In Vitro Fatigue Properties of Prototype Woven Vascular Prosthesis with Poly (trimethylene terephthalate) Filaments as Circumferential Yarns

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ABSTRACT

As far as we know, fatigue properties of woven vascular prosthesis with PTT filaments as circumferential yarns which could improve compliance due to their lower initial modulus and better elasticity had not yet studied. In this study viscoelastic properties of PTT filaments were studied and fatigue properties of woven vascular prostheses with PTT filaments as circumferential yarns were tested using an accelerated fatigue tester. The changes of each property before and after the fatigue testing show evidence of fatigue. It will be more evidence of fatigue with increasing fatigue cycles and PTT tubular samples show better fatigue behavior compared to PET tubular samples.

INTRODUCTION

To minimize compliance mismatch [1-3] between native arteries and woven Dacron® vascular prostheses whose compliance are 10 times lower than that of arteries [4], poly (trimethylene terephthalate) (PTT) filaments have been used as circumferential yarns in manufacturing woven vascular prosthesis [5] due to their lower initial modulus and better elasticity than that of PET filaments [1,3,6]. The compliance of woven vascular prosthesis with PTT filaments as circumferential yarns is about two times higher than that with PET filaments [7]. However, the long term fatigue properties of woven vascular prosthesis with PTT filaments as circumferential yarns have not yet been reported. Following the implantation of vascular prostheses into human body, there is a growing incidence of reported cases of late complications. It is therefore important to evaluate the fatigue performances of vascular prosthesis. Particular failure mechanisms include endoleaks, migration and thrombosis as well as yarn shifting, fabric distortion and perforation [8]. King et al. [9] reported a progressive loss in the bursting strength of commercial polyester arterial prostheses with increasing time of implantation in humans due to physical factors, such as the geometry change of knitted and woven structures. Berger et al. [10] reported that deterioration occurred of the 493 Dacron® arterial prostheses, which had been implanted for 3~15.3 years, showing thinning and breakage of filaments generating holes and graft dilatation due to mechanical fatigue. Diéval et al. [11] reported that longitudinal ruptures of PET knitted prosthesis are caused by mechanical fatigue. Intrinsic structural failure of Dacron® prostheses is a late exceptional complication, resulting from a loss of structural integrity of the graft [12]. Zhao et al. [13] tested woven PET tubular textile samples by an accelerated fatigue tester *in vitro*. The results showed that there were clearly observable relationships between the change in textile parameters and fatigue performance of the samples.

In this study, stress relaxation and elastic recovery properties of yarns were tested and analyzed. Samples of woven vascular prostheses with PTT filaments as circumferential yarns were tested in an accelerated fatigue tester [13]. For comparison purposes, fatigue performances of PET samples were also tested under the same conditions.

EXPERIMENTAL

A YG061 yarn tester (Laiyang, China) was used to test the yarn's stress relaxation and elastic recovery properties at 10 % rate of the yarn's elongation at break. Each property was tested for 10 times. An EnduraTec® accelerate fatigue tester (Bose Corp

Eden Praire, MN, USA) was used to provide a pulsatile pressure to tubular samples. The fatigue tester was operated at a frequency of 100 Hz applying a pulsatile sine wave in 18.67~26.66 kPa (140~200 mmHg) pressure range, which would be experienced by hypertensive patients [13]. The temperature of fluid (water) inside tubular samples was maintained as 37 ℃. Each sample was tested at two different repeat cycles, 26×10^6 and 100×10^6, which are equivalent to 10 and 38.5 months implanted inside human body, respectively [13]. Tubular woven samples were fixed over an oversized elastic latex tube to avoid bleeding and to transfer the pressure profile of flowing fluid to the samples. The changes in fabric densities in circumferential and longitudinal directions, tubular diameter, wall thickness, weight and porosity after fatigue tests were measured for 5 times to characterize the fatigue performance of tubular samples. Images were acquired from a Philips 505T Scanning Electron Microscope (SEM) (FEI – Hillsboro, OR, USA) using an accelerating voltage of 15 kV. TG245 Balance was used to test the weight of samples. The change of each property is calculated as shown in Eq. (1). Here the initial property is the property of control sample before fatigue test.

