's, scholars and research institutions began to analyze and study the ultrasonic welding mechanism. The Frankel and Wang studied the energy conversion and

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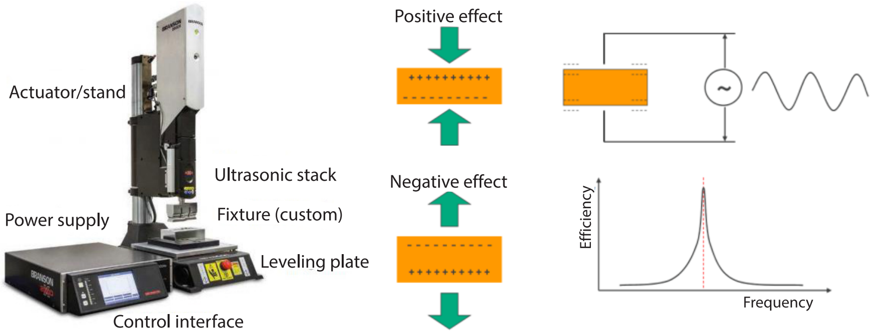

Figure 1. Ultrasonic welding machine and welding schematic diagram

connection mechanism of ultrasonic welding of polymer materials, and established a simple model to predict the temperature rise process when the interface temperature is below the glass state temperature. Through experimental and theoretical research, they found that the increase of amplitude can increase the rate of temperature rise. The relationship between welding strength and interface temperature is given through dimensionless analysis [3]. Based on the theory of viscoelastic heat generation, Yang *et al.* [4] calculated the energy conversion process at the joint of polyethylene ultrasonic welding, calculated the temperature distribution of the structure, and completed relevant experimental verification of the theoretical analysis. The process of energy transfer in ultrasonic plastic welding can also be regarded as the process of vibration wave propagation. Khmelev *et al.* [5] theoretically modeled ultrasonic welding of polymer materials from the perspective of wave transfer energy, and calculated the distribution of input energy of welding head in the welding joint area. The time required to achieve a temperature increase to the melting point at a given amplitude, workpiece thickness, and frequency is calculated Suresh *et al*. [6] researchers conducted a lot of modelling analysis based on ANSYS for welded joints of different polymer materials, provided corresponding temperature distribution, and compared it with the measured temperature in welding experiments for verification. However, the study did not consider the characteristics of energy storage modulus and energy dissipation modulus of polymer materials changing with temperature. Wang *et al.* [7] conducted numerical calculation and analysis of temperature field based on NiTi shape memory alloy ultrasonic welding, and explored the law of influence of ultrasonic amplitude on welding temperature field distribution. In analyzing and studying the temperature field distribution of simulated ultrasonic welding of aluminum and copper, Chen *et al.* [8] found that Johnson-Cook plastic model was used to simulate the deformation process of metal in the welding process at high strain rate, and it was concluded that the heat generated by plastic heat accounted for 25% of the total heat.

The quality of ultrasonic plastic welding depends on the amplitude of the transducer welding head, the pressure set and the welding time, which is determined by the aforementioned three factors. The welding time range and the pressure of the welding head can be adjusted according to the actual welding situation, and the amplitude is determined by the structure of the transducer and the amplitude converter. In the process of setting the ultrasonic welding parameters, there will be interaction, so the selection should be appropriate. If the energy exceeds the suitable value, it is easy to make the plastic melt too much, and the welding object deformation is large. If the energy set is too small, the welding between the objects is not strong, easy to weld or even fall off. Similarly, the pressure applied cannot be too large, or it will affect the appearance and quality of the product. At present, in the welding research of PP plastic material, Han *et al*. [9] takes ultrasonic indentation processing of PP honeycomb plate as the research object to study the influence of ultrasonic amplitude, pressure and welding time on product performance. Chinnadurai *et al.* [10] studied the ultrasonic welding process of PP and changed the weld strength by increasing the value of main process parameters. In the production process of medical device products, due to poor welding or unstable process, it is easy to lead to prefilled leakage in the welding part of the dialyzer, and even during treatment, it is unable to withstand pressure, and abnormal situations such as bleeding occur, leading to medical accidents. Therefore, it is very important to study the mechanism of welding between blood cap and shell of PP dialyzer.

