# THE EFFECT OF REUSE SOLUTION ON THE HIGH FLUX POLYAMIDE HOLLOW FIBER MEMBRANES IN HEMODIALYSIS

by

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# ABSTRACT

## THE EFFECT OF REUSE SOLUTION ON THE HIGH FLUX POLYAMIDE HOLLOW FIBER MEMBRANES IN HEMODIALYSIS

In order to question the safety of reuse of high flux polyamide hollow membranes used for hemodialysis, it is imperative to perform several experiments on both virgin high flux polyamide membranes and used fibers left in re-use solutions. SEM and AFM studies performed on virgin and used-processed fiber visualized the morphological changes. Rough wavy structure with defects was seen in used-processed fiber, whereas a smoother surface morphology was seen in virgin fibers. Big deep holes due to pore merging, more elliptical pores and defects were visualized in used-processed fibers. Thus, easy crack initiation and propagation is expected in used-processed fibers. Tensile tests also revealed the difference in mechanical properties of virgin and used-processed fibers and confirmed what was obtained from the SEM and AFM studies. Drop in ductility and toughness was observed in used-processed fibers. This study showed that dialysis environment caused structural changes on membranes which may cause clinical complications.

**Keywords:** Hemodialysis, high flux, polyamide, SEM, AFM, tensile test, XRD.

# ÖZET

## REUSE SOLUSYONUNUN YÜKSEK AKIMLI POLYAMİD MEMBRANLAR ÜZERİNDEKİ ETKİLERİ

Dünya nüfusunun artışı ve sosyal yapıdaki hızlı değişmeler kronik böbrek yetmezliğine bağlı hastaların sayısını artırmaktadır. Böbrek transplantasyonunun mümkün olmadığı durumlarda hemodiyaliz kaçınılmaz hale gelmektedir. Hemodiyaliz işeminin maliyeti, teknik güçlükleri ve hasta üzerinde menfi etkileri ile birlikte kullanılan membranların tekrar kullanımı sürekli olarak gündemi işgal etmektedir. Bu çalışmada tekrar kullanıma girmeden önceki işlemlerin "yüksek akımlı polyamid" membranlar üzerindeki etkisi incelenmiştir. Hiç kullanılmamış membranlarla kullanım sonrası tekrar kullanım için uygulanan kimyasal işlemin etkileri karşılaştırılmıştır. Bu gayeyle mekanik deneylerle birlikte, taramalı elektron mikroskop, atomik güç mikroskop, optik mikroskop teknikleri ile birlikte x ışınları difraksiyonu uygulanmıştır. Mikroskobik teknikler tekrar kullanım çözeltisinin ve mekanik etkilerin malzemenin mikroyapısında ve yüzey durumunda büyük değişiklikler meydana getirdiğini göstermiştir. X ışınları difraksiyonu kullanılmış ve tekrar kullanım çözeltisinde muamele edilmiş membranlarda yeni fazların oluşumunu ve kristal yapıdaki değişimi ortaya çıkarmıştır. Mekanik deneyler tekrar kullanım öncesi yapılan işlemin malzemenin mekanik özelliklerini düşürdüğünü göstermiştir. Sonuç olarak tekrar kullanım işlemi malzeme yapı ve membranların yapı ve özelliğini büyük ölçüde değiştirmekte ve kaliteyi düşürmektedir. Muhtemelen bu değişiklik klinik problemlere yol açar karakterdedir.

**Anahtar Sözcükler:** Hemodiyaliz, membran, polyamid, X ışınları difraksiyonu, taramalı elektron mikroskop, atomik güç mikroskop.

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| | |
|---|---|
| AAMI | Association for the Advancement of Medical Instrumentation |
| AFM | Atomic Force Microscope |
| CAN | Canadian |
| cps | Count Per Second |
| E | Youngs Modulus |
| EU | European Union |
| ESRD | End-Stage Renal Disease |
| I | Intensity |
| KUf | Ultrafiltration Coefficient |
| MPa | Megapascal |
| P | Load |
| PA | Polyamide |
| SEM | Scanning Electron Microscope |
| UK | United Kingdom |
| URR | Urea Reduction Ratio |
| U.S. | United States |
| XRD | X Ray Diffraction |

# 1. INTRODUCTION

## 1.1 Kidney Failure

The incidence of patients with end-stage renal failure as a comorbid condition has increased progressively in the past decades, first in the United States and Japan, but subsequently in all countries with a western lifestyle. Although there are explanations for this increase, the major factor is presumably diminishing mortality from hypertension and cardiovascular causes, so that patients survive long enough to develop end-stage renal failure [1].

The main job of kidneys is to remove toxic wastes a process called clearance and to remove excess water which is also called ultrafiltration.

Chronic kidney failure is a condition in which the kidneys become less and less able to perform their functions. This progressive loss of renal function takes over months or years. Finally, the kidneys stop working almost completely, and it is called end stage renal failure or ESRF. Dialysis or kidney transplant is then needed in order to take over the work of kidney and to keep the patient alive.

In the case of kidney failure, kidneys become less efficient at clearing the waste products from the blood which in turn leads to an accumulation of toxins in the blood. There are tens thousands of substances in blood.

The overall ability of the kidneys to clear wastes from the blood is assessed by measuring the blood levels of urea and creatinine. Urea and creatinine are not, in themselves, particularly harmful to the body. Creatinine is not even a toxin. However, tests that indicate the clearance of urea and creatinine from the body provide an indication of the clearance of all the thousands of harmful toxins that are produced by the body [2].

The normal blood level of urea is between 3.3 and 6.7 mmol/ l and the normal level of creatinine in the blood is known to be between 70 and 120 μmol/ l. Dialysis is usually started when a patient’s blood creatinine is between 600 and 800 µmol/ l. This level is equivalent to about 5% of the function of two normal kidneys [2].

Two methods are generally used to assess dialysis adequacy, URR and Kt/V. The reduction in urea as a result of dialysis, or the URR, is the urea reduction ratio, but it is commonly expressed as a percentage [3]. Kt/V is another method to quantify the dialysis efficiency where K stand for urea clearance, t dialysis time and V patient’s total body water. URR of 65 percent and a Kt/V of 1.2 have been determined to be benchmarks of dialysis adequacy [3, 4].

### 1.1.1 Demographical Data Of Dialysis Patients

The number of dialysis patients all over the world is seen in Figure 1.1.1.1. The number hemodialysis patients in Turkey according to years are shown in Figure 1.1.1.2.

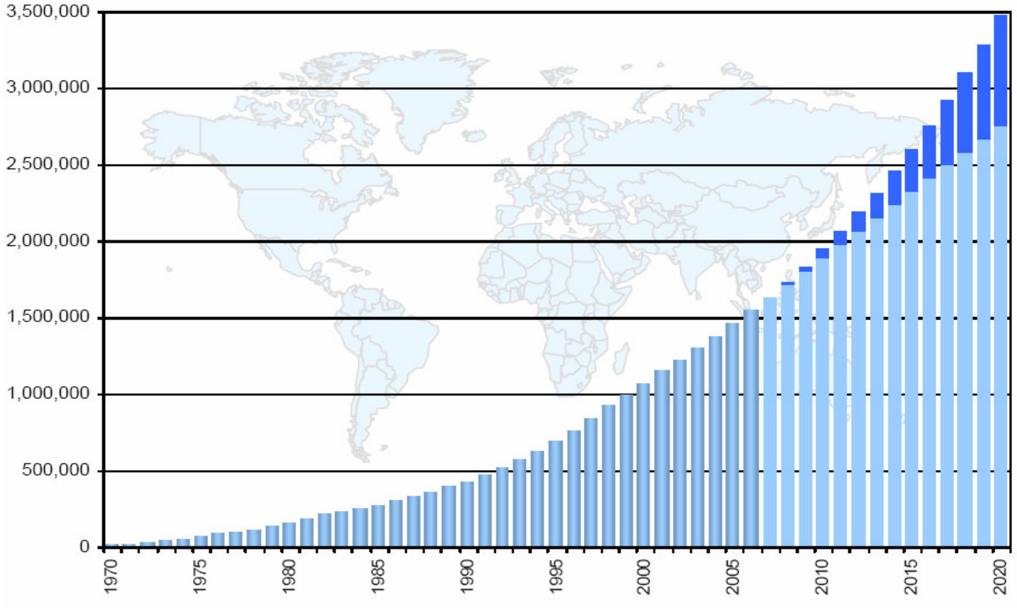

**Figure 1.1.1.1** Number of dialysis patients in the world and estimated number of dialysis patients until the year 2010 [5].

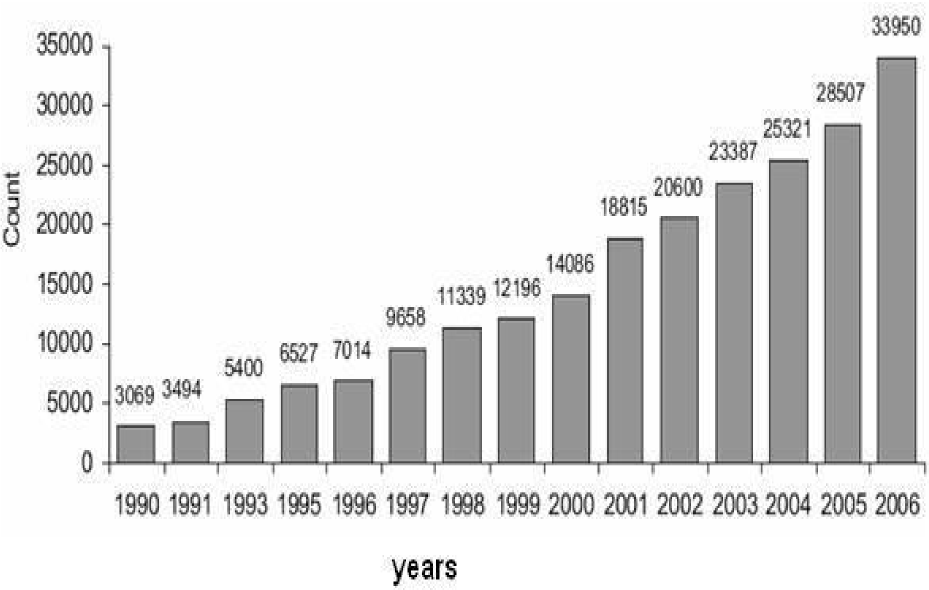

**Figure 1.1.1.2** Number of hemodialysis patients between the years 1990-2006 [6].

## 1.2 History of Hemodialysis

It is known that the first description of hemodialysis was made by Thomas Graham in 1854 who worked as a chemist in Glaskow University. Aside from being the first to describe the process of separating substances with a semi-permeable membrane, Graham also was the first to separate colloids and crystalloids using a parchment membrane. Abel et al. developed and tested the first efficient dialysis system at Johns Hopkins University School of Medicine in 1914 [7].

Lore et al tried to use intestinal membranes as dialysis membranes in 1920. The first human hemodialysis was performed in a uremic patient by Haas in 1924 at the University of Giessen in Germany. He used a tubular device made of collodion, cannulation of the radial and carotid arteries and the portal vein and hirudin for anticoagulation. The first flat hemodialysis membrane made of cellophane was produced in 1937 [7].

In 1943 Willem Kolff from the Netherlands introduced the rotating drum hemodialysis system using cellophane membranes and an immersion bath and the first recovery of an acute renal failure patient treated with hemodialysis was reported. In 1947, Nils Alwall developed a new system with a vertical stationary drum kidney and circulating dialysate around the membrane. Dialysis with ultrafiltration was also performed by him. In 1960, Kiil developed the plate dialyzer [7]. By the late sixties, hollow fiber artificial kidneys were also manufactured and dialysis started to be performed out-of-hospital in self care centers or even at home [8].

Regular hemodialysis was first introduced in Turkey in around 1965 [9]. In 1991, 71 per cent of kidney patients in the world were treated with dialysis membranes. After 150 years the term dialysis came to life, more than 450.000 uremic patients owed their lives to this therapy [10].

The evolution of biomaterials and technology made dialysis easier and simpler in the seventies leading to a dramatic growth in the number of patients on chronic renal replacement therapy [8].

## 1.3 Hemodialysis

A schematic diagram of a typical hemodialysis system is shown in Figure 1.3.1. The patient's blood is pumped into the dialyzer (artificial kidney) in which excess fluid and wastes are removed from the blood and then the cleaned blood returns to the patient. The hemodialyzer machine mixes and warms the dialysate solution and monitors what is in dialysate during dialysis session. The machine also monitors the blood pressure in access and also checks the blood for air to protect the patient. During hemodialysis the patient is anticoagulated in order to prevent the blood from clothing.

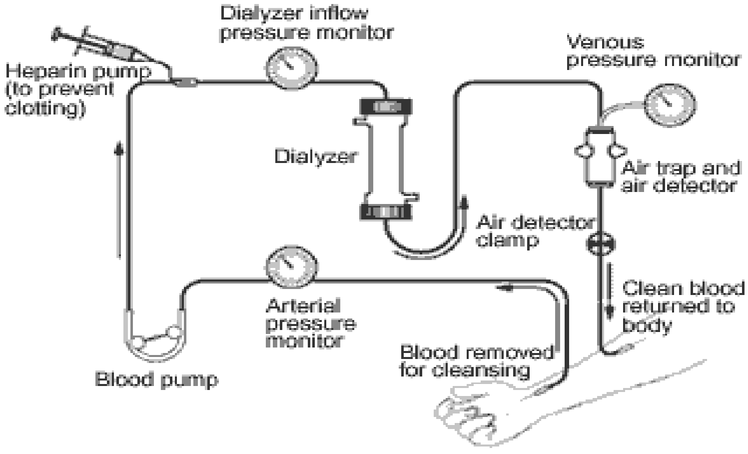

**Figure 1.3.1** A schematic diagram of a of typical hemodialysis system [3].

### 1.3.1 Dialyzers

The hollow fiber looks like a cylinder and it is filled with many tiny hollow fibers as shown in Figure 1.3.1. Dialysis membrane can be composed of one of four different materials: cellulose, substituted cellulose, cellulosynthetic, and synthetic [11].

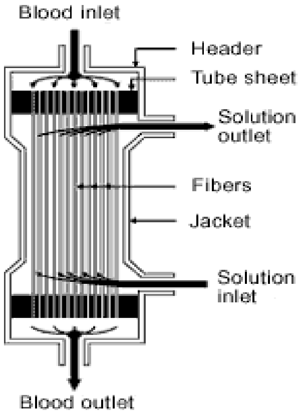

**Figure 1.3.1.1** A schematic diagram of hollow fiber dialyzer [3].

Dialyzers provide a semipermeable surface across which a diffusion gradient is created between a patient’s blood volume and a constantly repleted volume of dialysate [11]. The composition of dialysate nearly corresponds to that of plasma water. Dialysate contains sodium chloride, sodium acetate or sodium bicarbonate, calcium chloride, potassium chloride and magnesium chloride. Glucose may be included in some formulas [12]. In a typical hollow fiber dialyzer blood flow and dialysate flow are arranged in a countercurrent format to allow for maximal concentration gradients between blood and dialysate at any point along the length of the fiber bundle [11].

Clearance is likely the most useful and important characteristic of a dialyzer, because it is a critical factor in determining the dialysis prescription. Clearance as applied to hollow fiber dialyzers is identical to that utilized for the native kidney, namely the volume of blood completely cleared of a certain solute during a single passage through the organ or device. In the case of hemodialysis clearance can be calculated by measurement of actual solute removal (measurement of solute concentration in dialysate or filtrate factored by dialysate volume or flow rate). The mechanisms of solute transport out of the blood during extracorporeal therapy are adsorption, diffusion, and convection [11, 12].

It is known that smaller lighter solutes move rapidly along the concentration gradient than heavier solutes. A large solute beta-2 microglobulin (11,800 daltons) diffuses at a rate which is only 7% of the urea (60 daltons) diffusion rate. Therefore, there is negligible diffusion of large solutes such as beta-2 microglobulin through hemodialysis membranes. As the size of a molecule approaches the size of a pore, transport is further hindered by interaction with membrane walls [12]. The rate of diffusion through dialysis membranes can be increased in the following ways: (1) Increase area for diffusion: increase dialyzer surface area; increase porosity of membrane. (2) Reduce diffusion distance: reduce membrane thickness. (3) Reduce wall hindrance effect: increase membrane pore size [12] as much as possible without giving permission to the blood cells to escape from blood side to dialysate side.

Fluid moves under hydrostatic pressure from blood to dialysate. This process is called ultrafiltration. The amount of fluid transfer depends on pressure difference between blood and the dialysate. The ultrafiltration coefficient (KUf) is the number of mL of fluid transferred across the membrane per hour when 1 mmHg of pressure difference is applied.

Solute transfer with the flow of water is known as convective transport. The rate of solute convection is equal to the ultrafiltration rate times the sieving coefficient of the membrane for the solute of interest [12]. The sieving coefficient is the permeability of dialysis membranes to a particular solute and not its diffusability [11]. The sieving coefficient can be increased by increasing the membrane pore size [12].

### 1.3.2 High Flux Dialyzers

High flux dialysis is the form of hemodialysis that was developed in recent years to improve the efficiency of dialysis [13]. The use of a high flux membrane has steadily increased since the discovery of beta-2 microglobulin amyloidosis in 1985 [14]. It has succeeded in both improving the quality of dialysis and in shortening dialysis times [13].

High flux dialysis membranes offer improved clearance of larger molecular weight solutes, particularly beta-2 microglobulin [13, 15] with the larger pore sizes than low flux membranes. Patients exhibit improved cardiovascular stability [15, 16] and long term use of these membranes may delay the onset of dialysis-related amyloidosis [15].

Another important advantage of high flux dialysis is that higher blood and dialysate flows are used. In conventional dialysis, increasing the rate of blood flow minimally increases the amount of dialysis whereas with high flux dialyzers, when blood flow is increased up to 450 ml/min, significant improvements in dialysis efficiency can be obtained [13].