$$\text{property change}(\%) = \frac{\text{property after fatigue} - \text{initial property}}{\text{initial property}} \times 100 \qquad (1)$$

Tensile properties of filament yarns used as weft yarns in the circumferential direction of tubular woven sample are listed in *Table I*. For the purpose of comparison PET samples were also fabricated and the corresponding properties were tested. The target length of the samples was 80 mm. For all the samples, PET monofilaments, 30D (denier), were used as warp yarns in the longitudinal direction of the samples and the weave was 3/1 twill. The initial specifications and properties of the samples are listed in *Table II*.

TABLE II. Tensile property of circumferential filament yarns.

Sample	Filament yarn (Denier/filaments)	Young's modulus (MPa)	Breaking strength (MPa)	Elongation at break (%)
1	PTT 55D/24f	380.98	282.14	28.34
2	PET 30D/12f	860.73	545.48	22.17
3	PTT 75D/72f	431.12	360.22	30.31

Note: Range of actual value of standard deviation is ±2

TABLE II. Initial specifications and properties of tubular woven samples.

Sample	Fabric count (ends× Picks/mm)	Diameter (mm)	Thickness (mm)	Weight (g/m²)	Young's modulus (MPa)
1	11.83±0.58× 9.00±0.50	5.73± 0.064	0.39± 0.001	175.93	262.17
2	10.50±0.28× 8.67±0.28	5.69± 0.037	0.18± 0.001	112.95	802.90
3	10.50±0.50× 7.83±0.29	5.75± 0.037	0.32± 0.001	207.56	284.32

RESULTS AND DISCUSSION

Viscoelastic Properties of PTT Filament Yarns

Figure 1 shows the stress relaxation curves of PTT and PET filament yarns. It can be seen that the initial stress of PTT filaments is much lower than that of PET. This could be expected because of a lower Young's modulus of PTT filaments. With an increase of relaxation time, the stress of PTT filaments decreased much less than that of PET counterparts, which suggests a lower relaxation rate of PTT filaments and better elastic properties than PET. *Table III* shows the elastic recovery of the filament samples after five stretch cycles at three rates: 10 %, 15 % and 20 % of the yarn's elongation at break. The results show that the elastic recovery rates of PTT at three different elongation levels are all higher than that of PET indicating a superior elastic recovery property of PTT filament yarns, even at a high elongation rate.

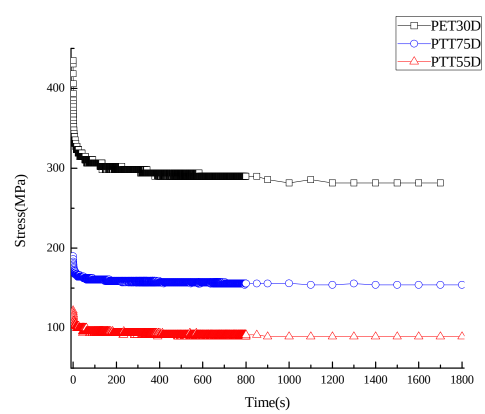

FIGURE 1. The stress relaxation curve of yarn samples at 10 % elongation rate.

TABLE III. Elastic recovery of yarn samples after five stretch cycles.

Sample	Filament yarn	At 10% elongation rate (%)	At 15% elongation rate (%)	At 20% elongation rate (%)
1	PTT 55D/24f	93.25	91.16	84.16
2	PET 30D/12f	83.66	61.99	49.42
3	PTT 75D/72f	85.03	82.37	78.79

Note: Range of actual value of standard deviation is ±2

With better elastic properties, resilience and greater breaking elongation as shown in *Table I*, PTT is expected to have better fatigue performance than that of PET. From the point of view of macromolecular chain, it is well known that the number of methylene groups in the repeat unit influences the physical properties of many polymers [14]. Three methylene groups between terephthaloyl in the repeat unit of PTT filaments show a Z shape arrangement, which allows for a certain flexibility of the chain. As results, the transformation of conformation appears to be reversible and possesses a good intrinsic elastic recovery in the macromolecular chains. This specific feature may provide a good explanation to the better performances in elastic recovery and fatigue testing for PTT than that of PET [15].

