Structure and properties of sewing thread made of modified polyphenylene sulfide and polytetrafluoroethylene

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Keywords: MPPS/PTFE sewing thread, surface morphology, tensile properties, thermal stability, melting number, melting rate

Abstract
The structure and properties of sewing thread made of modified polyphenylene sulfide and polytetrafluoroethylene (MPPS/PTFE) have important influence on its application in high temperature filter bag, which were characterized thoroughly by scanning electron microscopy (SEM), fourier transform infrared (FTIR) spectroscopy, thermogravimetry (TG) and differential scanning calorimetry (DSC). SEM shows that there were a lot of hairiness on the surface of MPPS/PTFE sewing thread, which were good for plugging pinholes in the filter bag. The mechanical properties of MPPS/PTFE sewing thread was worse than that of PTFE and MPPS sewing thread, but the flexibility of MPPS/PTFE sewing thread was improved by the addition of MPPS fibers. From the TG analysis, the thermal stability of MPPS/PTFE sewing thread was worse than that of PTFE sewing thread, but better than that of MPPS sewing thread, in which the initial thermal decomposition temperature was 527.6 °C, and the carbon residue rate was 30.8% in the nitrogen atmosphere at 800 °C. From the DSC analysis, the number of melting times has greater influence on melting temperature of MPPS/PTFE sewing thread than that of PTFE and MPPS sewing thread, and the melting temperature from the second melting was 23 °C smaller for PTFE fibers and about 22 °C smaller for MPPS fibers than that from the first melting, respectively. There were more irregular areas inside MPPS/PTFE sewing thread after the first melting, so the melting enthalpy of MPPS/PTFE sewing thread was became small. Meanwhile, the heating rate for the second melting has a little effect on melting temperature and melting enthalpy of MPPS/PTFE sewing thread. Therefore, the heating rate of 20 °C min−1 for the second melting was recommended in terms of cost.

1. Introduction
Sewing threads refers to the thread used for stitching textile materials, plastics, leather products, books and periodicals, etc. It has the characteristics of sewn ability, durability and appearance quality. On the market, there were a wide variety of sewing threads, which can be divided into two categories of sewing thread, namely industrial threads (used to stitch or join materials or fabrics) and surgical sutures (used for medical applications in wound closure). In this paper, sewing threads were used for stitching nonwoven materials, which were belong to industrial threads. More precisely, it was used to stitch filter fabrics used for filtering gases, which were come from industrial dust [1].

In recent years, with the increasing attention of government to environmental protection and the requirements for energy saving, strict limits have been placed on the pollution standards of industrial plants, for example, the dust concentration standard has been raised from 200 mg m−3 to 30–50 mg m−3. Therefore, traditional heavy industries, such as steel, cement, power generation and carbon black, have been started to adopt a series of measures [2, 3]. With regard to a large amount of high temperature flue gas which were produced in the process of traditional heavy industry (contains a large number of dust particles and some corrosive gases such as sulfur compounds and nitrogen oxides), the bag filter has developed rapidly in recent
years, the main reason was that the bag dust collector has high efficiency of dust removal [4–6], and has the characteristics of high temperature resistance, low influence by boiler combustion and dust characteristics, and stable operation [7, 8].

The filter bag in the bag collector was made of filter materials, sewing threads and related accessories. Sewing threads were one of the important auxiliary materials for filter bag [9, 10], it sews the filter material into a bag, which has the function of joining and suturing, so the strength of the sewing thread determined the strength of the dust bag at the seams. In the actual use, the filter bag will be affected by many environmental factors [11–13], such as temperature, humidity, tension [14], corrosive substance [15–17], etc, and then the degradation or aging will be occur.

In this process, destruction of sewing thread will also seriously affect the service life of the filter bag. Therefore, in order to improve the durability of the filter bag, the selected sewing thread for high temperature filtration shall generally meet the following requirements: high strength, low friction factor, good evenness of the strips, good flexibility, good thermal stability, high temperature resistance, and good chemical corrosion resistance [10, 17, 18].