High-flux dialyzers have KUf ranging between 20 – 60 mL/mmHg/hour, while low flux dialyzers have KUf < 10 mL/mm Hg/hour and medium-flux dialyzers have KUf that range between 10 – 19 mL/mmHg/hour. Because of the high ultrafiltration coefficients of high-flux membranes, high flux dialysis requires an automated ultrafiltration control system to avoid accidental profound intravascular volume depletion [12, 13].

Backfiltration of solutes and toxins from the dialysate to the blood is a potential but probably overstated complication of high flux dialysis [15]. The major possible disadvantage of high flux dialysis regards pyrogen reactions [13].

As it is stated above high flux dialyzers provide more efficient dialysis from health care point of view and make the patient feel more comfortable by providing less treatment hour. On the other hand cost is the major barrier to more widespread use of high flux dialysis [15].

## 1.4 Reuse of Dialyzers

Reuse of hemodialyzers can be defined as using the same hemodialyzers on the same patient more than once after cleaning and disinfecting according to the reuse guidelines developed by the Association for the Advancement of Medical Instrumentation (AAMI).

Dialyzers reprocessing has been since the late 1960s. By the mid most patients were treated with Kill dialyzers. The first examples of dialyzers reprocessing came into life in 1967 by Dr. Belding Scribner [17]. He reported that the blood compartment of a Kill dialyzer could be filled with a germicide, rinsed and used for the next treatment. By the late 1960's new coil dialyzers were preferred for reuse. By the late 1970's disposable parallel plate dialyzers were being reused. The dialyzers were sealed off with germicide in both blood and the dialysate sides which reduces the changes of contamination by bacteria [17].

When the hollow fibers came on the market in 1970, they proved to be well suited for reuse and reused hollow fiber dialyzers performed better than other reused dialyzers. In 1976, about 18% U.S. dialysis patients were treated with reused dialyzers [17]. Automated reprocessing machines were introduced in 1980's and contributed to the increasing trend to reuse dialyzers [18]. Economical strategy to reduce cost in United States leads to a peak in 1997, 82% U.S. dialyzers centers using reused dialyzers [17].

A recent survey (Fresenius International, Internal Market Survey, 2004) suggests that reuse prevalence among patients in the 25 European Union countries is ~5% but that the statistic is heavily influenced by a single country (Poland; 85%). The practice is negligible (<1%) in most EU (20 out of 25) countries and is legally proscribed in Portugal, Spain and France. The reuse prevalence in the UK, is approximately ~2% [19]. Japan, most of the Middle East and South America do not practice any dialyzer reuse [20].

In the United States, peracetic acid mixture, formaldehyde and gluteraldehyde have been the predominant types of germicide used in reuse practices [21]. Sodium hypochlorite (bleach) is often used in conjunction with formaldehyde or gluteraldehyde to remove residual blood proteins. More recently, heated citric acid has also been introduced to clean and disinfect dialyzers for reuse [22].

Reuse of dialysis membranes are exposed to harsh environment such as pressure, blood and germicide used during reprocessing. These factors can influence the characteristics of the used membrane and can affect the dialysis efficiency. Safety of reuse from health care point of view is still a hot research topic with the studies that reported inconsistent results with each other.

Recent reports focuses on the effects of different germicides on different types of membranes by considering small weight molecule clearance, beta-2 microglobulin removal, pyrogenic reactions and mortality and morbidity rates. Studies in the literature on synthetic membranes with different germicides have generally centered on polysulfone membranes. There are not enough studies on polyamide dialyzers in the literature. Since Polyflux used in this study is a synthetic polymer based membrane like polysulfone, it is also useful to investigate the studies on literature.

One possible important disadvantage of reuse is that it can reduce the clearance of small weight molecule such as urea and creatinine and also removal of beta-2 microglobulin. Most of the studies have reported that reprocessing does not significantly alter the clearance of urea and creatinine with different germicides. Poshi et al reported that on reuse of dialyzers progressive decline in urea and creatinine clearance rates was observed and also reported that reuse caused some morbidity but no mortality [23]. In a later study Leypoldt et al. reported that no significant changes in urea, creatinine, or phosphate clearances of high flux dialyzers after 15 uses when using renalin as the germicide was detected and also reported that beta-2 microglobulin clearance and dialysate total protein concentration decreased substantially with the reuse of high-flux dialyzers [24]. Ko et al. reported that urea clearance was well maintained after reuse with high flux polyamide membranes reprocessed by using gluteraldehyde and bleach and also reported that there was no significant decrease until the 10th reuse on beta-2 microglobulin clearance [25]. Mitwalli et al. also agreed that reuse of high flux dialyzer processed by using renalin does not affect its clearance capacity of low molecular weight solutes and he also reported that albumin leaks in the dialysate, progressively decreased with each hemodialysis session and also he reported that no short-term adverse events and effects on morbidity were noted [26]. In 2003 Rahmati et al reported that there was a trend for clearances to decline with increasing number of reuses of high flux polysulfone dialyzers reprocessed using citric acid and heat ($95^{o}$C) [27]. Recently Tonelli et al reported that there was no significant change in urea or creatinine clearance with additional reuse up to 25th use of high flux polysulfone when using citric acid and prolonged to heat exposure (CAH) which is an increasingly common alternative to purely chemical means of reusing dialyzers. In that study Tonelli et al also added that a sustained increase in beta-2 microglobulin clearance was observed after the fifth treatment compared with the first use and dialysate albumin loss increased significantly with additional reuses but did not increase significantly until treatment 25 times [28]. More recently, Geoffrey et al reported that high-flux Polyflux dialyzers provide more than adequate dialysis, while preventing the in vitro back-diffusion of bacterial endotoxin despite 15 reuses with renalin [29].

Most of the studies on clearance of low molecular weight solutes of high flux synthetic membranes treated by using different germicides reported that there was not a significant decrease in urea and creatinine clearance but some studies also reported that there was a trend for clearances of urea and creatinine to decline with increasing number of reuses but within the acceptable limits. Studies on albumin leaks and clearance of beta-2 microglobulin of reuse dialyzers processed with different germicides report conflicting results.

Studies on the effects of different types reuse hemodialyzers treated with different germicides on mortality and morbidity rates also report conflicting results. In 1987, Alter et al reported that pyrogenic reactions occurring in clusters were more often reported by centers that reused disposable dialyzers than by centers that did not [30]. Collins et al reported that their study of 1998 and 1999 incident Medicare hemodialysis patients found no significant differences in mortality and hospitalization risk between patients receiving dialysis with reuse dialyzers processed with different germicides such as formaldehyde, gluteraldehyde, peracetic acid or germicide/bleach combinations and those receiving single use dialyzers and also it is reported that there was no significant differences in outcomes associated with particular germicides such as formaldehyde, gluteraldehyde, peracetic acid or germicide/bleach combinations [21]. On the other hand, Held et al reported that patients treated in dialysis units that disinfected dialyzers with a peracetic acid, hydrogen peroxide, acetic acid mixture, or gluteraldehyde experienced higher mortality than patients treated in units that used formalin or in units that did not reuse dialyzers [31].

In literature there are not enough studies on the effects of different germicides on different types of membranes especially polyamide. Studies report conflicting results about comparison of urea, creatinine, beta-2 microglobulin clearance and mortality and morbidity rates of single use and reused different membranes processed with different germicides. Age, nutrition, hemodialysis age and some other factors can lead to these conflicting results. Further long term follow up studies should be needed.

## 1.5 Objective Of This Thesis

Although hemodialyzer reuse is used in some countries, it is still a divisive issue. Since studies on the effects of reuse on the patient outcomes such as clearance, mortality and morbidity rates and etc. do not give satisfactory results in literature, it is intended in this thesis to study the effects of reuse solution on polyamide type high flux hollow fiber membranes by comparing virgin and used-processed membranes in terms of the changes in morphology and mechanical properties and also alterations in crystallinity and to obtain conclusion whether reuse effects the structural stability of high flux polyamide type hollow fiber membranes.

# 2. MATERIALS AND METHODS

Experimental studies performed on both virgin and used-processed high flux Polyflux 17S hollow fiber membranes manufactured by Gambro is seen in Figure 2.1**.** In order to obtain used dialyzer, 17S virgin dialyzer was applied to a patient with End Stage Renal Failure. Hemodialysis session of three or four hours was implemented to the patient twice a week. The patient was not infected with hepatitis or HIV (or others) which was common among end stage renal failure illnesses. This was important in order to figure out the effects of hemodialysis treatment and reuse solution on membranes precisely otherwise some complications could give rise emanating from other illnesses.

**Figure 2.1** 17S virgin high flux dialyzer

## 2.1 Cutting Procedure

Both virgin and used dialyzers were cut at their upper parts with a sharp saw at Istanbul Technical University as seen in Figure 2.1.1 in order to visualize the vertical view of the bundle configurations under stereo-microscopy. The head sections of the membranes were cut into two parts to visualize the lateral view of the bundle configurations as seen in

Figure 2.1.2. Used and virgin fibers, on which experiments were performed, were also obtained by cutting procedure.

**Figure 2.1.1** Cutting procedure of upper head of the dialyzer.

**Figure 2.1.2** Cutting the upper part of the dialyzer into two parts.

## 2.2 Reprocessing Procedure

Germicides currently used in reuse are formaldehyde, peracetic/acetic acid/peroxide mixture (renalin), and gluteraldehyde. Formaldehyde was the most common germicide in use with manual reprocessing until the late 1980's [11]. Although in 1994 Held et al reported that patients treated in dialysis units that disinfected dialyzers with a peracetic acid, hydrogen peroxide, acetic acid mixture, or gluteraldehyde experienced higher mortality than patients treated in units that used formalin or in units that did not reuse dialyzers [31], there was a trend to use renalin instead of formaldehyde in mid 1990's. In 1995, 57.5% of U.S. dialysis facilities were using renalin, 37.9% were using formaldehyde, and 3.5% were using gluteraldehyde [11]. On the other hand Burdick et al reported that after dialysis, plasma proteins from the patient's blood coat the surface of the dialyzer membrane. This coating of plasma protein reduces the direct exposure of the blood to the dialyzer membrane and decreases complement activation during subsequent uses. This protective effect is reduced when bleach is used during the reprocessing, since bleach removes the protein layer [32].

In this study taking these into consideration, formaldehyde which was commercially available and bleach were used as germicides as in San et al and her colloquies studies [33].Used fibers and the upper part of the dialyzer obtained from the cutting procedure were washed with 9% isotonic NaCl solution in order to remove the blood residues roughly as seen in Figure 2.2.1. To ensure proper disinfection, the dialyzer must stay in the germicide for a certain amount of time. The contact time (amount of the time the germicide remains in the dialyzer) differs from each germicide. The contact time for formaldehyde is 24 hours [17]. The concentration of formaldehyde for disinfection is 4% [11]. Since in this study, formaldehyde and bleach were used together the fibers were left in 4% formaldehyde solution for 14 hours as instead of 24 hours as seen in Figure 2.2.2 and then they were washed with distilled water. After then they were left again in 5 % sodium hypochlorite (bleach) for 6 hours and finally they were washed again with distilled water and reprocessing procedure was ended. Used-processed fibers were stored in refrigerator for 24 hours before the experiments were performed on them.

**Figure 2.2.1** Washing procedure of the dialyzer.

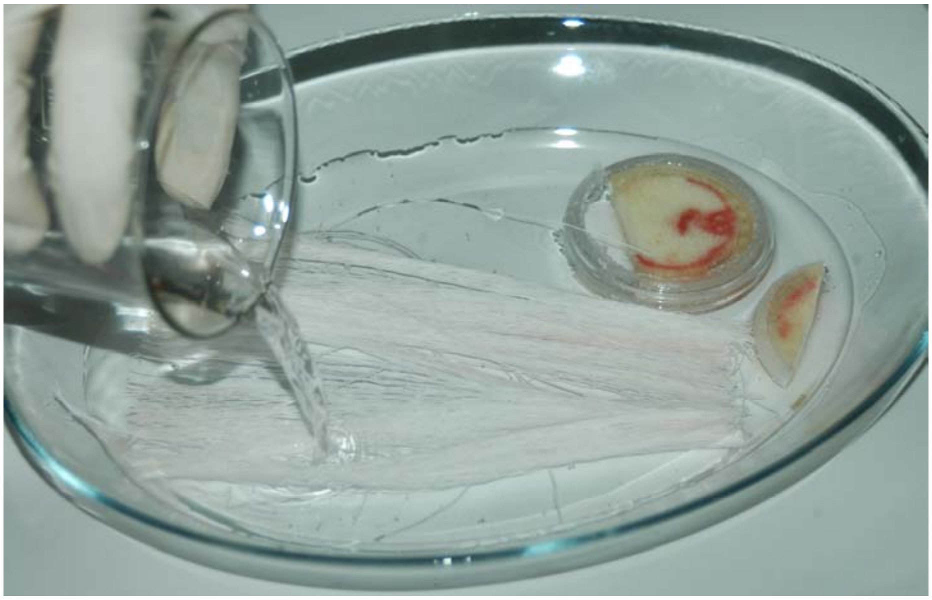

**Figure 2.2.2** Disinfecting procedure of the dialyzer.

# 3. MECHANICAL BEHAVIOR OF POLYAMIDE HOLLOW FIBERS

The mechanical behavior of materials is described by their elastic modulus, yield stress, ultimate tensile stress and strain to fracture, ductility and toughness etc. The engineering tensile test is commonly used to provide information about these characteristics of materials.

In the conventional engineering tensile test, an engineering stress-strain curve is constructed from the load versus elongation measurements applied the test specimen. The classical engineering stress curve of polyamide is shown in Figure 3.1.

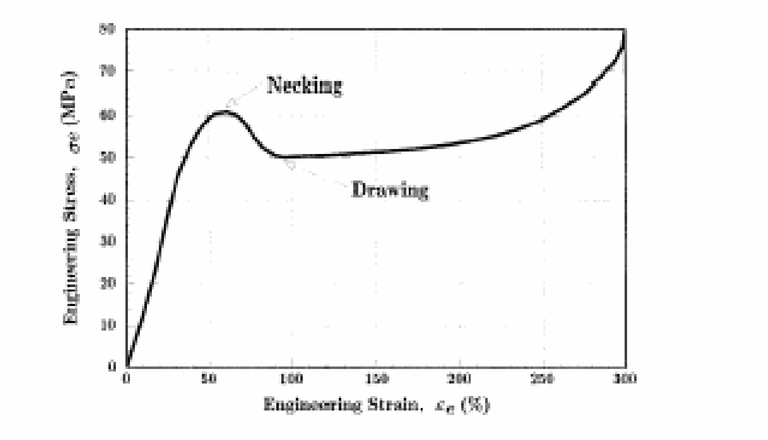

**Figure 3.1** Stress-strain curve for polyamide (nylon) thermoplastic [34].

In this curve, the engineering stress is the average longitudinal stress in the specimen which is obtained by dividing the load **(P)** by the original area of the cross section of the specimen (**Ao**) [35].

The strain is obtained by dividing the elongation by the gage length of the specimen by its original length [35].

The ultimate tensile strength, also called tensile strength, is the highest engineering stress reached prior to fracture. The engineering fracture strength is obtained from the maximum load even it is before fracture, since necking is observed usually the load during fracture is less [36].

In the elastic region for homogeneous isotrope lined materials, E is called modulus of elasticity or Young's modulus, which is the slope of the initial linear portion of the stress strain curve, is a measure of stiffness of the materials. An elastic strain decreases the packing density of the atomic array. In other words, the volume per atom is increased, as is the average interatomic spacing. An increase in the energy of the crystal must take place since the crystal in the no longer minimum binding energy. Hence, there is stored energy in an elastically deformed material [37]. Elastic strain reverses itself when the stress is removed. Nonlinearity in the curve is usually associated with stress-induced "plastic" flow in the specimen. Here the material undergoes to a rearrangement of its internal molecular or microscopic structure, in which atoms are being moved to new equilibrium positions. This plasticity requires a mechanism for molecular mobility, which in crystalline materials can arise from dislocation motion. Materials lacking this mobility, for instance by having internal microstructures that block dislocation motion, are usually brittle rather than ductile. The stress-strain curve for brittle materials is typically linear over their full range of strain, eventually terminating in fracture without appreciable plastic flow [34]. Plastic strain is permanent and it does not reverse itself when the stress is removed.

The yield strength is the stress required to produce a small specific amount of plastic deformation. The load at which the sudden drop occurs is called the upper yield point [35].

Strain hardening is the rise in the stress strain curve following yielding, as the material is increasing its resistance with increasing strain [36].

Initially, strain hardening is more than sufficient to compensate the thinning of the specimen. As the rate of the strain hardening decreases with increasing strain it no longer compensates this thinning. The point at which the thinning of the specimen is just balanced by the strain hardening, the specimen becomes plastically unstable and the specimen begins to neck down .Plastic flow is no longer uniform, it is concentrated in this necked region and failure occurs there see Figure 3.2 [37].

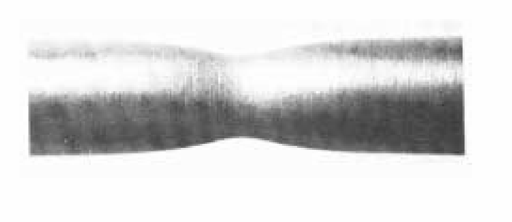

**Figure 3.2** Necking in a tensile specimen [37].

The polymer, however, differs dramatically from most ductile metals in that the neck does not continue shrinking until the specimen fails [38].

The toughness of a material is its ability to absorb energy and resist crack propagation and fracture. It can be considered to be the total area under the stress strain curve [39].The engineering fracture strain is one measure of ductility [36].

## 3.1 Motivation

Due to the favorable combination of easy abilities of processing and attractive mechanical properties, the use of polymer materials in structural applications has assumed large proportions over the last decades. To ensure proper operation under heavy duty conditions, these applications have to meet specific requirements regarding quality, safety, and mechanical performance [38]. Hemodialysis membranes made up of polymers used in clinical setting, are one of these important applications concerning a lot of patients who are exposed to dialysis treatment in order to continue their lives.