In this paper, a thermo-force indirect coupling finite element analysis model was established by using finite element analysis software to simulate and analyze the temperature field distribution between the blood cover and the shell of PP dialyzer in the ultrasonic welding process, and the influence of welding process parameters on the temperature field changes was studied. At the same time, the temperature sensor detection system is designed to collect the temperature data in the ultrasonic welding process and verify the feasibility of the welding model.

System description

Building a coupled model of thermal mechanical structural fields

During the welding process between the blood cap and the shell of a PP dialyzer, under the action of high frequency vibration and high temperature, the contact part will undergo phase transformation, which will have a certain impact on the convergence of the calculation. Therefore, this article uses the method of thermal mechanical indirect coupling to calculate the heat flux generated by friction and plastic deformation between the blood cap and the shell during the welding process:

$$v = 4f\xi \tag{1}$$

$$Q_f = \eta\frac{P}{A_f} = \frac{4\mu\eta f\xi F_n}{A_f} \tag{2}$$

$$Q_p = 4f\xi\sqrt{\left(\frac{Y_T}{2}\right)^2 - \left(\frac{F_D}{2A_D}\right)^2} \tag{3}$$

vhere v [ms^{-1}] is the average vibration friction velocity of the welding head, f [Hz] – the frequency of welding head vibration, ξ – the amplitude, μ – the friction coefficient, F_n [N] – the welding static pressure, P [W] – the heat generation power of interface friction, Q_f [W] – the heat flow rate generated by friction, Q_p [W] – the heat flux generated by plastic deformation of the material during the welding process, A_f [m^2] – the area of the friction zone at the welding interface, η – the proportion of frictional heat dissipation, Y_T [MPa] – the yield stress of the material, and A_D [m^2] – the area of the plastic deformation zone.

Based on the parameter model of PP material, the temperature field is first calculated and analyzed by loading the heat flux into the model. After obtaining the temperature field distribution results, the structural field analysis and calculation are carried out on the temperature field model. Then, the temperature field calculation is carried out again on the deformation model, and multiple iterations are carried out in sequence. Obtain the temperature field and deformation changes throughout the welding process [11].

At the same time, whether in ultrasonic welding between metals, between metals and composite materials, or between composite materials, the workpiece waiting to be welded is driven by the high frequency vibration periodic force from the welding head, and there will be strong non-linear contact at the welding interface of the workpiece, that is, the workpiece will be affected by periodic force and non-linear contact force vibration [12]. Therefore, the control equation can be expressed:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f_l + f_{\mathrm{n}}(x) \tag{4}$$

where M is the mass matrix, C – the damping matrix, K – the stiffness matrix, x – the displacement vector, f_l – the linear periodic force vector, and f_{n} – the non-linear contact force vector.

From the perspective of structural dynamics, ultrasonic vibration welding of lightweight materials can be understood as a non-linear periodic dynamic system [13], and its control equation can be transformed into a typical second-order dynamic system control equation:

$$\ddot{x}(t) + Ax(t) = f(x, \dot{x}, t, p) \tag{5}$$

where

$$A = M^{-1}K, \; M^{-1}\left[-C\dot{x}(t) + f_l + f_n(x)\right] = f(x, \dot{x}, t, p)$$

where p is the parameter vector.

Establishing a finite element model

When analyzing and calculating the welding temperature field, it is common use numerical calculations. For the formation of temperature field changes, differential methods will be directly chosen to explain [14]. In the processing of plastics, the plastic is heated to a viscous or highly elastic state. According to thermodynamic principles, the temperature field of an object over time is expressed as $T = f(x,y,z)$ [15], and the non-stationary heat conduction partial differential equation is expressed:

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + \dot{Q} \tag{6}$$

where T is the product temperature, x, y, z are the object in Cartesian co-ordinates, and t is the time. In the equation, the specific heat capacity, material density, thermal conductivity, temperature field distribution function, internal heat source, heat transfer time, and other main parameters of the material change with temperature [16].

