Research on laser welding of glass fiber reinforced polyphenylene sulfide

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Abstract: This study investigated the effects of two different structures of polyphenylene sulfide (PPS) on the laser welding performance of glass fiber reinforced PPS composites. The results showed that branched PPS significantly improved the transmittance of near-infrared light and enhanced the shear strength of the welded joint; the addition of glass fibers decreased the transmittance of the material and the shear strength of the welded joint.

Key words: polyphenylene sulfide; laser welding; mechanical properties; welding strength; transmittance

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Polyphenylene sulfide (PPS) material, with its excellent high-temperature resistance, corrosion resistance, and mechanical properties, is widely used in components such as electronic water pump housings, impellers, and rotors. Common connection methods for electronic water pumps include mechanical connection, sealed connection, and fastening connection. When selecting a connection method, it is necessary to fully consider the physical properties of PPS. In practical applications, the most suitable connection method needs to be chosen based on specific design requirements and working environments. For connection parts that require higher sealing performance, laser welding can be used to connect PPS components with other parts, enhancing the overall performance and reliability of the equipment. Currently, research on laser welding of PPS is relatively scarce, especially in glass fiber reinforced PPS systems. This study primarily focuses on the 30% glass fiber reinforced PPS system and the 40% glass fiber reinforced PPS system, providing some data for the application of laser welding in electronic water pump components and promoting its development.

1 Experimental part

1.1 Main raw materials

PPS, 1150C, linear injection molding grade, Xinhecheng Co., Ltd.; PPS, A, branched extrusion grade, commercially available; chopped glass fiber (GF), T443R, Shandong Mount Taishan Glass Fiber Co., Ltd.; bis(2,4-dicyclohexylphenyl) pentaerythritol diphosphite, S9928, Dover Chemical Company, USA; pentaerythritol stearate, PETS-AP, Fajee Co., Ltd., Italy; carbon black masterbatch, KO 3300, Taiwan Gaozhan International Co., Ltd.

1.2 Main instruments and equipment

The main instruments and equipment are listed in Table 1.

1.3 Sample preparation

The experimental formula table is shown in Table 2.

After mixing PPS, antioxidant S9228, and lubricant PETS evenly according to the formulation ratio in Table 2, they were added from the main feed port of the twin-screw extruder, and chopped glass fibers were added from the side feed port. The mixture underwent melt blending, extrusion, cooling, traction, and granulation through the twin-screw extruder to obtain glass fiber reinforced and modified PPS material. The granules were placed in a 150 ℃ oven for 3 hours of drying, and

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Table 1 List of main equipment

Device Name	Model	Manufacturer
Twin-screw extruder	HK36	Nanjing Keya Equipment Technology Co., Ltd
Injection molding machine	MA360	Haitian Group
Universal Testing Machine	Z020	ZWICK/ROELL
Pendulum impact testing machine	HIT25P	ZWICK/ROELL
Differential scanning calorimeter	DSC3	METTLER TOLEDO
Transmittance	Customization	Nanjing Dinai Laser Technology Co., Ltd
Laser welding equipment	Dn-Laser	Nanjing Dinai Laser Technology Co., Ltd

Table 2 Experimental formula table

Sample Number	PPS 1150C	PPS A	GF T443R	S9228	PETS	KO 3300
1	69		30	0.2	0.8	
2	46	23	30	0.2	0.8	
3	23	46	30	0.2	0.8	
4		69	30	0.2	0.8	
5		59	40	0.2	0.8	
6	68.5		30	0.2	0.8	0.5
7		58.5	40	0.2	0.8	0.5

Remarks: Samples 1~5 are light-transmitting plates, while Samples 6 and 7 are light-absorbing plates; Samples 1 to 4 of the light-transmitting plates are welded together with Sample 6, and Samples 5 and 7 are welded together.

then injection molded into standard test strips. The extruder temperature was maintained at 290~310 ℃, the screw speed at 400 r/min, the injection temperature at 300~340 ℃, the nozzle temperature at 340 ℃, the mold temperature at 140 ℃, the injection pressure at 80 MPa, the holding pressure at 70 MPa, the holding time at 12 s, and the cooling time at 18 s.