Since the dialyzers membrane function under pressure applied by blood, dialysate and the machine tensile, compressive and torsional forces occur on each membrane fibers. On the fibers; there are environmental effects on one hand, on the other internal and external pressures are available at 37 ºC. Pressure alterations by blood and dialysate lead to changing of these forces. In addition to these forces, turbulence of red blood cells causes frictional forces and higher tension on the surface of the fibers [39].

These forces in other words load and stress exerted on the fibers by blood and dialysate become serious from the mechanical point of view. Even at low stress levels, the mechanical behavior of polymers is often time dependent [40], so that creep, fatigue and fracture are expected to occur during 3-4 hour dialysis session. In addition to time dependency properties of polymers, pores on fibers should have to be taken into consideration seriously. Alterations may occur in size, shape and number of pores on each fiber. On the other hand hemodialysis membranes are exposed to chemical germicides for the reuse idea, these germicides may also cause morphological alterations on each fibers.

## 3.2 Experimental Technique

Instron 5569 Universal Testing Machine (Figure 3.2.1) being available in the Material Science and Engineering Department laboratories of Gebze Institute of Technology was used to run the mechanical test at room temperature. Mechanical tests were carried out on both virgin fibers and used-processed fibers obtained from the cutting procedure. Two types of mechanical tests were performed. One of them is monotonic loading until fracture, the other one is cyclic loading until fracture tensile test experiment.

Length of each fiber was measured and they were mounted on the machine with the help of sand paper at each end in order to make the specimen fixed Figure 3.2.2. Inner and outer diameters of specimens were entered to computer system.

In all experiments, the crosshead speed of Instron was kept constant at 50mm/min and the load cell of the machine was 5kN.

**Figure 3.2.1** Instron 5569 Universal Testing Machine.

**Figure 3.2.2** Specimen preparation.

## 3.3 Tensile Tests Results and Discussion

Monotonic loading tests performed on virgin polyamide hollow fibers were obtained by using Instron Universal Testing apparatus. Tests were repeated to validate the reproducibility of the results. Seven virgin polyamide hollow fibers were monotonically loaded until they ruptured. Stress strain curve of one fiber representing the average is shown in Figure 3.3.1.

In monotonic loading tensile test experiment of the fibers don't have an upper yield point as there are no decreases in the stress strain curve. In the inelastic region of all fibers, which begins after the elastic region, tensile stress increases gradually as the strain increases and finally reaches the ultimate strength as the maximum stress at the failure point but the rate of the increase is lesser in inelastic region than the linear elastic region. Strain hardening rate is higher in early regions of inelastic deformation but the rate of it decreases as the strain increases. In all fibers further elongation beyond the elastic region leads to increment in strain without forming a 'neck' and finally rupture of the material. The material behaves like a thermoplastic elastomer which is a soft and tough material.

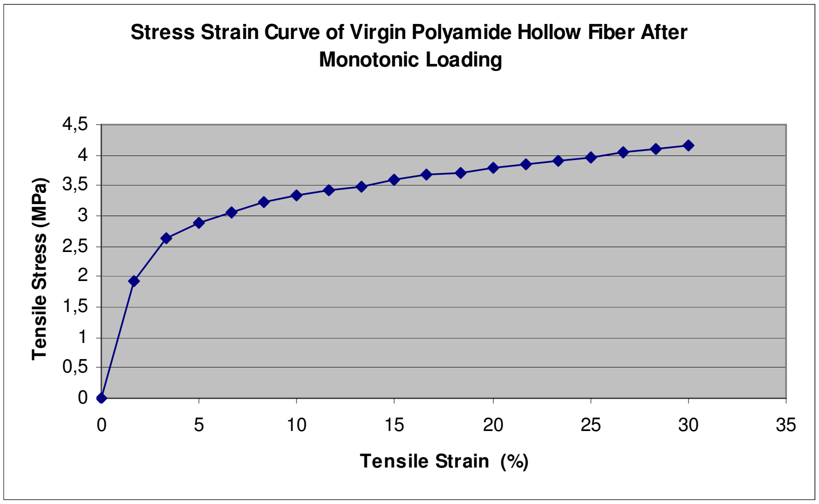

**Figure 3.3.1** Stress strain curves of virgin fiber after monotonic loading until fracture.

Cyclic loading tensile test experiments were performed on six virgin PA hollow fibers by using Instron Universal Testing Machine at room temperature in order to figure out exactly the effects of pressure applied by blood, dialysate and the machine on PA hollow membranes. Cyclic loading tensile tests were run in stress control until fifty percent of fracture stress. After 4 cycles, fifth loading was performed until fracture. At the fifth cycle the curve behaves like the monotonic loading experiment.

In all curves the strain gradually increases as the stress increases without forming a neck and it finally ruptures at the maximum tensile stress point. Tests were repeated to validate the reproducibility of the results. A sample representing the average stress strain curve of virgin polyamide hollow fiber after cyclic loading is seen in Figure 3.3.2. As in monotonic loading the fibers again don’t have an upper yield point stresses as the stresses continue to increase throughout the curves.

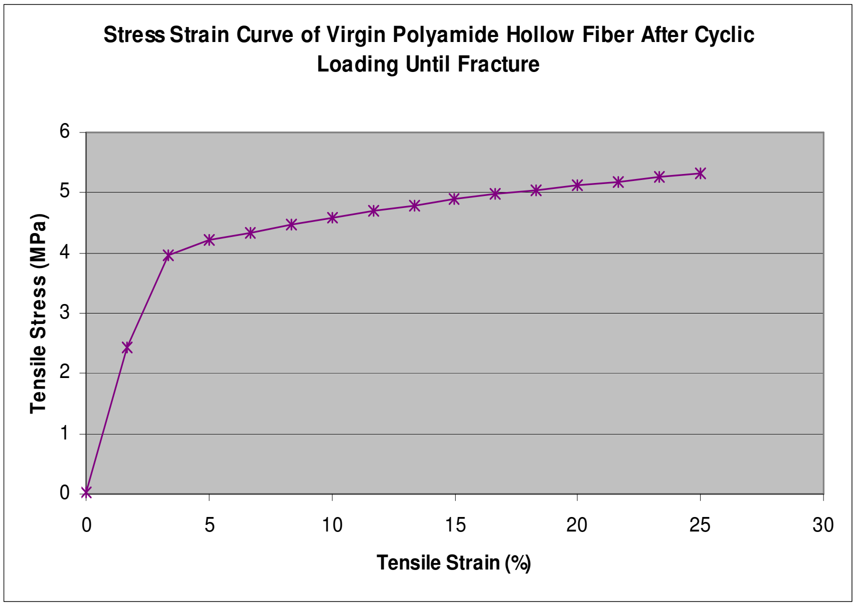

**Figure 3.3.2** Stress strain curve of virgin fiber after cyclic loading until fracture.

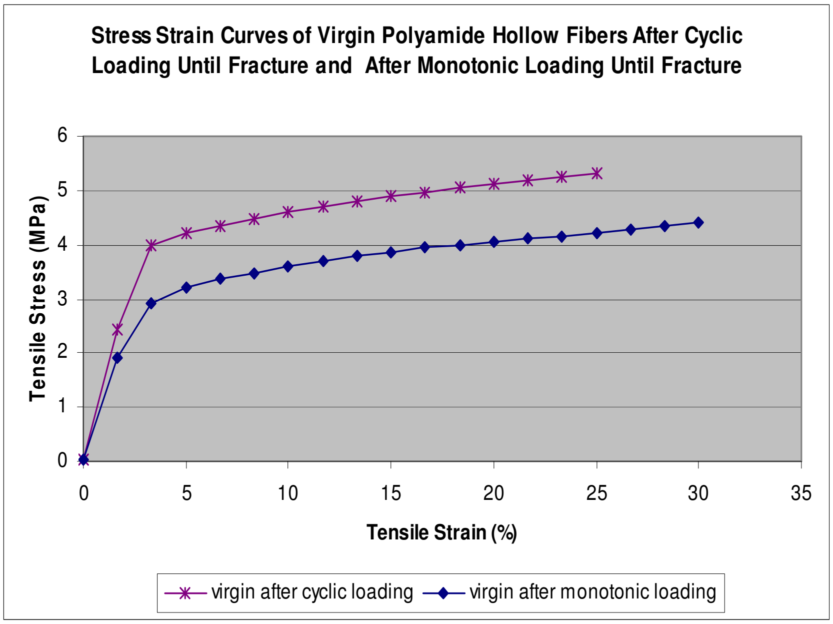

**Figure 3.3.3** Stress strain curves of virgin fiber after monotonic loading until fracture and after cyclic loading until fracture.

In Figure 3.3.3, stress strain curves of cyclic loading of virgin PA hollow fiber until fracture and stress strain curve of monotonic loading of virgin PA hollow fiber until fracture are seen together. Experimental analysis of these curves in terms of stress strain fracture and toughness is given in Table 3.3.1. It is easily observed from the Table 3.3.1 that, in cyclic loading there is an increase in yield stress imparted to the fiber by plastic deformation (strain hardening).

Energy absorbed during fracture, which is known as toughness, can be found by calculating the area under the stress strain curves of the fibers from the beginning of the experiments till the failure of the fibers. It is seen from Table 3.3.1 that toughness of the fiber that went under monotonic loading is greater than the other one. There is also decrease in ductility as well as toughness in cyclic loading experiment.

In cyclic loading, the stress at fracture point is greater than monotonic loading due to strain hardening but the percent strain is smaller than monotonic loading. Transition from ductility to brittle property is seen in cyclic loading. The fiber that went under cyclic loading experiment ruptures earlier than the other one. In other words, the strain at the failure point becomes smaller in cyclic loading which means that the fiber becomes weaker in cyclic loading experiment than in monotonic loading experiment.

**Table 3.3.1**

The analysis of Figure 3.3.3.

| | Tensile Strength (MPa) | Strain to Fracture (%) | Energy/Volume (MPa) |
|---|---|---|---|
| Virgin PA hollow fiber after monotonic loading | 4.396 | 30 | 189.247 |
| Virgin PA hollow fiber after cyclic loading | 5.26 | 23.332 | 173.282 |

Stress strain curves of used and processed polyamide hollow fibers were obtained by using Instron Universal Testing apparatus. Tests were repeated to validate the reproducibility of the results. An example representing the average of stress strain curve of used and processed polyamide hollow fiber after monotonic loading is given in the corresponding Figure 3.3.4.

It is seen from the Figure 3.3.4 that, the rate of strain hardening is not homogeneous in inelastic region. After rapid increase of stress in elastic deformation, yielding was followed by high strain hardening and a relatively lower strain hardening rate followed this region. Thus, it can be said that resistance to plastic deformation decreased close to fracture point.

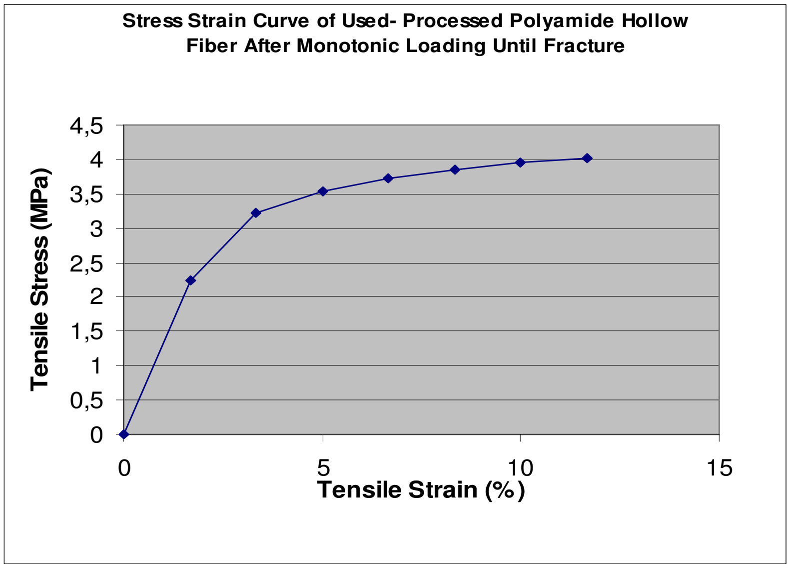

**Figure 3.3.4** Stress strain curve of used-processed hollow fiber after monotonic loading until fracture.

Figure 3.3.5 shows the stress strain curves of used-processed fiber and virgin fiber after monotonic loading until fracture during tensile test experiment. Results of these curves are given in Table 3.3.2. The curve that has longer elongation corresponds to virgin fiber and the curve that has smaller elongation corresponds to used-processed fiber. It is easily seen from the graph that stress at the fracture point of used fiber decreased and also there is a great decrease in the percent strain at the fracture point of used fiber. There are drops in toughness and ductility as well as stress and strain at fracture point.

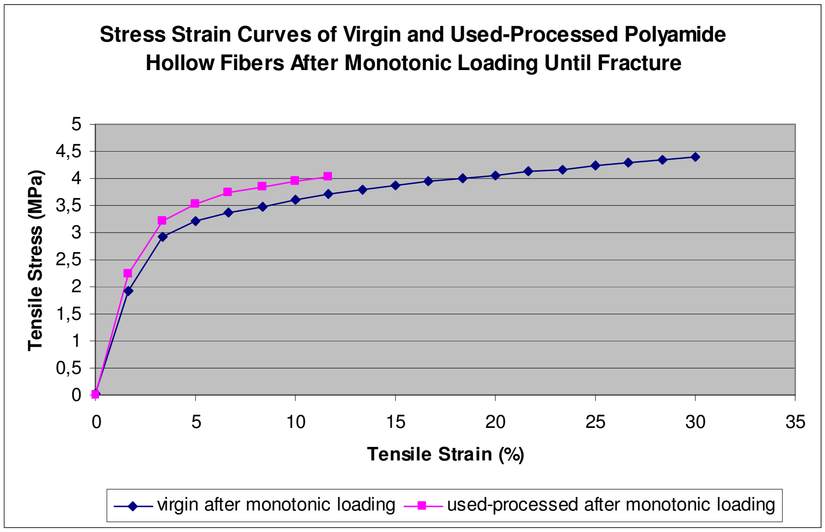

**Figure 3.3.5** Stress strain curves of virgin and used-processed hollow fibers after monotonic loading.

**Table 3.3.2**

The analysis of Figure 3.3.5.

| | Tensile Strength (MPa) | Strain to Fracture (%) | Energy/Volume (MPa) |
|---|---|---|---|
| Virgin PA hollow fiber after monotonic loading | 4.396 | 30 | 189.247 |
| Used-processed PA hollow fiber after monotonic loading | 4.025 | 11.666 | 32.938 |

Cyclic loading experiments in tension were performed on four used-processed polyamide hollow fibers. Tests were repeated to validate the reproducibility of the results. A sample representing the average is given in Figure 3.3.6.

In all experiments there are no upper yield points. After yielding, there is a rapid increase in strain hardening following this region rate of strain hardening becomes smaller close to fracture stress.

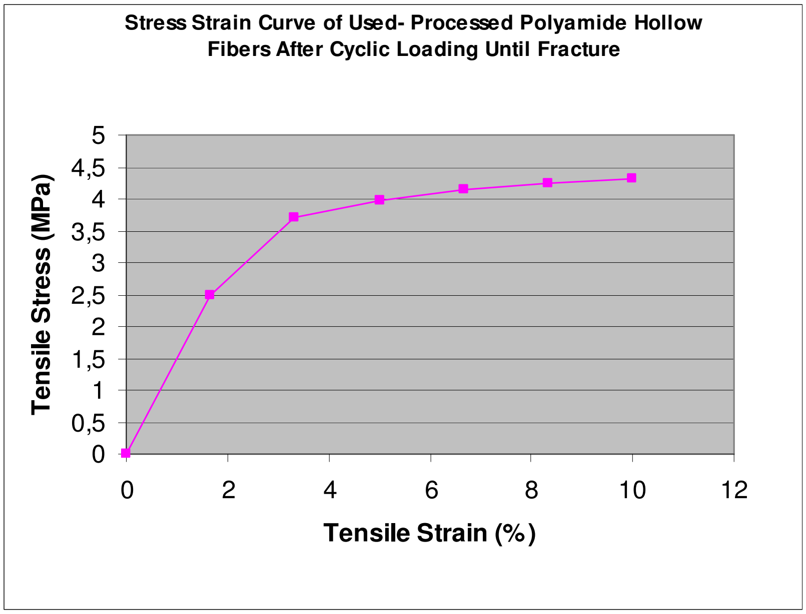

**Figure 3.3.6** Stress strain curve of used-processed hollow fiber after cyclic loading.

Stress strain curves of used-processed fiber after cyclic loading until fracture and stress strain curve of used-processed fiber after monotonic loading are seen together in the corresponding Figure 3.3.7. Experimental analysis results are shown in Table 3.3.3. In early regions of plastic deformation, strain hardening rate is higher in cyclic loading than that of monotonic loading. In cyclic loading, the stress and strain at fracture are less than that of the monotonic loading. There are also drops in toughness and ductility in cyclic loading with respect to monotonic loading of used fiber. In other words, more energy is needed in monotonic loading in order to get the same deformation occurring in cyclic loading.

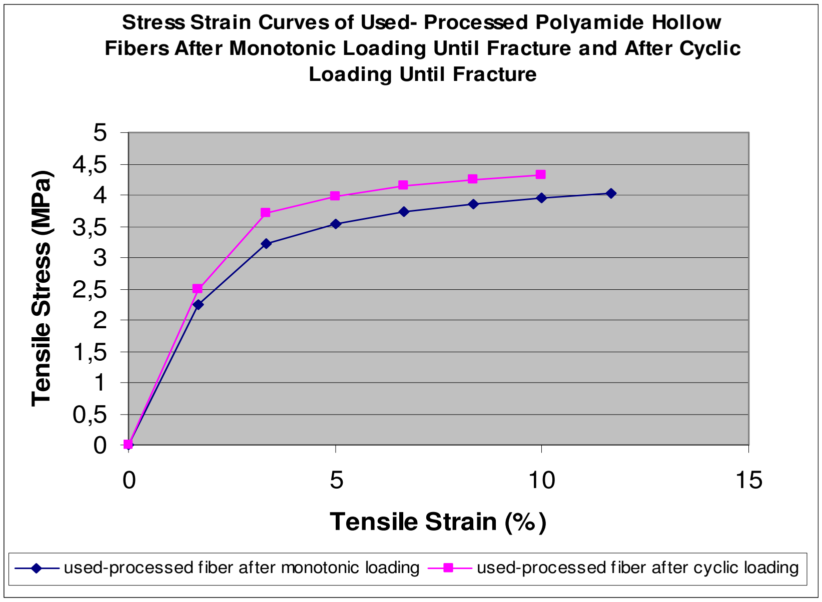

**Figure 3.3.7** Stress strain curves of used- processed polyamide hollow fibers after monotonic loading until fracture and after cyclic loading until fracture.