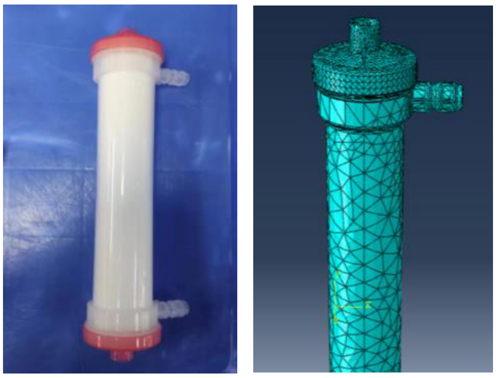

Figure 2. The PP dialyzer model grid division

In this article, finite element analysis software is used to construct a 2-D geometric simplified model for ultrasonic welding of PP dialyzer blood cap. By meshing it, simulation analysis results are gradually obtained. For temperature field analysis, temperature displacement coupling is used, with a ten-node quadric tetrahedral element C3D10 and reduced integration for grid division [17]. The grid division is shown in fig. 2. According to different parts, unit division and node parameter setting are carried out. The finite element model obtained after grid division has a total of 9260 units in the PP dialyzer shell, and the grid division around the middle welding area is relatively dense; The PP dialyzer blood cap has a total of 12169 units, and the grid size at the edge of the welding area increases relatively with the distance from the welding area [18]. The simulation analysis flowchart is shown in fig. 3.

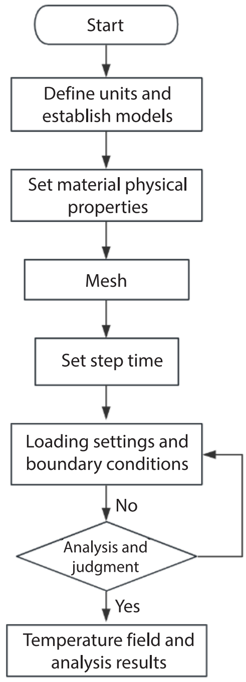

Figure 3. Simulation analysis process

Contact settings

This model establishes a single set of contact pairs for direct contact between the PP blood cap surface and the dialyzer shell surface. In face-to-face contact, the surface above the dialyzer shell is selected as the target surface, and the surface below the PP blood cap is the contact surface. The target surface contact element is selected as the ten-node quadric tetrahedral element C3D10. Fix the shell and apply an amplitude of energy to the blood cap. In the contact surface, mechanical properties such as initial temperature, thermal conductivity, expansion coefficient, and elastic modulus of the material are applied to the finite element model [19]. The physical properties of PP material are shown in tab. 1.

Table 1. Physical properties of PP material

Properties		Properties	
Density	0.89-0.92 g/cm^3	Thermal deformation temperature	102(1.82 MPa/°C)
Water absorption	0.01%	Embrittlement temperature	–8~8 °C
Young's modulus	1500 N/mm^2	Poisson's ratio	0.4203
Friction factor	0.51	Expansion coefficient	6-10 · 10^{-5} K^{-1}
Conductivity	0.24 W/mk	Tensile strength	29 MPa
Bending strength	50~58.8 MPa	Molding shrinkage rate	1~2.5%

Loading settings

The indirect coupling method using 2-D thermal coupling elements and 2-D structural elements is selected, and the specific locations of boundary condition loading in the table are shown in fig. 4.

The simulated loading conditions for ultrasonic welding are shown in tab. 2 [20]. The welding parameters set are: amplitude 100 μm. The welding trigger pressure is 200 N, the welding time is 1 second, the pressure holding time is 1 second, and the preset initial temperature of the material is 25 °C.

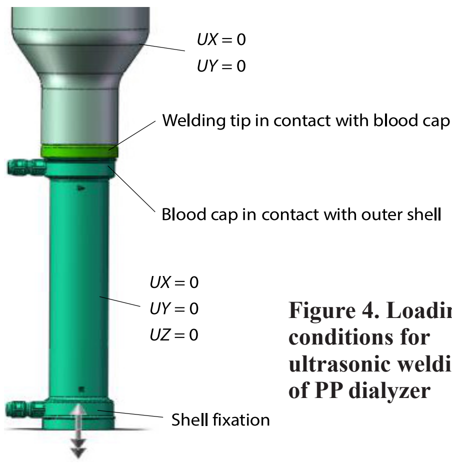

Figure 4. Loading conditions for ultrasonic welding of PP dialyzer

Table 2. Loading conditions for ultrasonic welding

Project	Loading condition	Boundary	Special conditions
Amplitude	Load the amplitude on the contact surface	The magnitude and range of amplitude	–
Force field	Apply force, *F*, as a uniformly distributed load to the surface of the blood cap	The welding head is set to the constraint of *UX*, and the dialyzer shell is set to the constraint of *UXYZ*	Set corresponding contacts on the contact surface