The characteristics of sewing thread also have its unique properties due to the different materials. According to the above requirements, there were several kinds of high-temperature resistant sewing threads commonly used at present, such as aramid (Nomex) sewing thread, polytetrafluoroethylene (PTFE) sewing thread, polyphenylene sulfide (PPS) sewing thread, glass fiber (GF) sewing thread, and so on. Among these sewing thread, the comprehensive performance of polytetrafluoroethylene (PTFE) sewing thread was the best [19], but its surface was very smooth and almost has no hairiness, which was important for blocking pinholes on the filter bag. Therefore, the sewing thread made of modified polyphenylene sulfide and polytetrafluoroethylene (MPPS/PTFE) was produced, which has combined the advantages of PPS and PTFE fibers.

However, until now there have been few comprehensive studies on the performance of sewing thread made of modified polyphenylene sulfide and polytetrafluoroethylene were investigated by some measurements, which were believed to lay a solid foundation for MPPS/PTFE sewing thread used in filtration field of high temperature flue gas.

2. Experimental

2.1. Materials

Three kinds of sewing thread used in this study were provided by Suzhou naide new material technology Co. Ltd (Jiangsu, PR china). They were the sewing thread made of modified polyphenylene sulfide and polytetrafluoroethylene (MPPS/PTFE, linear density: 247.23 tex), the sewing thread made of polytetrafluoroethylene (PTFE, linear density: 167.94 tex) and the sewing thread made of modified polyphenylene sulfide (MPPS, linear density: 65.17 tex), respectively. Their basic performance indexes were shown in Table 1.

The twist of MPPS/PTFE, PTFE, and MPPS sewing thread were measured by yarn twist counter (Y331N, China) according to the standard GB/T 2543.1-2015 and GB/T 2543.2-2001.

2.2. Testing and characterization

2.2.1. Microstructure observations

The microstructure of MPPS/PTFE, PTFE, and MPPS sewing thread were observed using scanning electron microscopy (SEM) (FLEX SEM1000, Hitachi, Japan).

2.2.2. Tensile test

The tensile test of MPPS/PTFE, PTFE, and MPPS sewing thread were carried out according to the standard GB/T 3916-2013 (determination of breaking strength and elongation at break of single yarn for textile winding (CRE
thread were 17.57 cN, in which the gage length was 500 mm, the cross-head speed of the tester was 250 mm min$^{-1}$ or 500 mm min$^{-1}$, and the pre-tension was 0.5 cN/tex for conditioning sample.

2.2.3. FTIR analysis
The infrared spectrum of MPPS/PTFE, PTFE, and MPPS sewing thread were recorded by an attenuated total reflection fourier transform infrared spectrometer (ATR-FTIR) (Nicolet 6700, Thermo Fisher, USA) in the region of 4000–600 cm$^{-1}$ at room temperature.

2.2.4. Thermal properties
The thermal analysis of MPPS/PTFE, PTFE, and MPPS sewing thread were conducted by a thermal gravimetric analyzer (TG 209 F1 Libra, Netzsch, Germany) and a differential scanning calorimeter (DSCQ20, TA, USA). For TG measurement, the sample in the form of powder (3 ~ 5 mg) was charged in an aluminum oxide crucible and heated from 30 °C to 800 °C at a heating rate of 20 °C min$^{-1}$ in a nitrogen atmosphere. For DSC measurement, the sample (3 ~ 5 mg) were charged in an aluminum crucible with lids of the DSC, and heated from 30 °C to 380 °C at a heating rate of 20 °C min$^{-1}$ in a nitrogen atmosphere, in order to eliminate the effect of thermal history, the sample will be hold 5 min at 380 °C, and then cooled to 30 °C at 20 °C min$^{-1}$ to obtain the recrystallization curve. After that, the sample was reheated to 380 °C at 10 or 20 °C min$^{-1}$ to get the second melting curve. The crystallization temperature ($T_c$) and melting temperature ($T_m$) were defined as the onset temperature of the recrystallization peak and melting peak, respectively.