Characterization of Fatigue Performance

Warp and weft densities, diameter, thickness and weight of the tubular woven samples are examined, respectively, after 26×10^6 and 100×10^6 cycles of fatigue tests and significant changes have been found. The percentage changes of the samples are plotted in *Figure 2*.

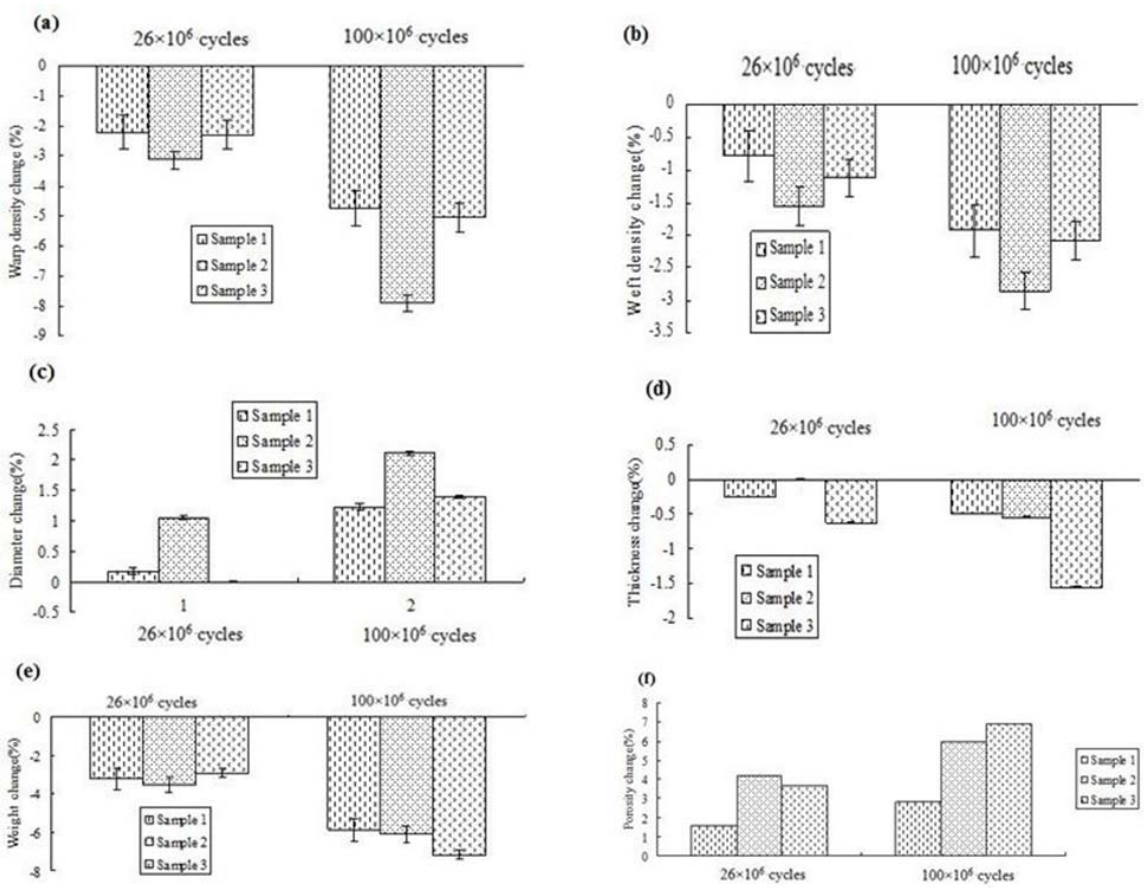

FIGURE 2. Properties of woven tubular samples after fatigue testing: (a) Warp density, (b) Weft density, (c) Filament diameter, (d) Thickness, (e) Mass per unit area, (f) Porosity.