**Table 3.3.3**

The analysis of Figure 3.3.7.

| | Tensile Strength (MPa) | Tensile Strain (%) | Energy/Volume (MPa) |
|---|---|---|---|
| Used-processed PA hollow fiber after monotonic loading | 4.025 | 11.666 | 32.938 |
| Used-processed PA hollow fiber after cyclic loading | 4.327 | 9.999 | 26.09 |

The stress strain curve of virgin fiber after cyclic loading and the stress strain curve of used-processed fiber after cyclic loading are shown together in Figure 3.3.8. Analysis of the test results are given in Table 3.3.4. There is less plastic deformation in used-processed fiber which means that the used fiber becomes more brittle than the virgin one does. Used-processed fiber also ruptures earlier than the virgin one in other words used-processed fiber becomes weaker than the virgin one. There is also decrease in stress and strain at fracture in used-processed fiber. In addition to these, big drops in toughness and ductility are observed in used-processed fiber.

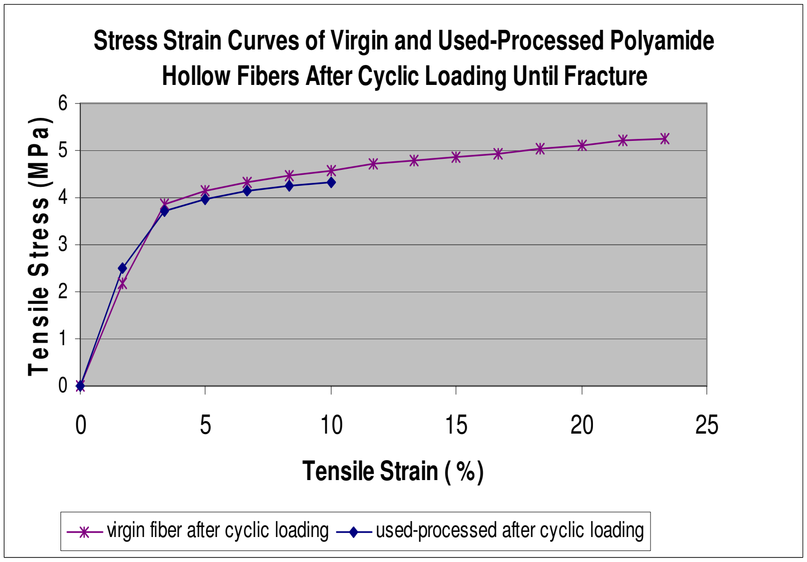

**Figure 3.3.8** Stress strain curves of virgin and used-processed fibers after cyclic loading until fracture.

**Table 3.3.4**

The analysis of Figure 3.3.8.

| | Tensile Strength (MPa) | Strain to Fracture (%) | Energy/Volume (MPa) |
|---|---|---|---|
| Virgin PA hollow fiber after cyclic loading | 5.26 | 23.332 | 173.282 |
| Used-processed PA hollow fiber after cyclic loading | 4.327 | 9.999 | 26.09 |

## 3.4 Discussion and Conclusion on Mechanical Tests Results

Polyamide hollow fibers used as membrane are manufactured with mechanical defects intentionally. Mechanical defects decrease mechanical parameters. In all mechanical tests, the fibers rupture without forming a neck.

In the case of PA hollow fibers used in the dialysis system even spherical or circular pores due to deformation become elliptical. Because of this reason local stress concentrations on the long axis of ellipse increase which in turn cause easy crack initiation and crack propagation. Thus, mechanical defects increase brittleness of the materials.

In the case of PA hollow fibers used in the dialysis system chemical attacks due to dialysis environment and processing for reuse application superposes on mechanical effects. Therefore samples being 'used-processed' toughness and ductility of the material decreases. In the case of cyclic stresses, the degree of decrease of toughness and ductility is higher.

# 4. SURFACE STUDIES

It is expected that pressure causes the surface morphology and structure of the fibers and can also have effect on the functioning of the fibers. On the other hand in addition to harsh dialysis environment such as blood and applied pressure, reuse solution can also change the morphological structure which may lead to decrease in efficiency of the dialysis. Surface structure, pore geometries and also the fracture surfaces of the virgin and used-processed membranes were studied by the help of scanning electron microscope (SEM) and also atomic force microscope (AFM) in order to reveal the structural changes between virgin and used-processed fibers.

SEM and AFM are the most two common methods in laboratories in order to get a high resolution surface investigations. Although they both give information about the surface topography, they work in different principles and provide different kinds of information. By the help of SEM, it is possible to observe not only the pores outside but also the pores far from the top surface. However, SEM fails to give information about the height of the surface whether it is smooth or rough. Thanks to AFM that it provides the vertical surface variations by giving three dimensional images. Since SEM and AFM provide different kinds of surface investigations which in turn complement each other, both of these techniques were used in this study to investigate the surface structure. In order to figure out the effects of dialysis environment and reuse solution on surface structure, SEM and AFM studies were performed on both virgin and used-processed hollow fibers.

SEM studies were performed on both virgin and used-processed hollow fibers after tensile test experiments in order to observe the effects of reuse solution together with the hemodialysis environment on surface structure of the fiber, pore morphology, fracture surface and also membrane thickness. AFM studies were performed on virgin and used-processed hollow fiber in order to investigate the vertical alterations of the surface in terms of smoothness and roughness. Stereo microscope is a useful tool in order to observe the bundle configuration of the fibers and the diameter of the fibers.

## 4.1 Stereo Microscopy Studies

Stereo microscopy studies were performed on virgin polyamide hollow fiber membranes in order to observe the diameter of a fiber and the bundle configuration of the hollow fibers by Olympus stereo microscope being available at Istanbul Technical University.

**Figure 4.1.1** Olympus stereo microscope.

The outer diameter of a virgin fiber is 315 μm [41]. The lateral view of a virgin fiber is visualized in Figure 4.1.2.

**Figure 4.1.2** Lateral view of a virgin hollow fiber.

Homogeneous blood and dialysate flow distribution improve small solute clearances, which can be achieved by modifying the configuration of the filter bundle [42]. The vertical and lateral view of bundle configuration of a virgin membrane is visualized in Figure 4.1.3 and in Figure 4.1.4, respectively. Different systems of non-parallel orientation of the fibers may help to maintain adequate distances between the external surface of adjacent fibers and to permit a more homogeneous distribution of the dialysate flow [43]. Non-uniform orientation of fibers in the bundle configuration observed in Figure 4.1.3 and in Figure 4.1.4 leads to increase of surface contact area between the membrane, blood and the dialysate. Increase in surface contact area provides more efficient dialysis.

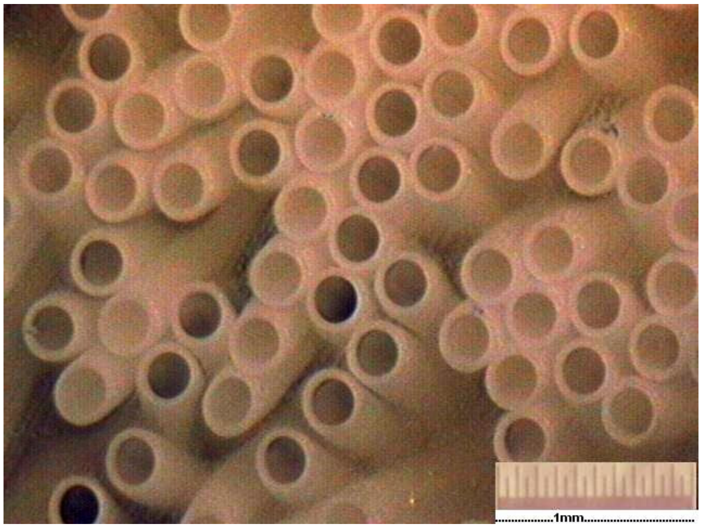

**Figure 4.1.3** Vertical view of bundle configuration of virgin hollow fibers membrane.

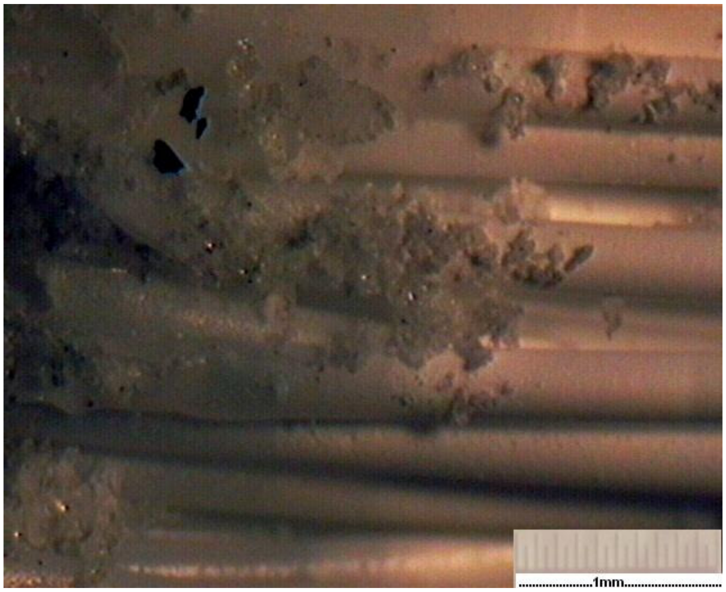

**Figure 4.1.4** Lateral view of bundle configuration of virgin hollow fibers membrane.

## 4.2 Scanning Electron Microscopy Studies

JEOL JSM-6060LV scanning electron microscope being available in Sakarya University was used to run scanning electron microscopy studies. Before the specimens went into SEM, they were gold coated by using Polaron SC7620 sputter coater in order to prevent the accumulation of static electron charge at the surface. Studies were performed on fracture surfaces and lateral surfaces of both virgin and used-processed hollow fibers after tensile test experiments. SEM studies were also performed on lateral surface of virgin hollow fiber on which no mechanical tests were performed.

SEM studies on the lateral surface of virgin hollow with different magnifications are seen in Figure 4.2.1 and in Figure 4.2.2.

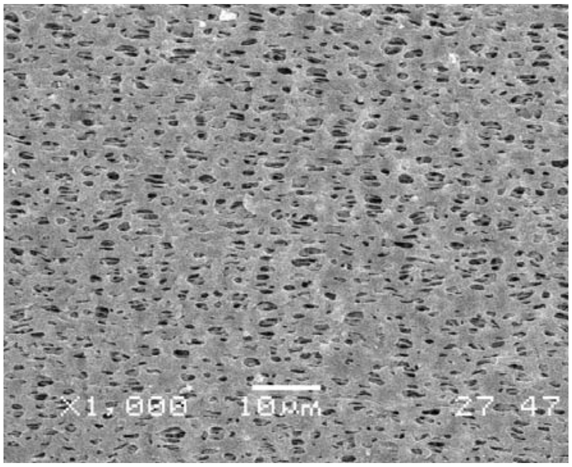

**Figure 4.2.1** Lateral side view of virgin polyamide hollow fiber

Pores with different magnitudes distributed throughout the surface are visualized in Figure 4.2.1. Figure 4.2.2 shows the inner morphology of the pores. From outside to the inside of the surface, different pore sizes and pore distributions are visualized. There are also some thin ligaments far from the top surface connecting the nearby two pores.

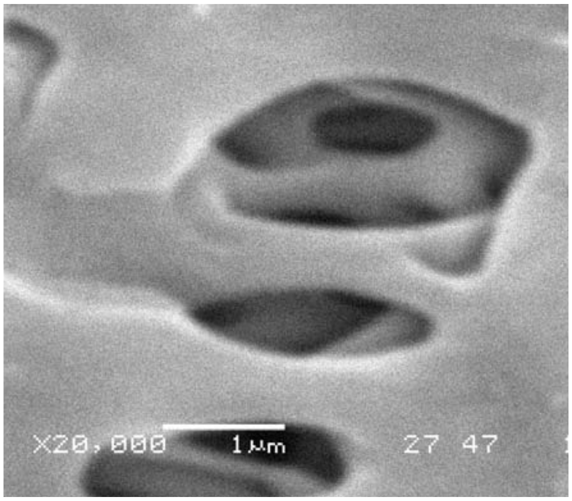

**Figure 4.2.2** Lateral surface view of virgin hollow fiber.

The lateral surfaces of virgin hollow fiber after monotonic loading until fracture test are visualized in Figure 4.2.3 and in Figure 4.2.4. Defects due to monotonic loading on the surface morphology are revealed in Figure 4.2.3. When lateral surface view of virgin hollow fiber (Figure 4.2.2) and lateral surface of virgin hollow fiber after monotonic loading until fracture (Figure 4.2.4) are compared together it is observed that pore shapes become more elliptical after monotonic loading.

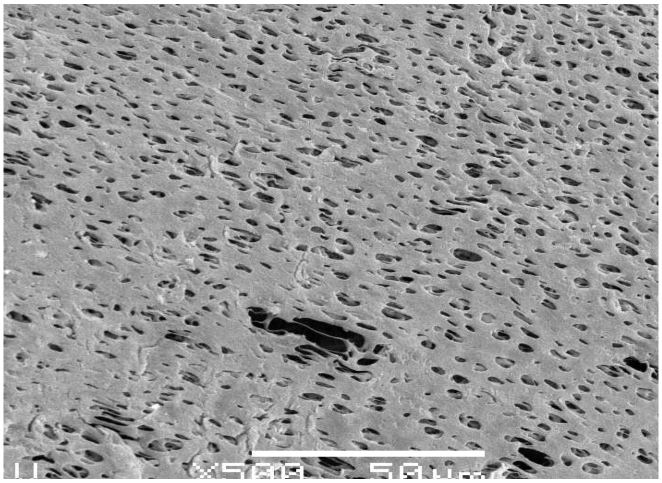

**Figure 4.2.3** Lateral surface of virgin hollow fiber after monotonic loading until fracture test.

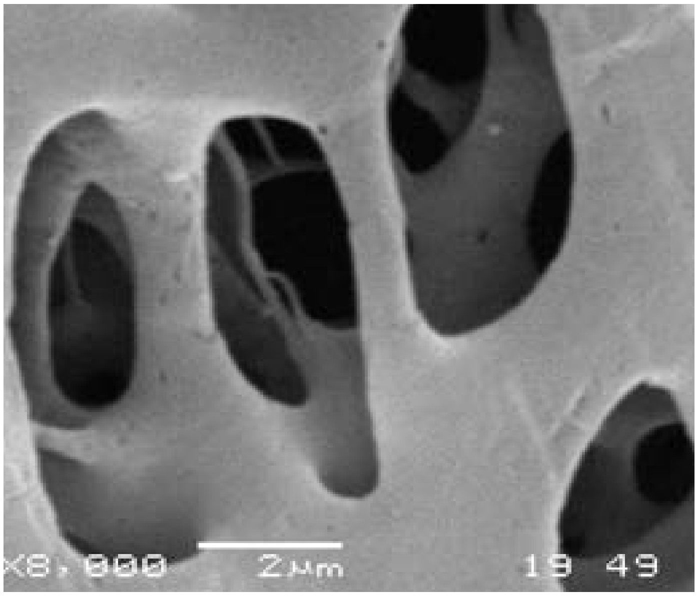

**Figure 4.2.4** Lateral surface of virgin hollow fiber after monotonic loading until fracture test.

The lateral surfaces far from fracture of virgin hollow fiber after monotonic loading are seen in Figure 4.2.5 and in Figure 4.2.6.

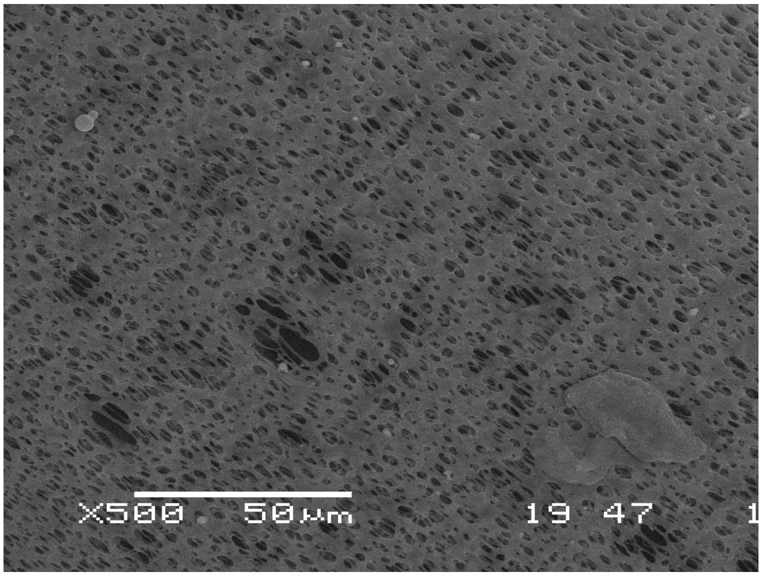

**Figure 4.2.5** Lateral surface far from fracture of virgin hollow fiber after monotonic loading.

Defects are easily visualized in Figure 2.4.5 and elliptical pore shapes are observed in Figure 4.2.6.