3. Results and discussion

3.1. Microstructure observations
The microstructure of MPPS/PTFE, PTFE, and MPPS sewing thread were presented in figure 1. It can be seen that there were a lot of hairiness on the surface of MPPS/PTFE and MPPS sewing thread, which was presented by figures 2(a) and (c). However, the surface of PTFE sewing thread was very smooth (figure 2(b)). In the meantime, the figures 2(a1) and (b1) shows that the surface of PTFE fiber was not uniform and there were a lot of micron-scale holes clearly visible. But the micron-scale holes was not found in MPPS fibers (figure 2(c1)). And there were some substances between the fibers that hold them together, which may have been introduced during the modification of PPS fibers.

By analysis, it can be concluded that the hairiness on the surface of MPPS/PTFE sewing thread was introduced by MPPS fibers. Due to the inevitable pinhole gap at the suture of the filter bag, the dust containing air flow will escape from the pinhole gap, which will lead to the instantaneous increase of dust emission after the filter bag was cleaned, thus affecting the overall ultra-low emission effect. So the hairiness on the surface of MPPS/PTFE sewing thread was good for plugging pinholes in the filter bag and then it will indirectly improve filtration efficiency [20]. In the meantime, the micron-scale holes in the PTFE fibers was also useful for filtration [21–23]. So MPPS/PTFE sewing thread has combined the advantages of PTFE and MPPS sewing thread.

3.2. Tensile test
Table 2 shows the tensile properties of MPPS/PTFE, PTFE and MPPS sewing thread when the sample clamping length was 500 mm. As shown in table 3, the average breaking strength of MPPS/PTFE, PTFE and MPPS sewing thread were 17.57 cN/tex, 24.80 cN/tex and 20.63 cN/tex respectively, and the elongation at break were 9.41%, 5.42% and 17.33% respectively. By comparison, it can be seen that the breaking force of MPPS/PTFE sewing thread was the highest, but its breaking strength was the lowest. So it can be concluded that the tensile properties of MPPS/PTFE sewing thread need to be improved although it was still meet the requirement for filtration [1].

The stress-strain curves of MPPS/PTFE, PTFE and MPPS sewing thread were shown in figure 2(a). It can be seen that the initial modulus of MPPS/PTFE sewing thread was larger than that of MPPS sewing thread, but less than that of PTFE sewing thread. By the calculation, it can be found that the initial modulus of MPPS/PTFE sewing thread was 4.02 cN/tex, while the initial modulus of PTFE and MPPS sewing thread were 7.49 and 1.78 cN/tex, respectively, which can be seen in figure 2(b). PTFE was a high molecular weight compound because of the strongly bonded fluorine atoms and exhibits semi-crystalline nature, so the initial modulus of PTFE sewing thread was the largest [1, 23]. From the above analysis, it can be concluded that the flexibility of MPPS/PTFE sewing thread was improved by the addition of MPPS fibers, which can also be verified by the elongation at break of MPPS/PTFE sewing thread.

3.3. FTIR analysis
FTIR spectrum of MPPS/PTFE, PTFE and MPPS sewing thread were depicted in figure 3. Compared with the FTIR spectrum of PTFE sewing thread (figure 2(b)), there were three apparent peaks can be seen at 1205 cm$^{-1}$,
Figure 1. SEM images of (a) and (a1) MPPS/PTFE sewing thread with the magnifications of 100× and 3000×; (b) and (b1) for PTFE sewing thread with the magnifications of 100× and 3000×; (c) and (c1) for MPPS sewing thread with the magnifications of 100× and 3000×.