Results and discussion

Effect of welding time on temperature field

The ultrasonic welding parts of the shell and blood cap of PP dialyzer were simplified according to the working efficiency in the actual simulation. Under the condition that other parameters remain unchanged, the amplitude $f = 100$ μm, the applied pressure $P = 200$ N, the distance from the center 25 mm, and the finite element analysis results of the welding temperature field distribution at different welding times are set, as shown in fig. 5. The temperature distribution and deformation of ultrasonic welding at different times can be seen. With the increase of time, the maximum temperature of welding also increases. The heat center area is mainly distributed in the joint of PP dialyzer shell and blood cover. The heat increases with the increase of time, and beyond a certain time, it will make the blood cap joint position melt too much, resulting in large deformation, and the plastic deformation in this position is also large.

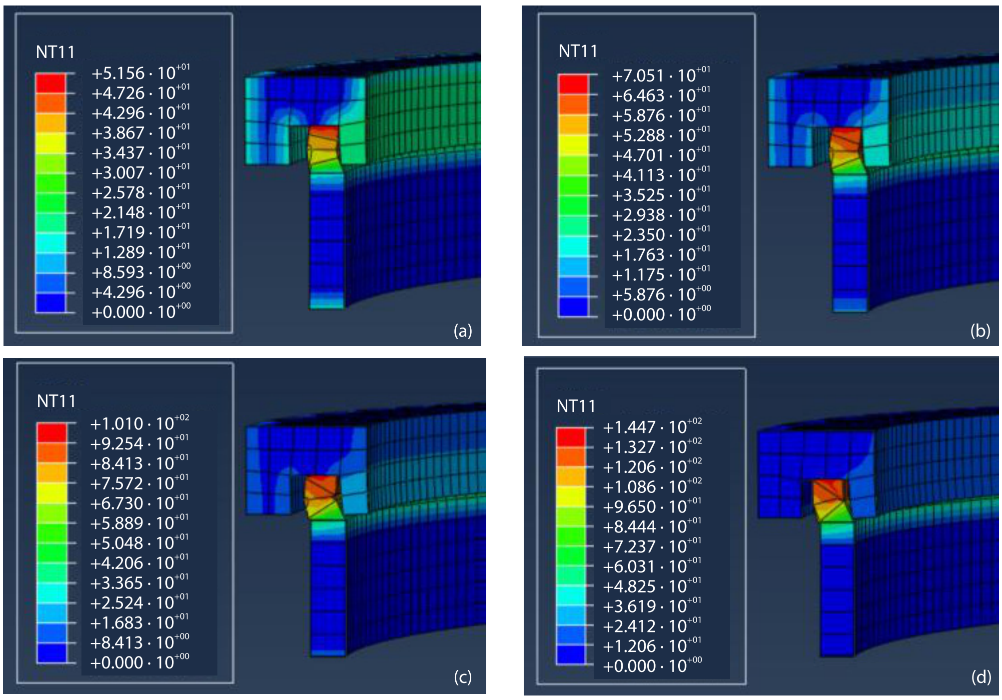

Figure 5. Temperature field distribution of PP dialyzer at different welding times; (a) T_1 = 200 ms, (b) T_2 = 400 ms, (c) T_3 = 600 ms, and (d) T_4 = 800 ms

In order to study the temperature change of the center position of the welding area during the whole welding process, it is necessary to avoid the influence of excessive heat caused by ultrasonic welding on the end-face performance of the dialyzer [21]. Therefore, in the finite element model, the temperature variation data of different welding locations 10 mm, 15 mm, and 25 mm away from the blood cap welding center O were extracted. The temperature variation of this node over time is shown in fig. 6.