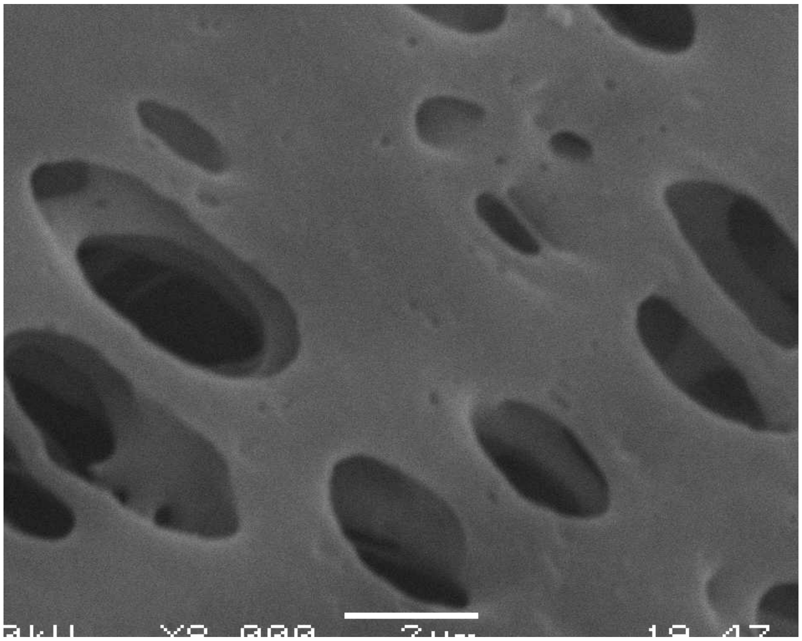

**Figure 4.2.6** Lateral surface far from fracture of virgin hollow fiber after monotonic loading until fracture.

SEM studies performed on lateral surface of virgin hollow fiber after cyclic loading until fracture test are visualized in Figure 4.2.7. Defects and damages due to cyclic stressing and big pores due to merging of pores are easily visualized in Figure 4.2.7. SEM studies performed on lateral surface far from fracture of virgin hollow fiber after cyclic loading are seen in Figure 4.2.8, and in Figure 4.2.9.

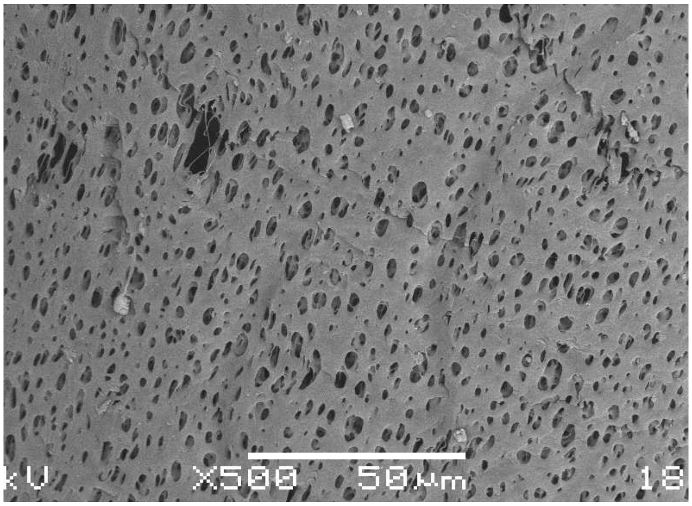

**Figure 4.2.7** Lateral surface of virgin hollow fiber after cyclic loading until fracture.

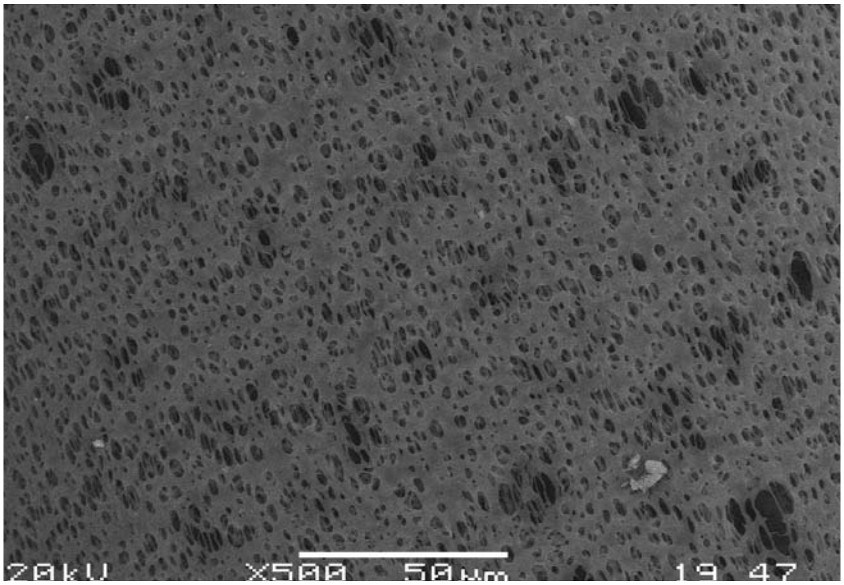

**Figure 4.2.8** Lateral surface far from fracture of virgin hollow fiber after cyclic loading.

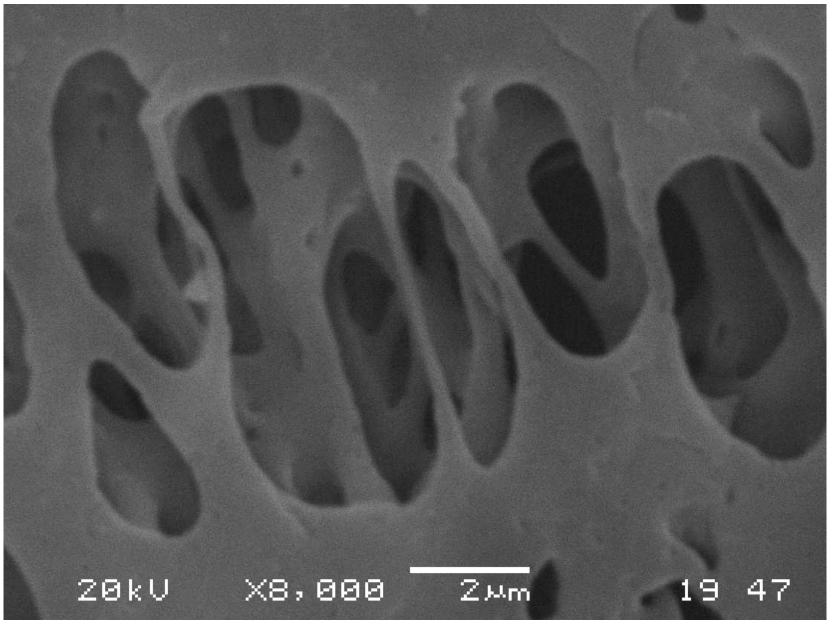

**Figure 4.2.9** Lateral surface far from fracture of virgin hollow fiber after cyclic loading.

Defects such as big ruptures and big pores due to stress created by cyclic loading tensile test are easily seen in Figure 4.2.8. Elongated pores are easily visualized in Figure 4.2.9 and also Figure 4.2.9 shows that pores become closer at each other by forming thin ligaments because of the stress created by loading unloading reloading test. Figure 4.2.6 and Figure 4.2.9 show that becoming close to the fracture surface the pore shape turn into a more elliptical shape. This illustrates that elliptical pore shape is more prone to rupture than the circular one. When the lateral surfaces of virgin hollow fibers after monotonic loading (Figure 4.2.6) and cyclic loading (Figure 4.2.9) tensile tests, it is observed that pore shapes become more elliptical and also the ligaments connecting the nearby two pores become thinner in Figure 4.2.9.

SEM studies on the fracture surface of virgin hollow fibers after monotonic loading are seen in Figure 4.2.10, Figure 4.2.11 and in Figure 4.2.12.

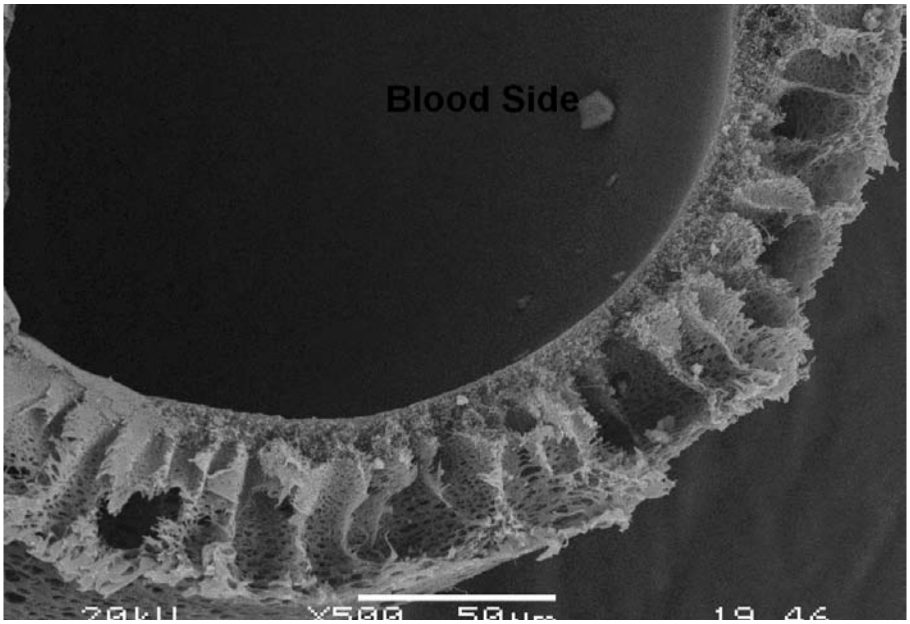

**Figure 4.2.10** Fracture surface of virgin hollow fiber after monotonic loading.

Pores with different magnitudes are seen in Figure 4.2.10, Figure 4.2.11 and in Figure 4.2.12. Decreasing of pore size from the dialysate side to the blood side is clearly seen in Figure 4.2.11. Even close to the blood side, defects and big pores are seen in Figure 4.2.10, Figure 4.2.11 and in Figure 4.2.12. Figure 4.2.12 also reveals a big hole resulting from rupturing of ligaments between the pores.

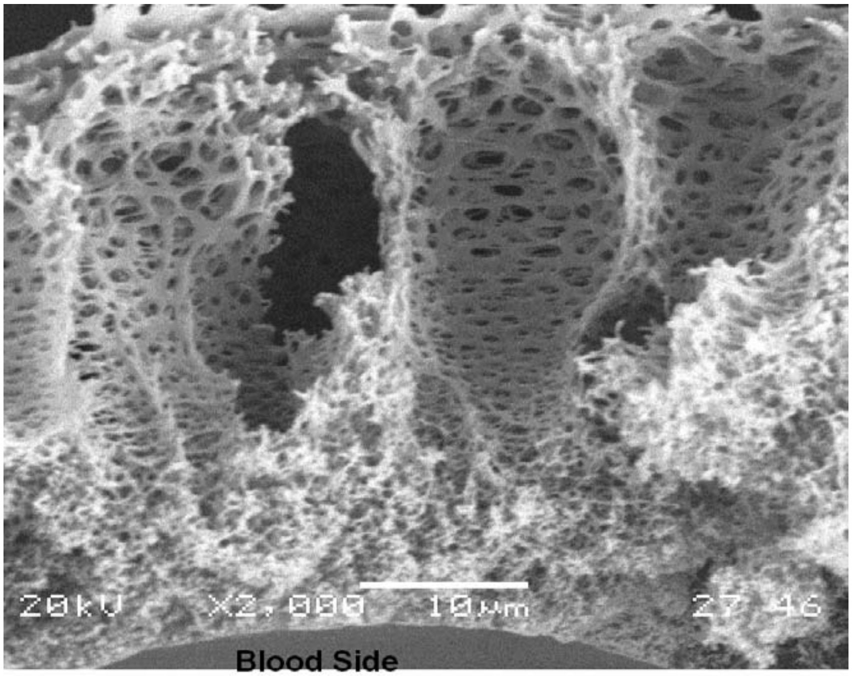

**Figure 4.2.11** Fracture surface of virgin hollow fiber after monotonic loading.

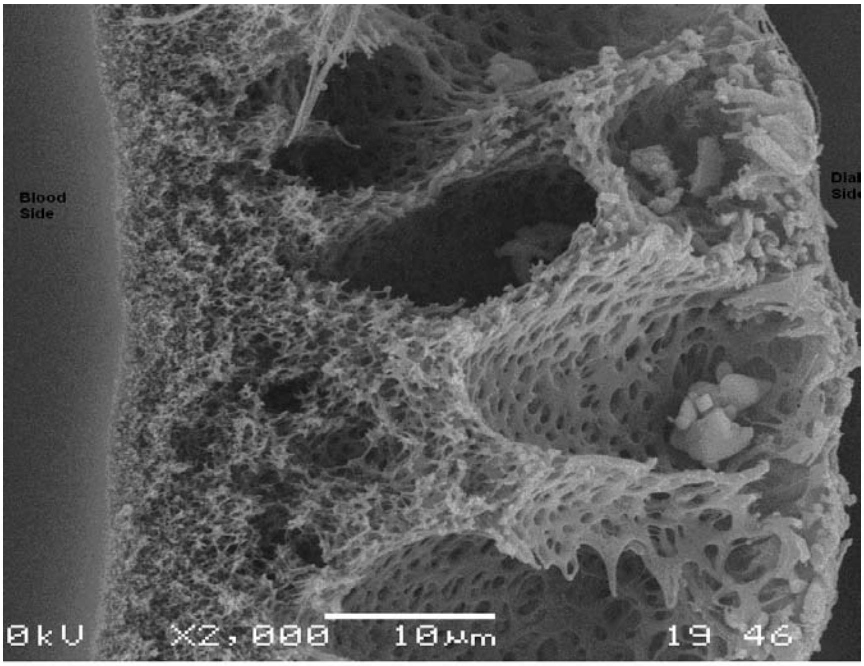

**Figure 4.2.12** Fracture surface of virgin hollow fiber after monotonic loading.

SEM studies performed on fracture surface of virgin hollow fiber after cyclic loading test are seen in Figure 4.2.13, Figure 4.2.14, Figure 4.2.15 and Figure 4.2.16. Big elongated pores and also big ruptures are seen in Figure 4.2.13, Figure 4.2.14, Figure 4.2.15 and Figure 4.2.16. Merging of pores are easily visualized in Figure 4.2.13 even close to blood side, defects are visualized in Figure 4.2.13, Figure 4.2.14 and in Figure 4.2.15.

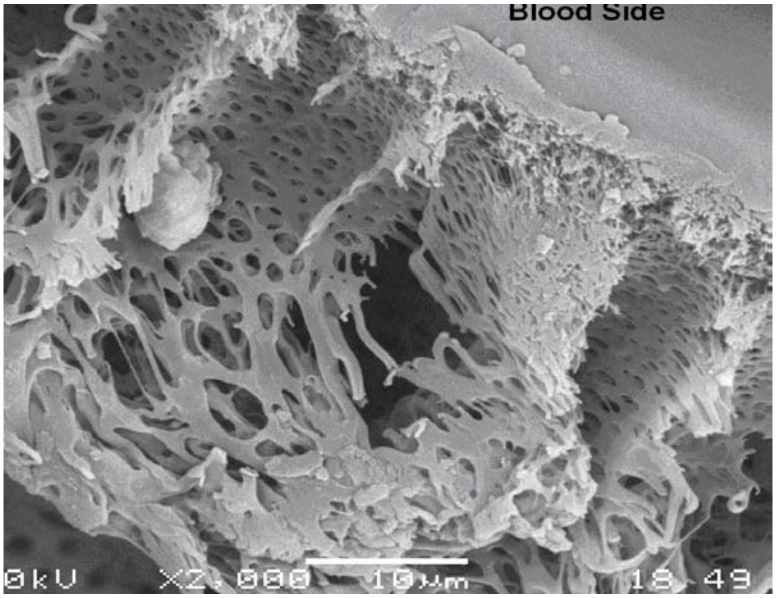

**Figure 4.2.13** Fracture surface of virgin hollow fiber after cyclic loading.

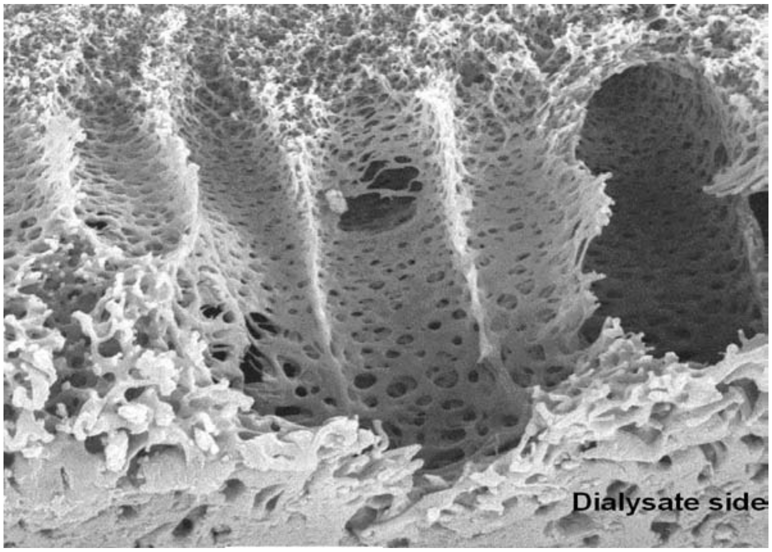

**Figure 4.2.14** Fracture surface of virgin hollow fiber after cyclic loading.

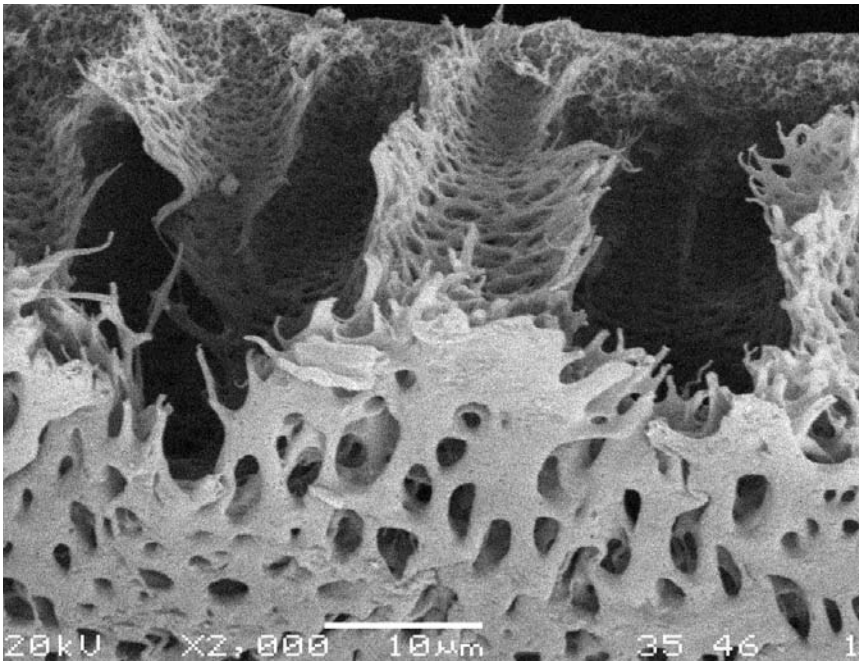

**Figure 4.2.15** Fracture surface of virgin hollow fiber after cyclic loading until fracture.

SEM studies performed on lateral surface of used-processed hollow fiber after monotonic loading are visualized in Figure 4.2.16 and in Figure 4.2.17.