Figure 2. (a) Stress-strain curves and (b) modulus of sewing thread.
Table 2. Tensile property’s parameters of sewing thread.

| Index   | Breaking force (cN) | Breaking strength (cN/tex) | Breaking elongation (mm) | Elongation at break (%) | Work of fracture (cN * mm) | Breaking time (s) |
|---------|---------------------|-----------------------------|--------------------------|-------------------------|---------------------------|------------------|
| MPPS/PTFE | 4343.55             | 17.57                       | 47.06                    | 9.41                    | 152 986.05               | 11.29            |
| PTFE    | 4165.25             | 24.80                       | 27.08                    | 5.42                    | 73 994.36                | 6.50             |
| MPPS    | 1344.30             | 20.63                       | 86.66                    | 17.33                   | 62 864.75                | 10.40            |
Table 3. Thermal properties of sewing thread obtained from TGA.

| Sample   | $T_d$ (°C) | $T_{peak}$ (°C) | $V_{peak}$ (mg min$^{-1}$) | Char yield (%) |
|----------|------------|-----------------|-----------------------------|----------------|
| MPPS/PTFE | 527.6      | 582.7           | 1.5                         | 30.8           |
| PTFE     | 558.9      | 620.4           | 1.1                         | 0.0            |
| MPPS     | 489.7      | 576.6           | 0.3                         | 50.4           |

Figure 3. FTIR spectrum of (a) MPPS/PTFE sewing thread; (b) PTFE sewing thread; (c) MPPS sewing thread.
1159 cm\(^{-1}\) and 638 cm\(^{-1}\) for MPPS/PTFE sewing thread (figure 2(a)), respectively, which were consistent with the peak value of infrared spectrum of PTFE sewing thread, namely 1206 cm\(^{-1}\), 1151 cm\(^{-1}\) and 636 cm\(^{-1}\). The band at 1205 cm\(^{-1}\) was assigned as the anti-symmetric stretching vibration peak of \(-\text{CF}_2\), while the band at 1159 cm\(^{-1}\) was assigned as the symmetric stretching vibration peak of \(-\text{CF}_2\). The above two peaks have little effect on the crystallinity of materials. The band at 638 cm\(^{-1}\) was assigned as the bending vibration absorption peak of C−F, which was related to the spiral conformation of polytetrafluoroethylene molecular chain rule [24]. These three bands all led to the excellent mechanical properties of MPPS/PTFE sewing thread.

Compared with the FTIR spectrum of MPPS sewing thread (figure 2(c)), the bands at 3086 cm\(^{-1}\), 2923 cm\(^{-1}\) and 2851 cm\(^{-1}\) from MPPS/PTFE sewing thread were assigned as C−H telescopic vibration peak of benzene ring. Meanwhile, the band at 2162 cm\(^{-1}\) was assigned as the telescopic vibration peak of three bonds. Since S was connected, the peak at 1600 cm\(^{-1}\) splits into two peaks, resulting in a spectral band at 1573 cm\(^{-1}\), which was the stretching vibration absorption peak of benzene ring C=C double bond. The band at 1470 cm\(^{-1}\) was assigned as the vibration absorption peak of benzene ring C=C, while the bands at 1391 cm\(^{-1}\), 1161 cm\(^{-1}\) and 1092 cm\(^{-1}\) were assigned as the telescopic vibration absorption peak within the benzene ring surface double bond skeleton. The remaining bands at 1071 cm\(^{-1}\), 1009 cm\(^{-1}\), 807 cm\(^{-1}\), 743 cm\(^{-1}\) were assigned as the sulfoxide telescopic vibration absorption peak, the deformation vibration peak in plane C=CH, the bending vibration absorption peak outside the plane, the vibration peak of benzene ring outside plane C−H deformation, respectively. From previous research, it was found that the bands at 1159 cm\(^{-1}\) and 807 cm\(^{-1}\) were important for property analysis [7, 25]. Because the functional groups within the material determine the properties of the material, so it was important to study the infrared spectrum of MPPS/PTFE, PTFE, and MPPS sewing thread.