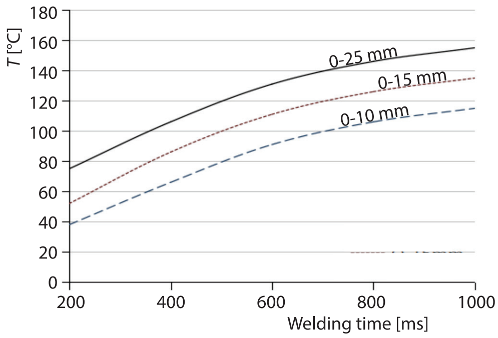

Figure 6. Temperature changes in the welding area location

Effect of amplitude on temperature field

Distribution of ultrasonic welding temperature field of PP dialyzer at different amplitudes (90 µm, 100 µm, 110 µm, and 120 µm). According to the simulation analysis, with the continuous increase of ultrasonic amplitude, the maximum temperature of the temperature field also gradually increased, and the range of high temperature region gradually expanded, and increased along the edge position. When the amplitude is 90 µm, the maximum temperature does not exceed 120 °C. When the amplitude is 120 µm, the maximum temperature does not exceed 150 °C. As shown in fig. 7, when the amplitude is 120 µm, the maximum temperature reaches 95% of the melting point of PP, and the resulting deformation will be greater.

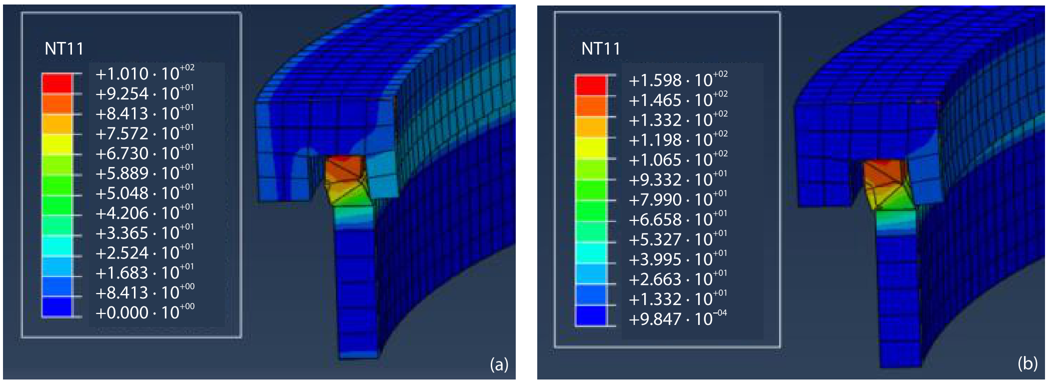

Figure 7. Changes of welding temperature field in PP dialyzer with different amplitudes; (a) f_1 = 90 ms and (b) f_2 = 120 ms

Effect of initial pressure on temperature field

In the process of verification, different initial pressures need to be analyzed. Figure 8 shows the change of welding temperature field under different initial pressure of PP dialyzer. Therefore, with the amplitude of 110 µm as the initial condition, the simulation test was carried out under 100 N, 150 N, 200 N, and 250 N and other forces. When the initial speed is constant and the pressure holding time is 1s, the initial pressure applied to the ultrasonic welding temperature field of the PP shell, in the application range of 100-250 N, the temperature change range is within 5%, and the change influence factor is not large.