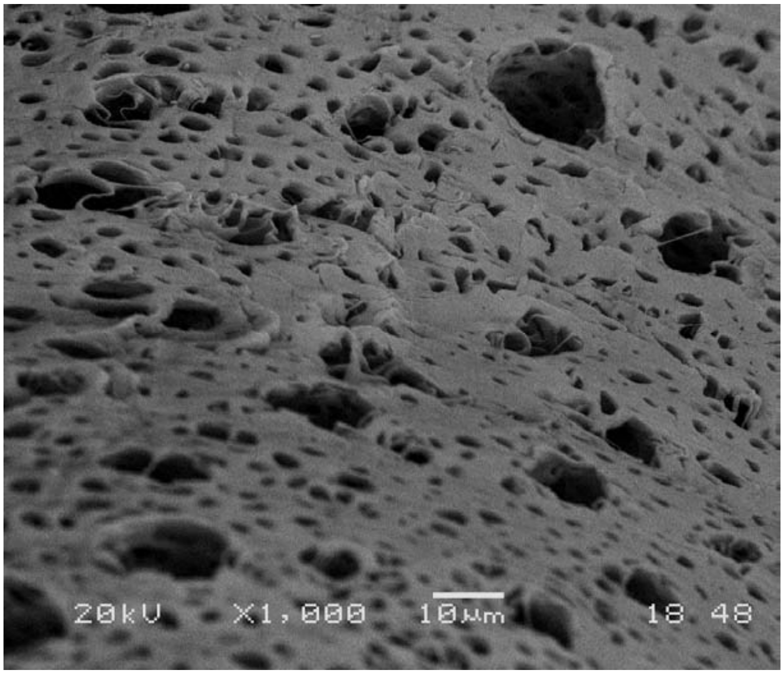

**Figure 4.2.16** Lateral surface of used-processed hollow fiber after monotonic loading.

In addition to stress, chemical attacks caused merging of pores that created big holes as seen in Figure 4.2.16. Figure 4.2.17 figures out the changing of pore shapes and thinning of ligaments between the nearby two pores. When the lateral surface of virgin hollow fiber after monotonic loading (Figure 4.2.3) and lateral surface of used-processed hollow fibers (Figure 4.2.16) are compared together, the effect of chemical attack is visualized. Pore sizes become bigger and the number of merging of pores and also the degree of pore merging increases in used-processed hollow fiber after monotonic loading (Figure 4.2.16).

SEM studies on lateral surface far from fracture of used-processed hollow fiber after monotonic loading are visualized in Figure 4.2.18.

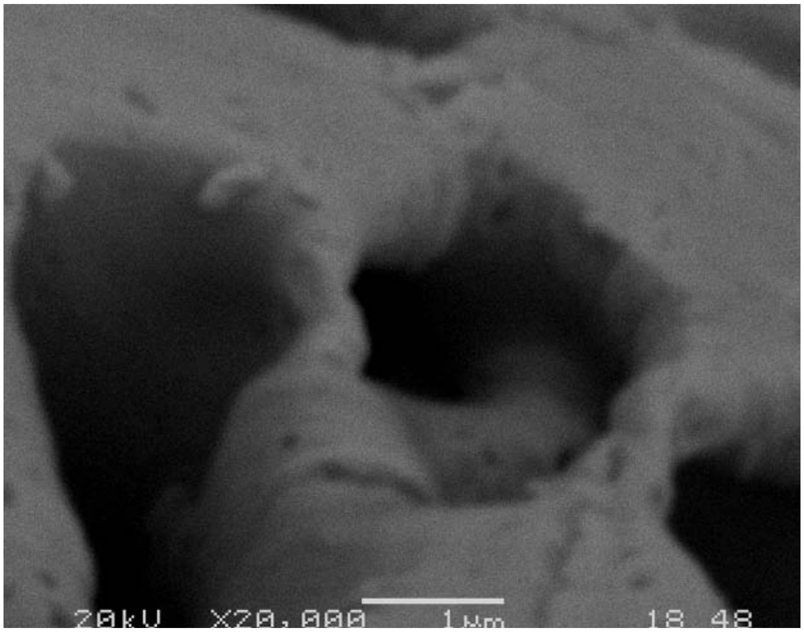

**Figure 4.2.17** Lateral surface of used-processed hollow fiber after monotonic loading.

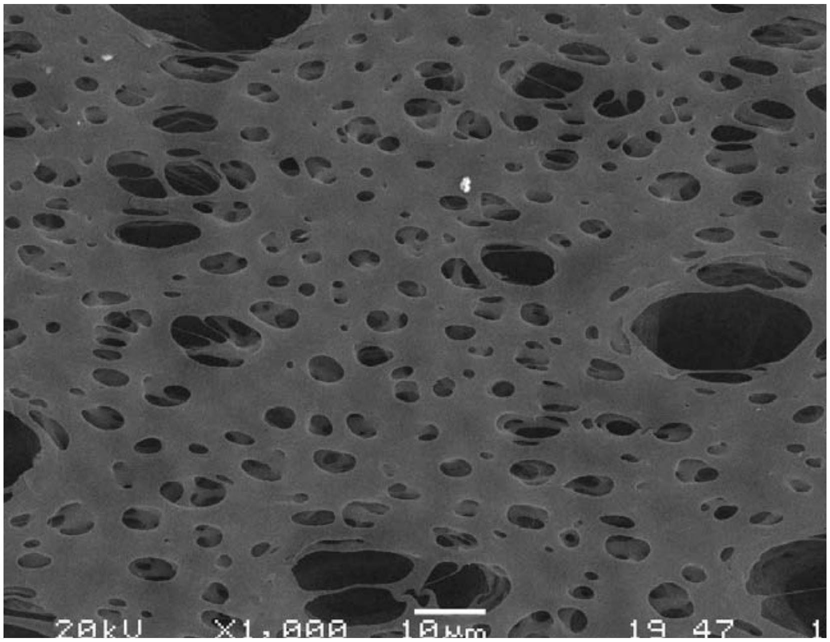

**Figure 4.2.18** Lateral surface far from fracture of used-processed hollow fiber after monotonic loading.

Even far from fracture surface, merging of pores on the lateral surface of the fiber are seen in Figure 4.2.18. In addition to dialysis environment, chemical attacks also affect the inner pore morphology. Merging of pores is also visualized in the inner side of the lateral surface in Figure 4.2.18.

SEM studies performed on the fracture surface of used-processed hollow fiber are visualized in Figure 4.2.19 and in Figure 4.2.20. Big cracks, elliptical pores and merging of pores are seen in Figure 4.2.19 and in Figure 4.2.20. Decrease in thickness diameter is observed in Figure 4.2.20 when it is compared with Figure 4.2.12. Even close to the blood side, rupturing of ligaments and merging of pores is also visualized in Figure 4.2.20.

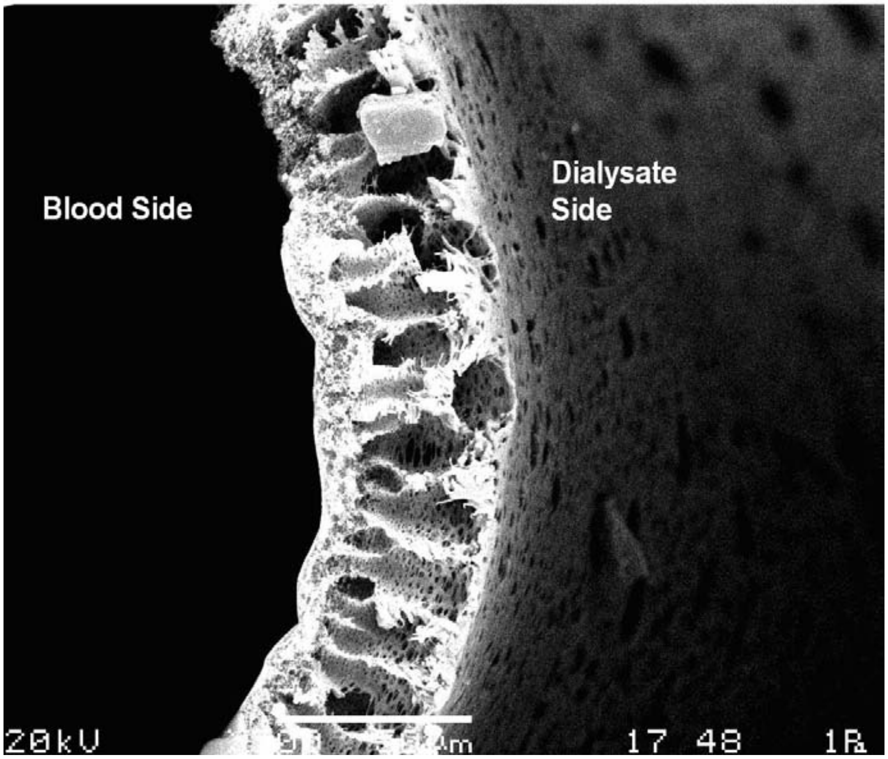

**Figure 4.2.19** Fracture surface of used-processed hollow fiber after monotonic loading.

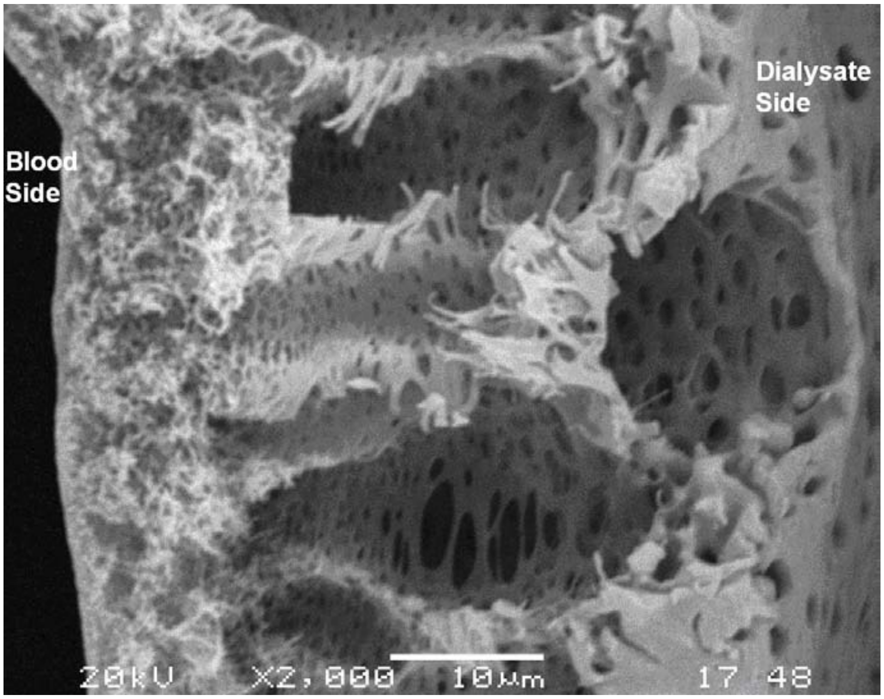

**Figure 4.2.20** Fracture surface of used-processed hollow fiber after monotonic loading.

SEM studies performed on the lateral surface of used-processed hollow fiber after cyclic loading are seen in Figure 4.2.21.

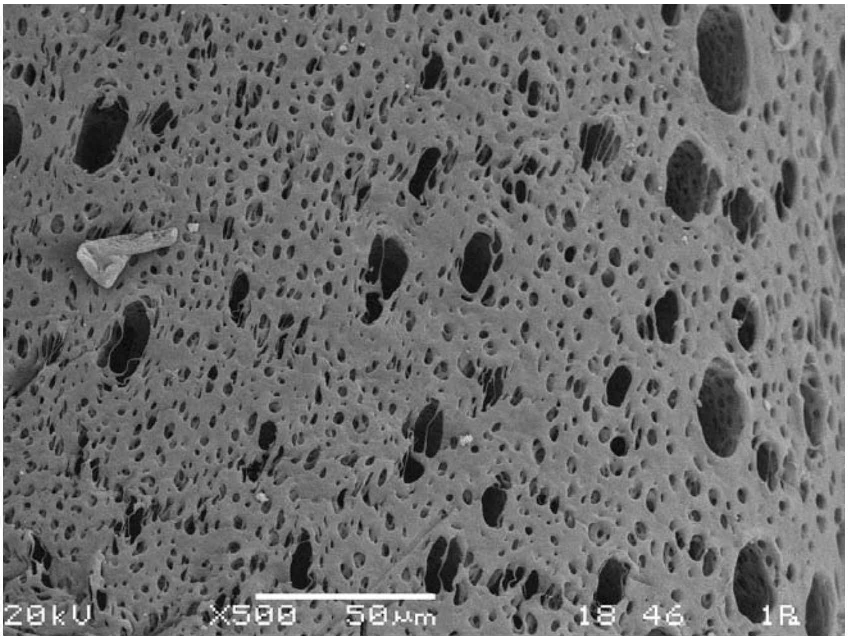

**Figure 4.2.21** Lateral surface of used-processed hollow fiber after cyclic loading.

Pore merging due to dialysis environment, stress created by mechanical test and also chemical attack, caused big deep holes in Figure 4.2.21. Pore merging and big holes are also visualized inside the pores.

SEM studies performed on lateral surface far from fracture of used-processed hollow fiber after cyclic loading are seen in Figure 4.2.22, Figure 4.2.23, and in Figure 4.2.24.

Big deep holes due to pore merging throughout the surface are visualized in Figure 4.2.22 and in Figure 4.2.23. Figure 4.2.24 reveals merging of pores on both outside surface and also on the pores inside.

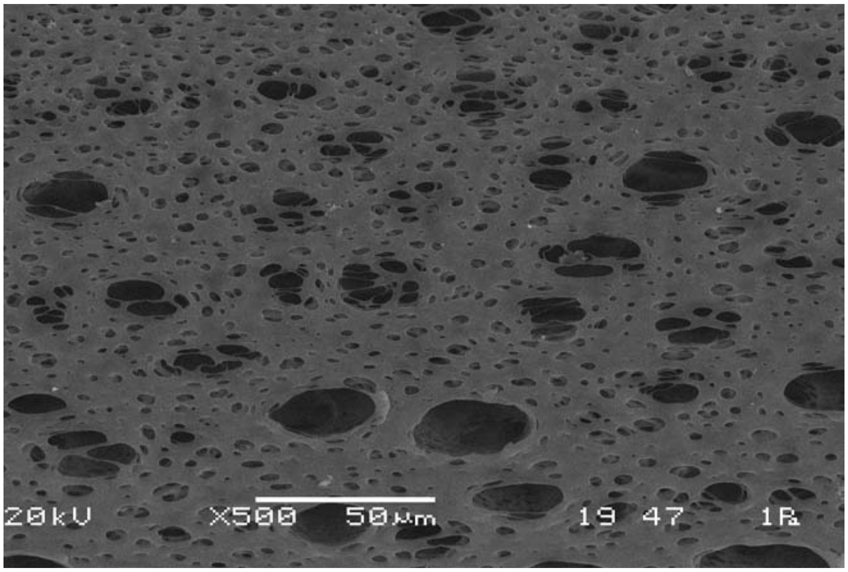

**Figure 4.2.22** Lateral surface far from fracture of used-processed hollow fiber after cyclic loading.

When the lateral surfaces far from fracture surface of virgin (Figure 4.2.8, Figure 4.2.9)and used-processed fibers (Figure 4.2.23) after cyclic loading tensile test experiments are compared together, it is observed that the pore size increases and also there are more bigger holes due to merging of pores in used-processed fibers. In used-processed fibers the pore shapes are more circular than pores of virgin fibers. Since the fibers become weaker because of chemical attack and hemodialysis environment, the ligaments rupture easier than the virgin fibers' so the pores merge and bigger circular holes occur.