3.4. Thermal properties

Thermogravimetric Analysis (TG or TGA) can be used to measure the relationship between the quality change of materials and the temperature change, so as to analyze the thermal stability of materials. This can explain the heat resistance of the material itself from a microscopic perspective, which was of great significance for understanding the applicable temperature range of MPPS/PTFE, PTFE and MPPS sewing thread in the high-temperature environment of bag dust collection. The initial decomposition temperature and the residual mass at the termination temperature of the materials can be used to indicate the stability of the material. The higher the residual mass at the termination temperature, the less combustible gas in the cracking products. Due to the larger heat absorption of the residue, the amount of heat released by the fiber combustion was correspondingly reduced, and the fiber was difficult to crack, preventing the material from continuing to burn, thus making its flame retardant and high temperature resistance relatively higher [26].

TG and DTG curve of MPPS/PTFE, PTFE and MPPS sewing thread [27] were depicted in figure 4, and characteristic degradation temperatures were given in table 3. The decomposition temperature (T\(_d\)) was defined as the temperature at the corresponding point when the weight loss was 5%.

It can be seen that MPPS/PTFE, PTFE and MPPS sewing thread exhibit a single degradation stage under the nitrogen atmosphere. For MPPS/PTFE sewing thread, it can be found that the decomposition temperature (T\(_d\)) was 527.7 \({}^\circ\text{C}\), the temperature at maximum decomposition rate from the DTG curve was 582.7 \({}^\circ\text{C}\), and the residual carbon rate was 30.8%. For PTFE sewing thread, it can be found that the decomposition temperature (T\(_d\)) was 558.9 \({}^\circ\text{C}\), which was higher than that of MPPS/PTFE sewing thread, the temperature at maximum decomposition rate was about 620.4 \({}^\circ\text{C}\), and the residual carbon rate was around 0.0%. For MPPS sewing thread, it can be found that the decomposition temperature (T\(_d\)) was 489.7 \({}^\circ\text{C}\), the temperature at maximum decomposition rate from the DTG curve was 576.6 \({}^\circ\text{C}\), and the residual carbon rate was 50.4%, which was larger than that of MPPS/PTFE and PTFE sewing thread. By comparison, it can be concluded that the thermal stability of MPPS/PTFE sewing thread was worse than that of PTFE sewing thread, but better than that of MPPS sewing thread.

PTFE was a symmetrical linear polymer with no branched chain, which has a perfluorocarbon molecular structure. The fluorine atoms act as a protective layer around the carbon chain, and C−F has the highest energy of any single bond, which contributed to the excellent thermal stability of PTFE sewing thread. So the addition of PTFE fiber increased the thermal properties of MPPS/PTFE sewing thread.

Differential scanning calorimeter was a dynamic temperature analysis technology, which can record the thermal effect of the sample with the change of temperature. As shown in figure 5, the melting point temperature (T\(_m\)) and the crystallization temperature (T\(_c\)) were noted on the DSC curves of MPPS/PTFE, PTFE and MPPS sewing thread.

For MPPS/PTFE sewing thread, there were two melting temperatures, namely 287.86 \({}^\circ\text{C}\) and 342.23 \({}^\circ\text{C}\), which were consistent with that of MPPS fiber and PTFE fiber respectively. So the crystallization temperature (T\(_c\)) also have two values, 169.34 \({}^\circ\text{C}\) for MPPS fiber, and 317.34 \({}^\circ\text{C}\) for PTFE fiber. The above differences between MPPS fiber and PTFE fiber indicated that the thermal stability of PTFE fiber was better than MPPS.
fiber. For PTFE sewing thread, the melting temperature was 342.13 °C and the crystallization temperature was 316.70 °C; these temperatures were similar to that of MPPS/PTFE sewing thread. For MPPS sewing thread, the melting temperature was 287.53 °C and the crystallization temperature was 196.96 °C. The melting temperature of MPPS sewing thread was same as that of MPPS/PTFE sewing thread, but the crystallization temperature was about 28 °C higher than that of MPPS/PTFE sewing thread. But there was no glass transition temperature on the DSC curve, the possible reason may be the still high degree of crystallinity of MPPS fiber and PTFE fiber.