Figures 2a and *2b* show that the warp and weft densities of the samples are decreased after the fatigue tests. The reduction of warp density is greater than that of weft due to the effect of the applied pulsatile pressure. The effect is greater in the circumferential direction of the tubular samples than in the longitudinal direction [13]. The less change in fabric count of PTT samples than PET ones could be expected because the change is mostly contributed to the plastic deformation of filament yarns and PTT filaments have better elastic properties especially elastic recovery as shown in *Table III*. *Figure 2c* shows that the diameters of the tubular samples increase, which indicates the dilatation of the samples after the fatigue tests. The dilatation is by far the most often-cited cause of prosthesis failure and it could follow or indeed induce yarn breakage, rents, slits, or bleeding [8]. As can be seen in *Figure 2c*, the samples with PET as circumferential yarns dilate more easily than that with PTT. Again, the better elastic properties of PTT filaments play a key role. *Figures 2d* and *2e* show that the thickness and weight of the samples are all decreased after the fatigue tests due to the decrease in fabric count and diameter dilation. The changes in porosity shown in *Figure 2f* are calculated from the changes in thickness and weight of the samples. It can also be well expected because of the reduction in fabric count after the fatigue test. The changes of all the parameters of the samples in *Figure 2* show the fatigue effect after repeat loading.

Theoretical analysis also suggests that the elongation of woven fabrics under constant cyclic loads includes three parts, i.e.: decrimping of the fabric arising from yarn slippage, yarn decrimping, and finally yarn elongation [16]. Due to the elongation of the samples in the circumferential direction during the fatigue test, the structure properties of the samples would be changed after fatigue test. The plastic deformation that can not be recovered will induce the increase of diameter and the decrease of fabric count especially for warp density in the circumferential direction after fatigue test.

PTT samples with the larger yarn size are more easily fatigued. It is seen from *Figure 2* that the changes in porosity of the PTT samples with 75D/72f filament as weft yarns are greater than that with 55D/24f filaments. Filaments inside the multifilament yarns may spread or accumulate under the influence of pulsatile pressure applied on each yarn [13]. The larger the yarn size, the more rigid the sample, and the more easily they creep or deform plastically. The number of filaments inside weft yarns has great influence on the change of thickness, mass per unit and porosity.

Figure 3 shows the SEM photomicrograph of the control and fatigued samples. It shows that with increasing fatigue cycles, more damage and abrasion could be observed. After 26×10^6 cycles of the fatigue test, there is less damage in the warp with monofilaments but an indication of abrasion in the weft with multifilament yarns, especially for PET samples shown in *Figure 3d*. After 100×10^6 cycles of the fatigue test, there is still no obvious damage in the warp but obvious abrasion and damage in the weft. As shown in *Figure 3h*, some filaments in the weft yarn of 75D/72f PTT has already broken. When the samples under the influence of a persistent applied stress the yarns experience interactive forces, such as friction, abrasion and compression forces. In addition, there are frictions between fabrics and the latex tube. As a result, the macroscopic and microscopic structure of the sample will be changed and neighboring yarns within the fabric will be flexed and abraded after the fatigue tests.