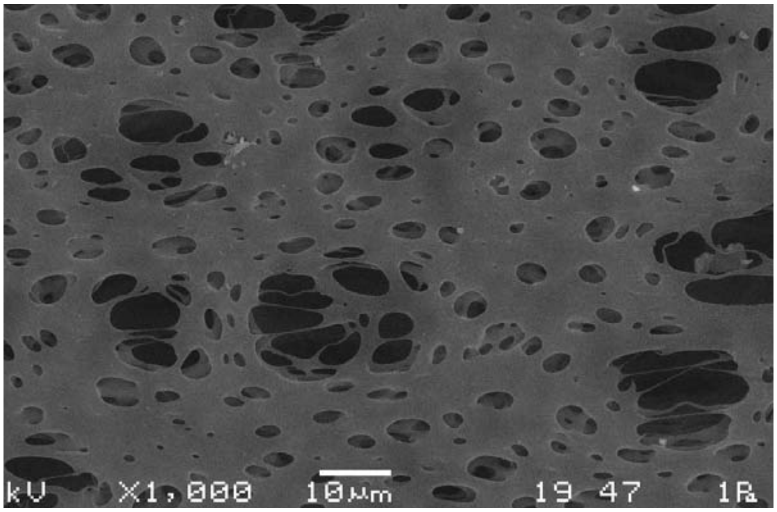

**Figure 4.2.23** Lateral surface far from fracture of used-processed hollow fiber after cyclic loading.

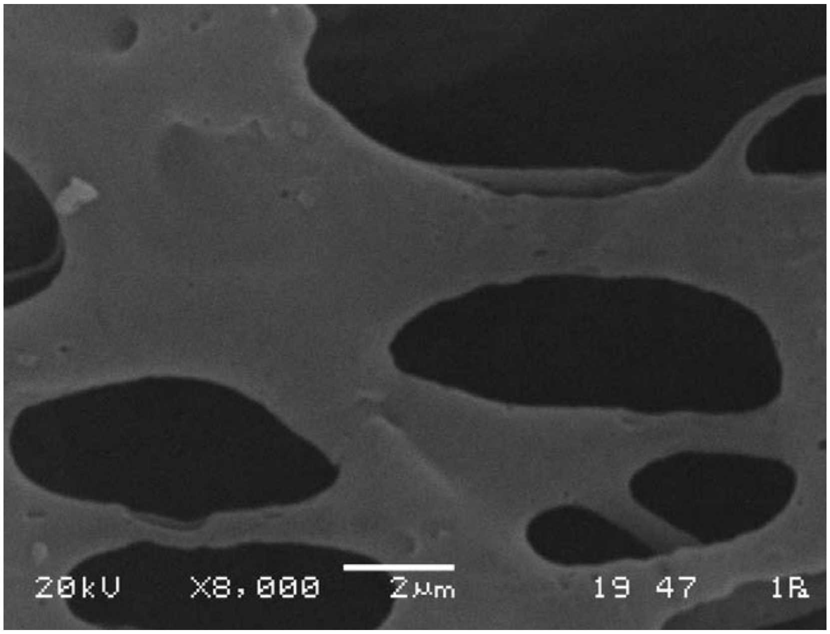

**Figure 4.2.24** Lateral surface far from fracture of used-processed hollow fiber after cyclic loading.

SEM studies on the fracture surface of used-processed hollow fiber after cyclic loading are visualized in Figure 4.2.25 and in Figure 4.2.26.

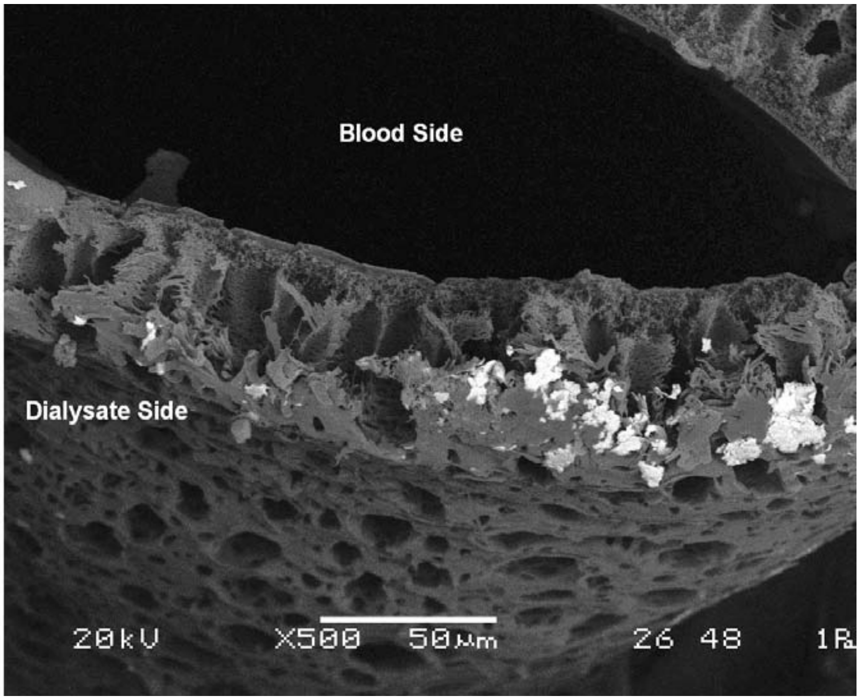

**Figure 4.2.25** Fracture surface of used-processed hollow fiber after cyclic loading.

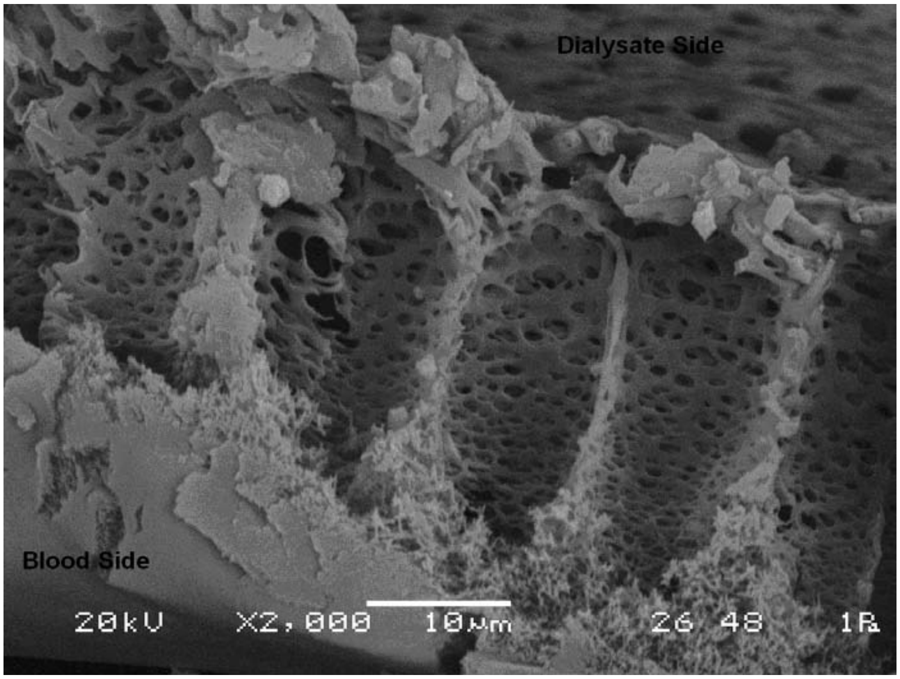

**Figure 4.2.26** Fracture surface of used-processed hollow fiber after cyclic loading.

Merging of pores and ruptures are visualized in Figure 4.2.25 and in Figure 4.2.26. There are also some residues from processing procedure on the fracture surface in Figure 4.2.25. Figure 4.2.26 also reveals the cracks elongating inside the blood side of the fiber and deformation of pores close to the blood side. Pores on the blood side can not be visualized due to limited capacity of the microscope.

## 4.3 Atomic Force Microscopy Studies

AFM studies operating at non-contact modes were performed on virgin and used-processed fibers by using Q Scope Universal SPM atomic force microscopy being available in Sakarya University.

AFM studies on both the virgin and used-processed fiber's outer wall surfaces give high resolution surface topographical information. AFM studies are especially important since they provide 3-dim images and reveal the data of the surface altitude. Images taken on the dialysate contact surface of virgin fibers are displayed with different magnifications in Figure 4.3.1, and Figure 4.3.2 in three dimensions. Magnifications and altitudes are displayed on the figures. Dimples with different sizes and distributions are visualized throughout the surface in Figure 4.3.1. Manufacturing defects such as hills and dimples are revealed out in Figure 4.3.1.

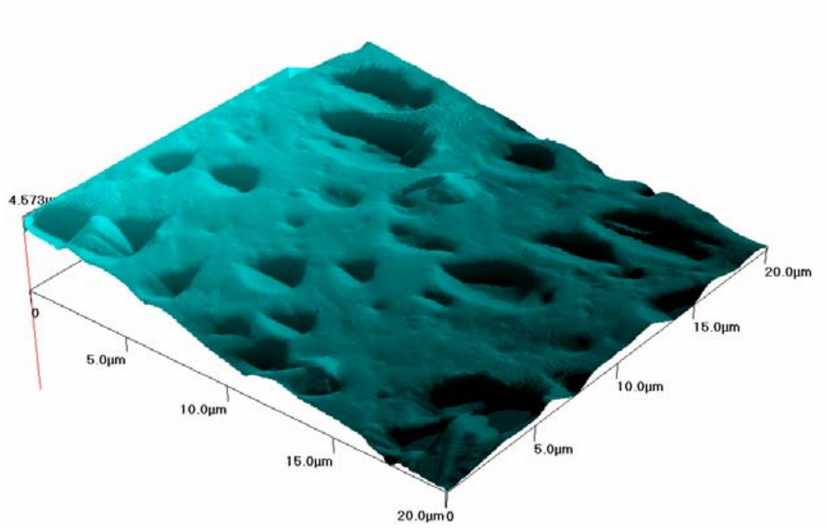

**Figure 4.3.1** AFM image of virgin fiber.

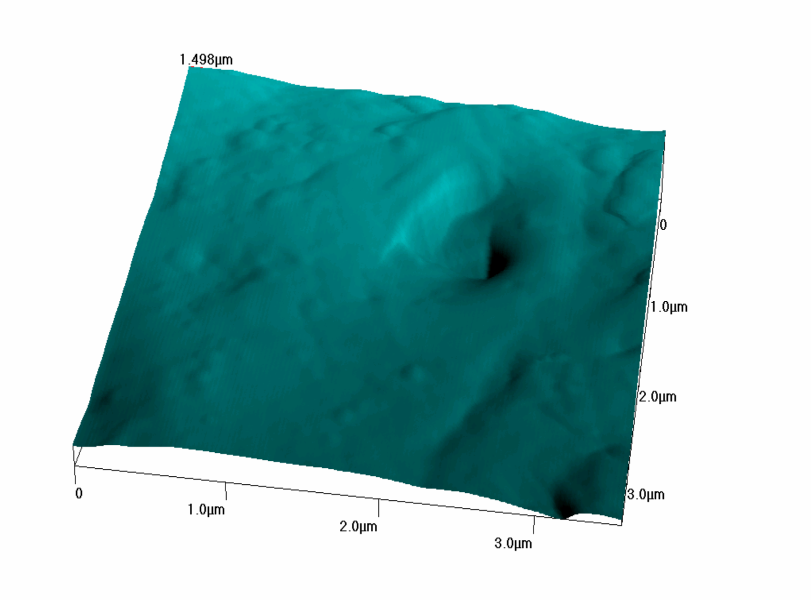

**Figure 4.3.2** AFM image of virgin fiber.

Images taken on the dialysate contact surface of used-processed fibers are displayed with different magnifications in Figure 4.3.3 and in Figure 4.3.4. Rough and wavy surface morphology is observed in Figure 4.3.3 and in Figure 4.3.4. Radial cavities elongating in one direction from one end to the other are visualized in Figure 4.3.3. More defects and damages than the virgin one are also visualized in Figure 4.3.3 and in Figure 4.3.4.

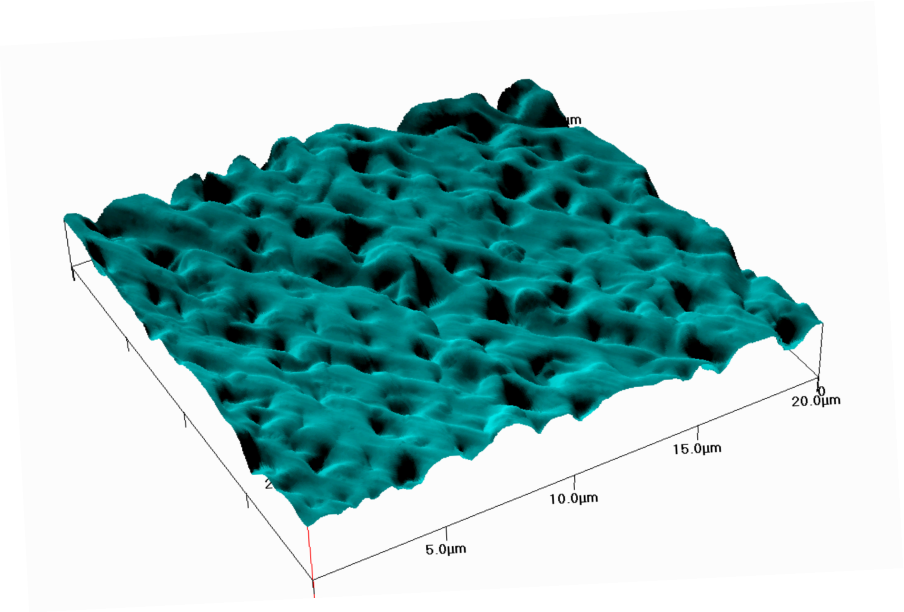

**Figure 4.3.3** AFM image of used-processed fiber.

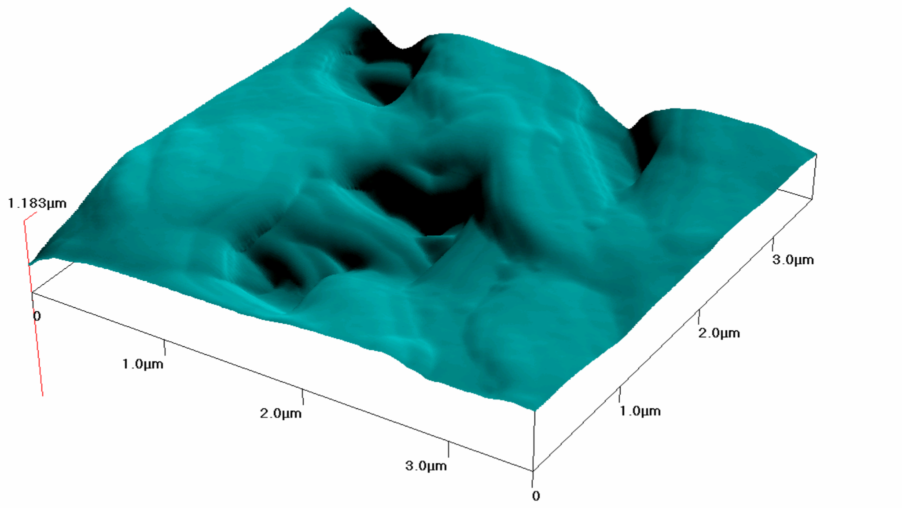

**Figure 4.3.4** AFM image of used-processed fiber

Discrepancies between virgin and used-processed fibers are easily visualized by incomplete mesh analysis of AFM studies on virgin and used-processed fibers in Figure 4.3.5 and in Figure 4.3.6. Rough wavy structure is seen in used-processed fiber, whereas virgin fiber possesses smoother surface morphology. Defects and damages are also seen in used-processed fibers.

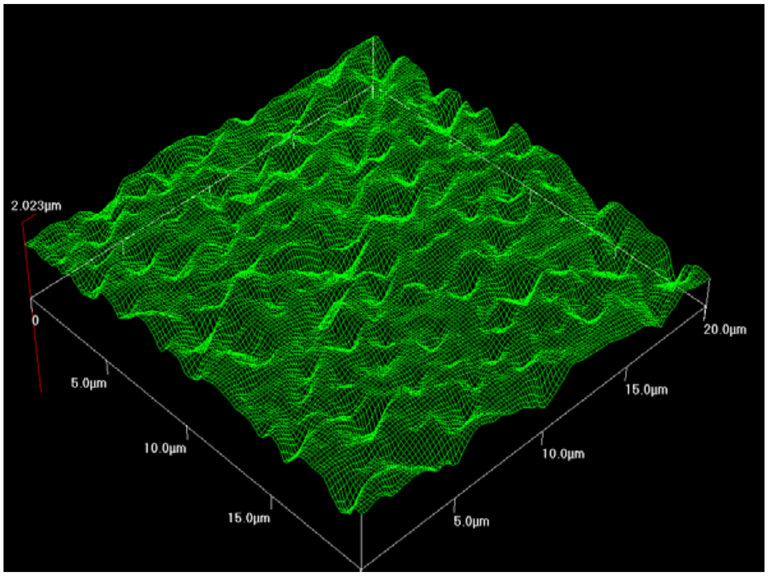

**Figure 4.3.5** AFM image of used-processed fiber.

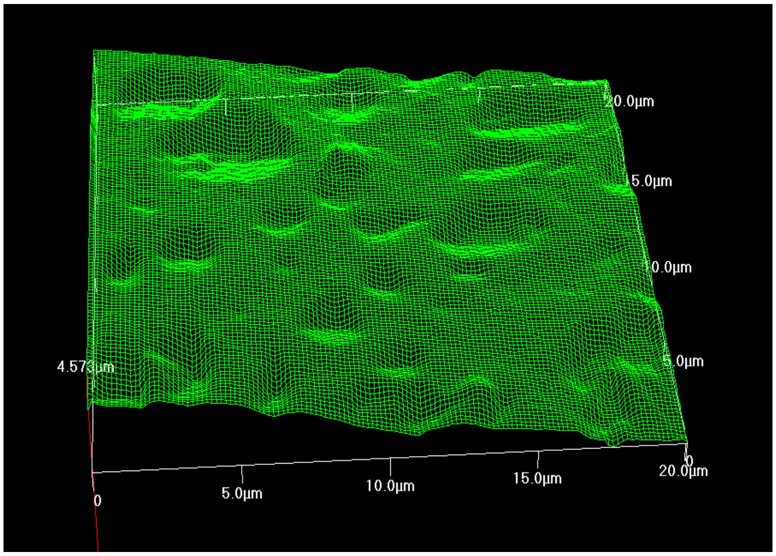

**Figure 4.3.6** AFM image of virgin fiber.

# 5. X-RAY DIFFRACTOMETRY STUDIES

Polymers are mostly expressed by saying that they have only a partial crystallinity [44]. Since the polymers contain long chains, different parts of the same chain become incorporated into different crystallites. Because of this reason, polymers that connect crystallites are badly entangled and not completely crystalline. In general, polymers may contain depending on the conditions 20-50% of amorphous material which is illustrated in Figure 5.1. The crystalline parts of the polymers are important in many applications since they may give the polymer the rigidity and hardness. On the other hand, the amorphous part of the polymer is also important because the amorphous regions in the chains have enough mobility and they can absorb impact energy through their skeletal motions. A partially crystalline polymer is therefore much tougher than the same polymer would be if it were 100% crystalline [44].