1.4 Performance testing and methods

1.4.1 Tensile strength

When tested according to ISO 527, the dimensions of the tensile test strip are 150 mm × 10 mm × 4 mm, with a tensile speed of 50 mm/min.

1.4.2 Bending strength

When tested according to ISO 178, the dimensions of the bending specimen are 120 mm × 10 mm × 4 mm, with a testing speed of 2 mm/min.

1.4.3 Notch impact strength of cantilever beam

According to ISO 180 testing, the specimen size is 80 mm×10 mm×4 mm, with a notch depth of 2 mm and a V-shaped notch.

1.4.4 Impact strength of simply supported beam without notch

Tested according to ISO179, the dimensions of the sample strip are 80 mm × 10 mm × 4 mm.

1.4.5 Transmittance

The sample size is a 60mm×60mm×1.5mm square plate, with a test wavelength of 980nm.

1.4.6 Welding process

The dimensions of the welded strip are 125 mm×13 mm×1.5 mm. The welding process involves a welding speed of 300 mm/min, a welding power of 100W, 3 welding passes, and a welding area of 10×2 mm^2.

1.4.7 Welding strength

The transparent plate samples 1-4 and sample 6 were welded together, while sample 5 and sample 7 were welded together. The welded samples were loaded at a constant speed of 5mm/min to obtain the maximum tensile force. The ratio of the maximum tensile force to the area of the welding surface is the welding strength.

1.4.8 Melting temperature, crystallization temperature, and crystallinity

Tested according to ISO11357-1, with a sample quantity of 5 mg, the test temperature range is 50~330 ℃, and the heating and cooling rates are both 10 ℃/min.

2 Results and discussion

2.1 Thermal property analysis of different PPS

Figure 1 depicts the DSC curve graphs of two types of PPS structures. The endothermic direction represents the melting peak during the second heating process, while the exothermic direction indicates the crystallization peak during the cooling process. The crystallization peak and melting peak positions of the branched structure PPS A are notably lower

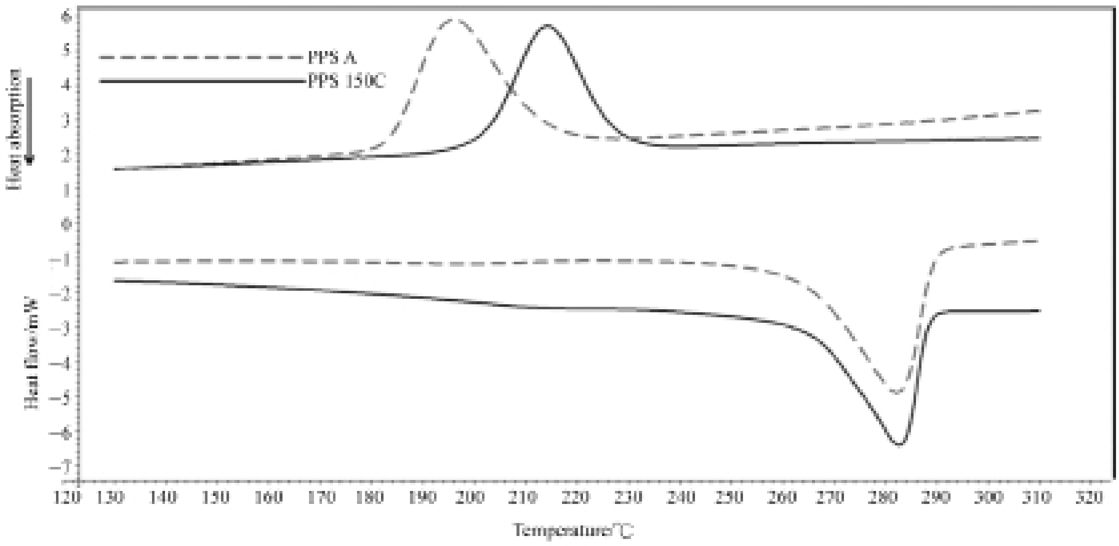

Figure 1 DSC curve diagram of PPS materials with different structures (both heating and cooling rates are 10 ℃/min)

than those of the linear structure PPS 1150C.