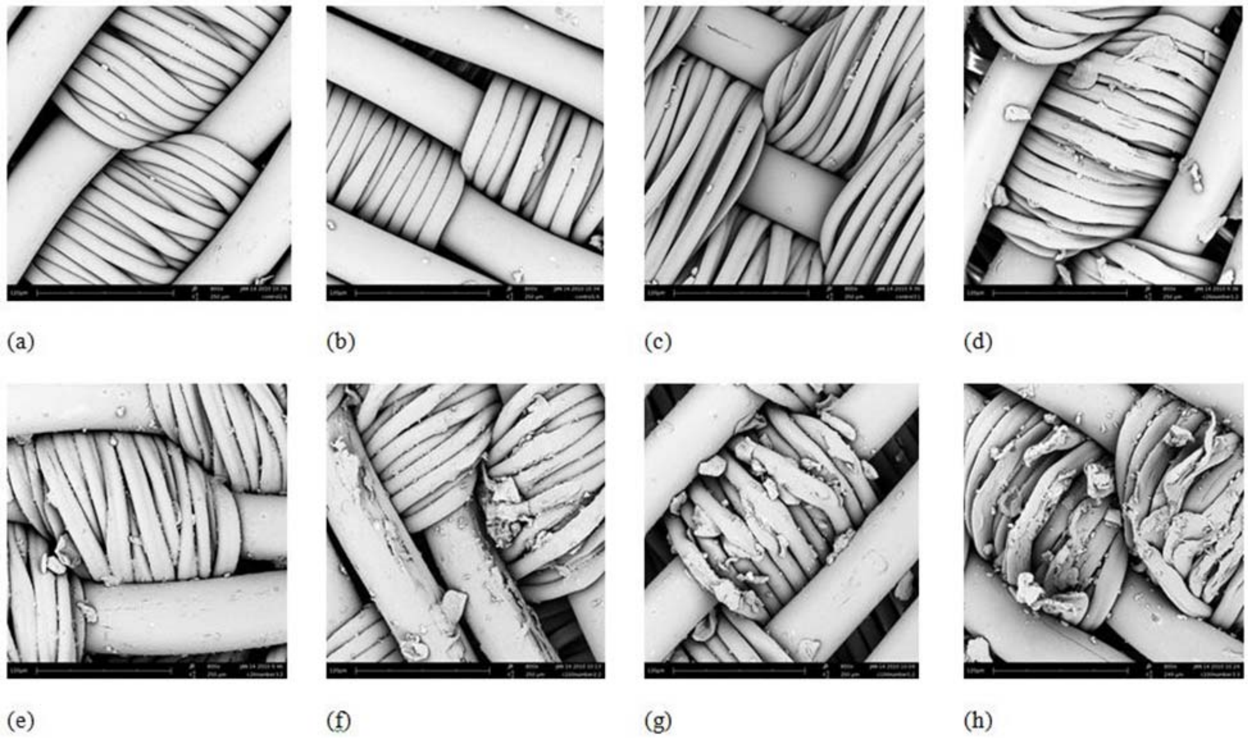

FIGURE 3. SEM photomicrograph of samples' internal surface (Magnification 800×): (a) Control sample 1; (b) Control sample 2; (c) Control sample 3; (d) Sample 2 after 26×10^6 fatigue cycles; (e) Sample 3 after 26×10^6 fatigue cycles; (f) Sample 1 after 100×10^6 fatigue cycles; (g) Sample 2 after 100×10^6 fatigue cycles; (h) Sample 3 after 100×10^6 fatigue cycles.

CONCLUSIONS

In this study, the fatigue properties of woven vascular prosthesis with PTT filaments as circumferential yarns, which could improve radial compliance due to their lower initial modulus and better elasticity, are examined. The stress relaxation tests of PTT filaments show that the relaxation rate is lower and the elastic recovery is much better than those of PET filaments. Therefore, PTT filaments are expected to have better fatigue performances. The tubular woven samples with PTT filaments as circumferential yarns were tested using an accelerated fatigue tester. The changes of the properties, such as fabric densities, tubular diameter and porosity show the evidence of fatigue. More cycles of fatigue tests were, more clearly the evidence of fatigue of the samples. In addition, samples with PET filaments as circumferential yarns fatigue more easily and faster than the PTT counterparts. Therefore, PTT could be a better candidate for woven vascular prostheses in terms of fatigue properties than PET. Further work is continuing with the *in vitro* fatigue performance of mechanical and elastic properties as well as *in vivo* study of PTT vascular prostheses.

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