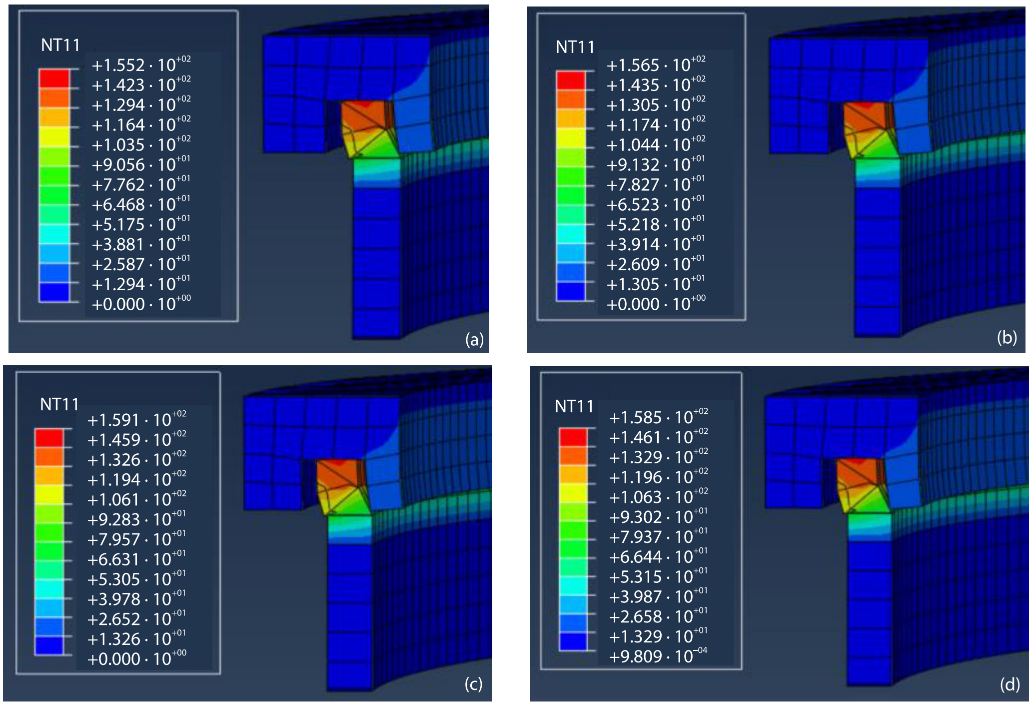

Figure 8. Welding temperature field under different initial pressure of PP dialyzer; (a) P_1 = 100 N, (b) P_2 = 150 N, (c) P_3 = 200 N, and (d) P_4 = 250 N

Experimental validation of the welding process of PP dialyzer

Establishment of experimental platform

In the article, a self-made temperature acquisition circuit board is used, with STM32 as the main control chip to collect thermocouple voltage signals. The control software converts the collected voltage signals into temperature values and displays them on the computer through serial communication. The thermocouple is evenly wrapped with a layer of 0.1 mm aluminum foil and attached to the welding area of the PP dialyzer blood cap [22]. The working principle of the surface collection process around the welding of the dialyzer is shown below.

Temperature Sensor calibration and temperature measurement

In the actual temperature collection process, the temperature sensor on the circuit board collects voltage values, which need to be converted into temperature collection data using mathematical formulas. In this experimental platform, the AD signal amplification module is used to obtain the voltage signal, and the theoretical calculation equation is:

$$T = Ux + b \tag{7}$$

The driving voltage of different amplifier modules and the specific thermocouple model will affect the conversion formula between voltage signal and temperature value. In this regard, when welding and debugging self-made circuit boards, it is necessary to calibrate and test the voltage signal and temperature of the collected circuit. In order to collect the actual temperature of the dialyzer relatively accurately, combined with the corresponding voltage values at different temperatures, the calculation equations for calculating the calibrated temperature and voltage are fitted:

$$T = 0.6U + 18 \tag{8}$$

where T is the temperature value and U – the collected voltage value. The calibration-linearity diagram is shown in fig. 9.

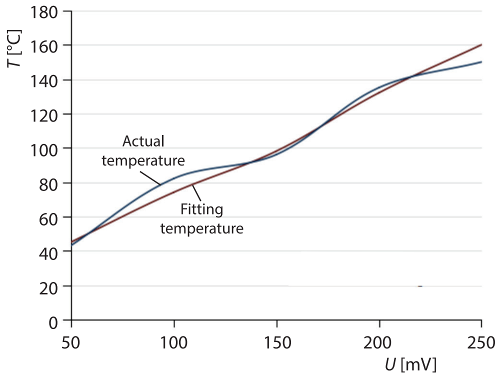

Figure 9. Calibration curve of thermocouple temperature measurement formula

Test

Above the blood cover of the dialyzer, a temperature sensor of the patch type is installed, and it is around one side of the dialyzer, and is uniformly attached. In this experiment, the PP dialyzer was welded by Binexin ultrasonic welding machine, and the PP dialyzer was clamped and fixed by self-designed fixture. After the test, the connection between the shell and blood cap of the PP dialyzer was dissected and observed. The PP dialyzer welding test equipment and welding results are shown in fig. 10.