Table 3 Thermal properties of PPS materials with different structures

Material	Melting temperature /°C	Crystallization temperature /°C	Crystallinity /%
PPS 1150C	282	214	56.2
PPS A	281	196	46.9

Table 3 presents the DSC test results for PPS 1150C and PPS A. The results indicate that the crystallinity of linear PPS 1150C is 56.2%, whereas the crystallinity of branched PPS C is 46.9%. The crystallization temperature of linear PPS 1150C is 214 ℃, whereas that of branched PPS C is 196℃. This difference arises from the relatively regular molecular chain structure of linear PPS, which facilitates the formation of an ordered crystal structure between molecular chains. In contrast, branched PPS, with its molecular chains containing branches, encounters hindrance during the formation of a crystal lattice, thereby reducing the crystallinity of the material. During the cooling process, the ordered molecular chain structure of linear PPS is more prone to arrange into a crystal lattice, leading to some crystallization at relatively high temperatures. Conversely, the complex branched structure hinders lattice arrangement, requiring lower temperatures to ensure crystallization. Consequently, the crystallization temperature of branched PPS A is lower than that of linear PPS 1150C, and its crystallinity is also lower than that of branched PPS A.

2.2 The influence of different PPS on mechanical properties

Table 4 presents the mechanical properties of different glass fiber reinforced PPS systems. The results indicate that samples 1 to 4 belong to the 30% glass fiber reinforced PPS system. Among them, sample 1 exhibits higher tensile and bending strengths than sample 4. However, sample 1 shows lower Izod notched impact strength and Charpy impact strength compared to sample 4. Samples 2 and 3 are mixtures of PPS 1150C and PPS A, with PPS A increasing at a certain ratio. As the proportion of PPS A increases, the tensile and bending strengths of the material gradually decrease. Conversely, the impact strength of the material increases with the increase in the proportion of PPS A. The 40% glass fiber reinforced PPS A system exhibits higher tensile, bending, and impact strengths than the 30% glass fiber reinforced PPS A system.

Table 4 Mechanical properties of different glass fiber reinforced PPS materials

Sample Number	Tensile strength / MPa	Flexural strength/MPa	Bending modulus / MPa	Notched impact strength of cantilever beam / ($kJ·m^{-2}$)	Impact strength of simply supported beam / ($kJ·m^{-2}$)
1	170	230	9 750	7.7	30
2	165	224	9 510	8	35
3	159	223	9 280	8.3	35
4	149	214	9 050	9.2	38
5	176	250	12 000	11	47

The linear structure of PPS 1150C exhibits higher chain regularity than the branched structure of PPS A, resulting in glass fiber reinforced modified materials with relatively higher strength and rigidity compared to the branched system. The branched structure of PPS is beneficial for providing toughness to materials.

2.3 The impact of different PPS on near-infrared light transmittance

PPS is a kind of semi-crystalline material, and its crystallinity and filler directly affect the light transmittance. Table 5 shows the light transmittance of different glass fiber reinforced PPS materials. Comparing sample 4 and sample 5, when the glass fiber content increases from 30 parts to 40 parts, the light transmittance of the material decreases from 10.4% to 7.7%, indicating that the addition of glass fiber filler significantly reduces the light transmittance of PPS. This is because the refractive index of glass fiber is around 1.4, while the refractive index of PPS resin is around 1.77, with a significant difference between the two. When the laser beam reaches the interface between PPS and glass fiber, it undergoes refraction and diffuse reflection, resulting in a decrease in the transmittance of the laser beam.