In the figure 6, the effects of the number of melting times and heating rate on melting temperature of MPPS/PTFE sewing thread were compared and analyzed.

For MPPS/PTFE sewing thread, the melting temperature from the second melting was lower than that from the first melting, about 23 °C for PTFE fibers and 22 °C for MPPS fibers, respectively. For PTFE sewing thread, the melting temperature from the second melting was about 13 °C smaller than that from the first melting. And for MPPS sewing thread, the melting temperature from the second melting was also about 13 °C smaller than

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**Figure 4.** TG and DTG curve of (a) MPPS/PTFE sewing thread; (b) PTFE sewing thread; (c) MPPS sewing thread.
that from the first melting. From the above analysis, it can be concluded that the number of melting times has greater influence on melting temperature of MPPS/PTFE sewing thread than that of PTFE and MPPS sewing thread.

Meanwhile, by comparing the effect of heating rate on melting temperature, it was found that the heating rate has a little effect on it of MPPS/PTFE, PTFE and MPPS sewing thread. So considering the time cost, the heating rate of 20 °C min−1 was recommended.

The effects of the number of melting times and heating rate on melting enthalpy of MPPS/PTFE, PTFE and MPPS sewing thread were presented in figure 7. From this figure, it can be concluded that the number of melting

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**Figure 5.** DSC curve of (a) MPPS/PTFE sewing thread; (b) PTFE sewing thread; (c) MPPS sewing thread.
times has great influence on melting enthalpy of MPPS/PTFE, PTFE and MPPS sewing thread. The melting enthalpy from the second melting was smaller than that from the first melting because there were more irregular areas inside MPPS/PTFE, PTFE and MPPS sewing thread after the first melting. By comparison, it can be found that the heating rate has little influence on melting enthalpy of MPPS/PTFE, PTFE and MPPS sewing thread, because the difference between the heating rate of 20 °C min⁻¹ and the heating rate of 10 °C min⁻¹ was small.

Figure 6. Effects of the number of melting times and heating rate on T_m of (a) MPPS/PTFE sewing thread; (b) PTFE sewing thread; (c) MPPS sewing thread.
4. Conclusions

The structure and properties of MPPS/PTFE sewing thread were studied by some testing methods in this paper to provide reference for its application in the field of high temperature dust removal.

It was found that the surface of MPPS/PTFE sewing thread has a lot of hairiness, which were good for plugging pinholes in the filter bag, although the tensile properties of it was decreased a little, but the flexibility of MPPS/PTFE sewing thread was improved by the addition of MPPS fibers. Meanwhile, MPPS/PTFE sewing thread has excellent heat resistance and thermal stability, which was better than MPPS sewing thread, but worse than PTFE sewing thread. From the DSC analysis, the number of melting times has greater influence on melting temperature of MPPS/PTFE sewing thread than that of PTFE and MPPS sewing thread, and the melting temperature from the second melting were 23 °C smaller for PTFE fibers and about 22 °C smaller for MPPS fibers than that from the first melting, respectively. And the number of melting times has great influence on melting enthalpy of MPPS/PTFE sewing thread, because there were more irregular areas inside MPPS/PTFE sewing thread after the first melting. Moreover, it can concluded that the heating rate has a little effect on melting temperature and melting enthalpy of MPPS/PTFE sewing thread, so the heating rate of 20 °C min⁻¹ should be more suitable for MPPS/PTFE sewing thread.

Acknowledgments

The authors would like to acknowledge Suzhou naide new material technology Co. Ltd for the materials. It was supported by “the Fundamental Research Funds for the Central Universities (No: 2232019D3-12). It was also supported by “National Natural Science Foundation of China” (No: 51903034).

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Figure 7. Effects of melting number and melting rate on melting enthalpy of sewing thread.
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