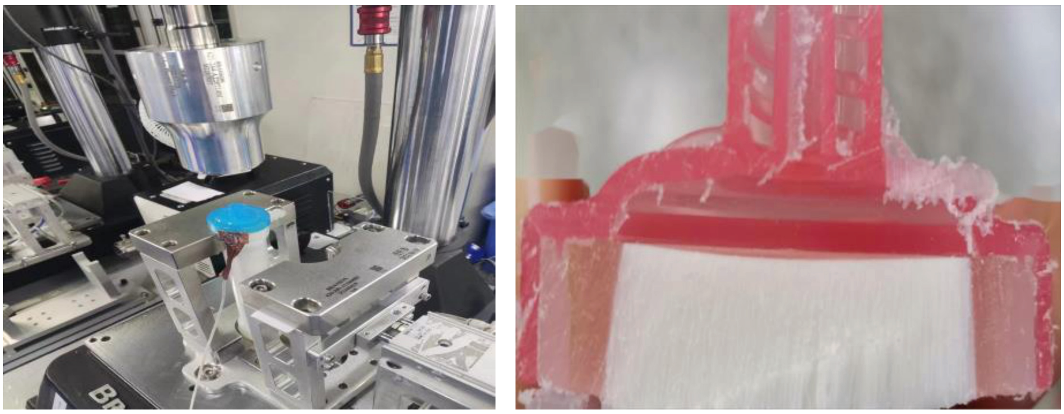

Figure 10. The PP dialyzer welding testing equipment

Collect the temperature changes at a distance of 25 mm from the center point of the blood cap during the welding start process and cooling process, and compare the temperature data simulated by experiments and finite element analysis as shown in the fig. 11.

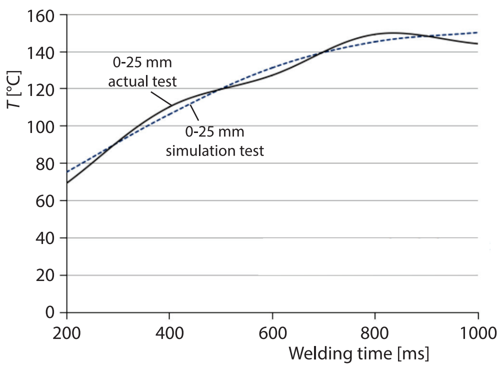

Figure 11. Test temperature comparison verification

It is not difficult to find from the fig. 11 that the deviation between the overall temperature of the test and that of the simulated test is not more than 5%. The maximum temperature of the simulated result is 150 °C, while the actual measured maximum temperature is 145 °C, with a contrast difference of 4.5%. However, in the actual measurement process, some measured values will still be lower than the simulation value, mainly because the process change point is large during cooling, affected by the ambient temperature and other effects. The weld of PP dialyzer shell and blood cap is opened, and it is found that the weld is firmly welded together, and the welding part produces uniform melting state, which plays a good effect. The change of temperature field studied in this paper is mainly to study the melting state generated in the process of ultrasonic welding of PP material, which makes the blood cap and the shell bond, and to study the influence of the highest temperature on the surface damage of the material and the connection firmness. Therefore, the finite element analysis can intuitively assist in analyzing the temperature field distribution characteristics during welding test. Therefore, in the process of processing, it is necessary to debug the time parameters in line with the welding effect, too high welding often, directly lead to the product temperature is too high to weld through the shell, and in the design of the shell, it is necessary to fully consider the impact of the middle area of the shell distance on the setting of the welding line. It is of great significance for the mass production and listing of follow-up products to ensure product quality.

Conclusions

- A 2-D thermal-force coupling finite element analysis model is obtained in this paper, and the temperature field distribution of ultrasonic welding of PP dialyser is simulated and analyzed. The model analysis is very close to the test data in the process of ultrasonic heating, and the temperature difference between the two is not more than 10 °C, and the error is not more than 5% of the maximum temperature.
- In the simulation analysis, the highest welding temperature is in the outer edge of the PP dialyzer blood cap joint position, if the welding time is longer, the plastic deformation is more obvious, the melting state of PP material is more intuitive, and the heat generated is more.
- Combined with the welding parameters used in the paper, vibration generates heat energy through the vibration and friction of the sensing bonding surface of the welding working part to melt the joint position of the blood cap. The vibration will stop when the molten material reaches its interface, and the short pressure holding will make the melt solidify on the bonding surface, which will make the curing effect of the joint better.
- Under the condition that other welding parameters are set unchanged, by changing the ultrasonic amplitude parameters, welding time parameters, initial pressure, *etc.*, the longer the ultrasonic time, the temperature of the welding area will increase, in order to ensure the quality of the dialyzer, it should be within 0.8-1 second. The increase of ultrasonic amplitude will make the welding temperature continue to rise, and in order to avoid poor welding, the amplitude should not exceed 120 μm.

The initial pressure has little effect on the temperature field. Further study the stability of welding process from the mechanism to ensure the quality of products. In the future, it is also necessary to study the profile effect of the product after welding.

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