Table 5 Transmittance of different glass fiber reinforced PPS materials

Sample Number	1	2	3	4	5
Light transmittance / %	4.6	6.4	8.2	10.4	7.7

The results of samples 1 to 4 indicate that for the 30% glass fiber reinforced PPS system, sample 1 exhibits a low light transmittance of only 4.6%. However, sample 4, which uses branched PPS as the substrate, has a light transmittance more than twice that of sample 1, reaching 10.4%. When branched PPS is blended with linear PPS in different proportions, the light transmittance is improved to some extent. This is because linear PPS 1150C has a high crystallinity and a low light transmittance, as the crystalline regions scatter light, reducing its transmission. Conversely, branched PPS A with low crystallinity exhibits higher light transmittance due to its lower crystallinity.

2.4 The influence of different PPS on laser welding

In this study, when the laser welding speed is fixed at 300 mm/s and the welding power is 100W, the welding is not secure or not welded together when the welding is performed twice. When the welding is performed four times, the surface of the welding transparent layer is prone to welding damage, resulting in poor appearance quality. Therefore, in this study, the preferred laser welding process is with a welding speed of 300 mm/s, a welding power of 100W, and a welding frequency of three times.

Table 6 Welding performance of different glass fiber reinforced PPS materials

Sample Number	1	2	3	4	5
Proportion of body fracture	0/5	1/5	3/5	4/5	0/5
Welding strength / MPa	25.7	29	32.6	34	29.8

There are three ways in which laser welding materials can fail: body fracture, shear peeling of the welding surface, and fracture of the welding seam. The fracture modes of glass fiber reinforced PPS are manifested in two ways: body fracture and shear peeling of the welding surface. Table 6 presents the welding performance results of different glass fiber reinforced PPS materials. The results indicate that 30% glass fiber reinforced PPS 1150C fails entirely through shear peeling of the welding surface, with a welding strength of 25.7 MPa. The addition of a small amount of branched PPS A causes the material to fail through body fracture, and as the proportion of branched PPS A increases, the proportion of body fracture failure becomes higher. When the resin matrix is entirely composed of branched PPS A, the proportion of body fracture accounts for 4/5, and its welding strength also increases to 34 MPa, which is more than 1.3 times the welding strength of PPS 1150C.

The glass fiber reinforced PPS 1150C system exhibits low light transmittance and low welding strength. During the tensile process, the weld interface first undergoes shear peeling, leading to damage. Compared to linear PPS 1150C, the glass fiber reinforced branched structure PPS A system has higher light transmittance, allowing more laser beam energy to penetrate the transparent plate and reach the light-absorbing plate interface. This enables the light-absorbing plate to absorb and generate more heat, which is then transferred to the transparent plate, increasing the adhesive force between the two plates and thus enhancing the welding strength of the material. When the maximum tensile force during welding exceeds the material's inherent strength, the material will undergo bulk fracture, resulting in product failure.

Compared to 30% glass fiber reinforced PPS A, the light transmittance of 40% glass fiber reinforced PPS A decreases, and its welding strength also decreases to a certain extent, with a welding strength of 29.8 MPa, which falls between Sample 2 and Sample 3, corresponding to the light transmittance results. However, the tensile strength of 40% glass fiber reinforced PPS A is as high as 176 MPa, and the maximum tensile force after welding is not sufficient to cause damage to the body, so the proportion of body fracture is 0/5.

3 Conclusion

(1) The crystallinity, melting temperature, and crystallization temperature of linear PPS 1150C are all higher than those of branched PPS A.

(2) For the glass fiber reinforced PPS system, the tensile strength and bending strength of linear PPS 1150 C are higher than those of PPS A, but its impact strength is slightly lower than that of PPS A.

(3) In the glass fiber reinforced PPS system, branched PPS significantly enhances the transmittance of near-infrared light and improves the shear strength of welded joints.

(4) Glass fibers reduce the light transmittance of PPS materials. Using branched PPS A as the substrate, the light transmittance of 40% glass fiber reinforced PPS is 7.7%, and that of 30% glass fiber reinforced PPS is 10.4%.