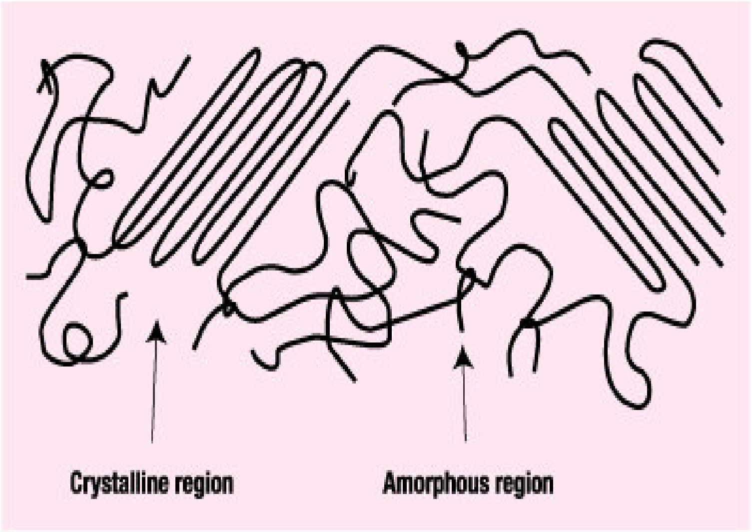

**Figure 5.1** The semi-crystalline structure of polymers [45].

## 5.1 Materials and Methods

X-Ray Diffractometry is a common tool in order to observe crystallinity and also the change in crystallinity. Polymers used in hemodialysis would be partially crystalline depending on manufacturing method and degree of crystallinity may alter under stress in aggressive environment. XRD studies were performed on virgin and used-processed fibers after tensile tests experiments in order to observe the effect of stressing and reuse solution on the crystallinity of the fibers.

Rigaku Dmax 2200 XRD (Figure 5.1.1) being available at Gebze Technology of Institute was used to perform x-ray diffraction studies. Copper x-ray tube was used. Voltage and the currents values were 40kV and 40mA, respectively. The scanning speed was 4 degree per minute.

**Figure 5.1.1** Rigaku Dmax 2200 XRD.

## 5.2 Results And Discussions Of XRD Studies

It is well known that mostly mechanical straining may cause new orientations and or new orientations in polymeric materials. In this study, the material on which mechanical stressing is performed is polyamide with the defects. Therefore with the defects; it is necessary to take into account the contributions of the defects in addition to mechanical stressing on bulk and chemical attacks due to the environment to which the material is exposed. Figure 5.2.1 showing the XRD results of virgin polyamide membrane without stressing and the virgin one stressed under monotonic loading until fracture, it is seen that there is a sharpening in the main peak height on the diagram with respect to the diagram representing virgin membrane. There is also a new peak seen at 25.842 two-theta (deg) on the diagram representing the virgin fiber after monotonic loading.

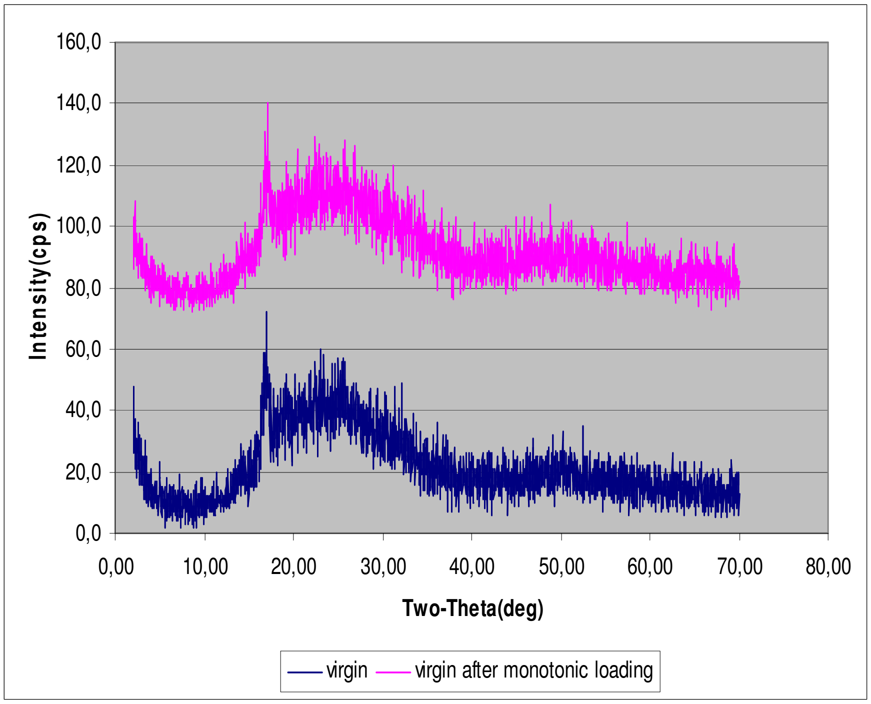

**Figure 5.2.1** XRD diagrams of virgin and virgin after monotonic loading.

Figure 5.2.2 shows both virgin and used-processed membrane stressed under monotonic loading. Main peak seen at 17 two-theta (deg) in the XRD diagram of used-processed membrane shows increase which means that chemical effect together with stressing contributes to the change of the crystallinity.

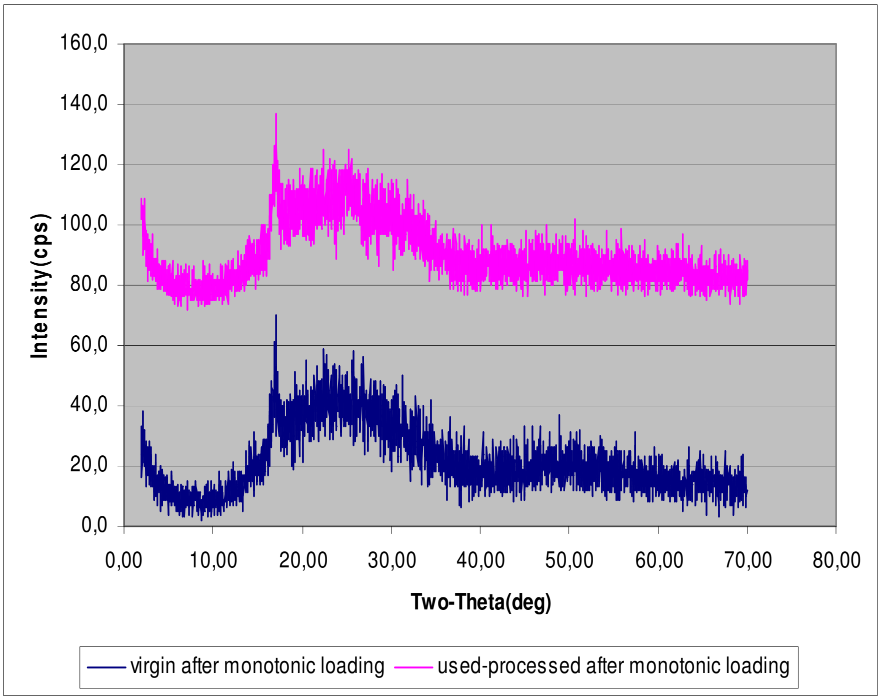

**Figure 5.2.2** XRD diagrams of virgin and used-processed after monotonic loading.

Figure 5.2.3 shows virgin and used-processed membranes exposed to cyclic loading. XRD diagram of used-processed membrane with respect to virgin one's shows nucleation and growth of new orientation, which are shown by obtaining new peaks at 31.382 two-theta (deg) and 45.6 two-theta (deg).

Figure 5.2.4 shows the comparison of virgin one without stressing and used processed one under cyclic loading. Cyclic loading causes new nucleation sides which are represented by two new peaks seen at 31.382 two-theta (deg) and 45.619 two-theta (deg) on the XRD diagram.

Figure 5.2.5 shows the XRD diagram of virgin membrane without stressing and the virgin one after cyclic loading. Cyclic loading causes new orientations and new phases by forming a new peak with high intensity at 25.901 two-theta (deg).

All the steps consisting of chemical effects being exposed to blood and reprocessing germicides and mechanical stressing are responsible of the nucleations and growth of the phases, thus reuse germicides are alone and together with stressing alters polyamide membranes.

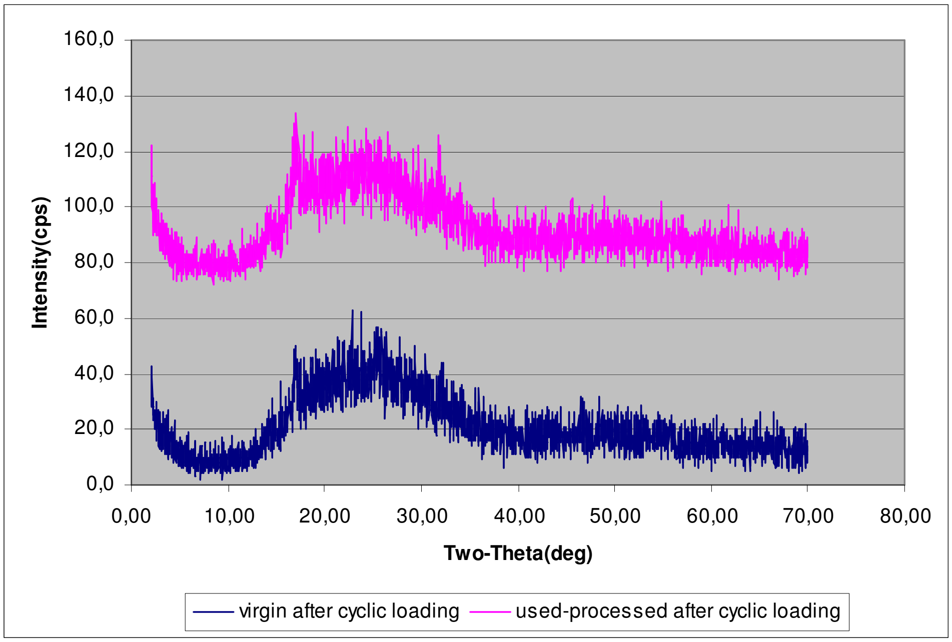

**Figure 5.2.3** XRD diagrams of virgin and used-processed fibers after cyclic loading until fracture.

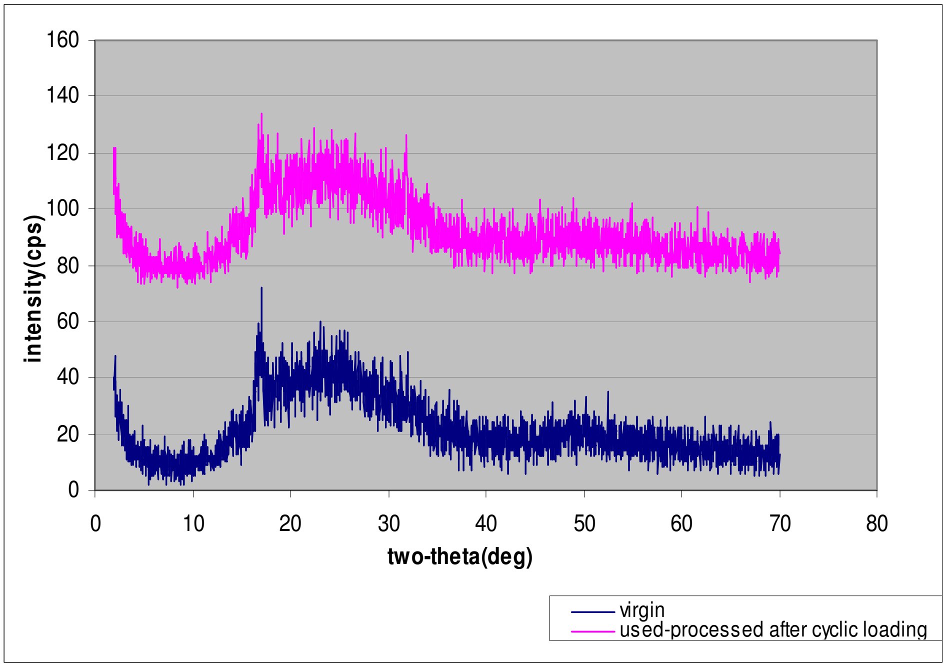

**Figure 5.2.4** XRD diagrams of used-processed fiber after cyclic loading and virgin fiber.

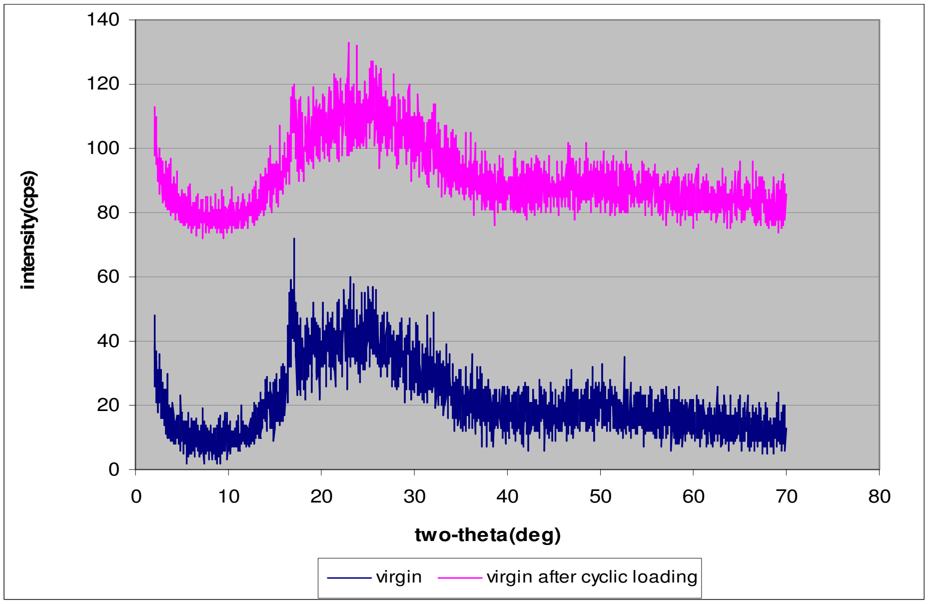

**Figure 5.2.5** XRD diagrams of virgin fiber after cyclic loading and virgin fiber.

XRD results of the membranes in terms of intensity (counts) and two-theta degree are given in Table 5.2.1.

**Table 5.2.1**
XRD results of the membranes.

| Membrane Type | Peak at two-theta (deg) | Intensity (counts) |
|---|---|---|
| Virgin Fibers | No peak | - |
| | 17.059 | 15.9 |
| | No peak | - |
| | No peak | - |
| | No peak | - |
| Virgin fibers after monotonic loading | No peak | - |
| | 17.119 | 15.8 |
| | 25.842 | 7.6 |
| | No peak | - |
| | No peak | - |
| Virgin fibers after cyclic loading | No peak | - |
| | 16.960 | 12.5 |
| | 25.921 | 10.7 |
| | No peak | - |
| | 46.761 | 6.3 |
| Used-processed fibers after monotonic loading | No peak | - |
| | 17.020 | 18.3 |
| | 25.500 | 9.3 |
| | 31.802 | 9.4 |
| | No peak | - |
| Used-processed fibers after cyclic loading | 14.382 | 5.9 |
| | 17.201 | 11.7 |
| | No peak | - |
| | 31.382 | 13.9 |
| | 45.619 | 10.7 |

# 6. DISCUSSION

The number of people are becoming older and sicker in today’s modern world is increasing and the number of dialysis patients are growing rapidly. In order to reduce the healthcare cost, new solutions should be offered. Reuse of dialyzer is an old solution which is still a controversial issue whether it is safe or not from health care point of view.

Researches have focused on the effects of reuse on small and middle weight molecule clearance, pyrogenity reactions and mortality and morbidity rates. To our knowledge, there are no studies on the effects of hemodialysis environment and reuse solution on the stability of dialyzers used during hemodialysis in open literature.

SEM studies performed on lateral surfaces (far from fracture) of virgin fibers in order to investigate the effect of stressing via monotonic loading tensile test which resemble the pressure applied to the dialyzer by blood, dialysate and the machine reveal that stressing change the circular pore shape into an elliptical pore shape. Moreover, SEM studies performed on virgin fibers lateral surfaces (far from fracture) in order to investigate the effect of alternating stress via cyclic loading tensile test experiments which resemble the pressure fluctuations during hemodialysis session and repeated pressure applied on the dialyzers on each session reveal that pore shape becomes more elliptical than the monotonic stressing and the pores become close to each other forming ligaments which is a prior step of pore merging. This situation is also revealed by tensile test experiments that cyclically loaded fibers rupture earlier than the monotonically loaded fibers.

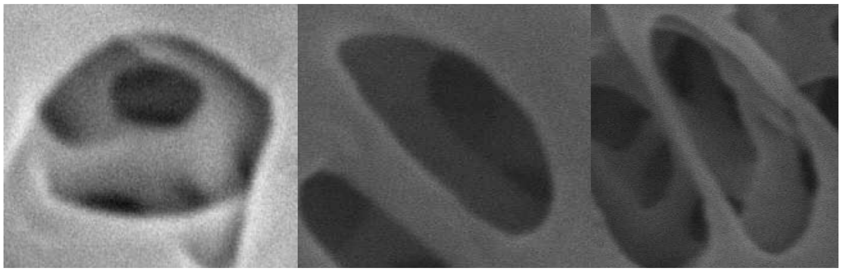

**Figure 6.1** SEM pictures of virgin PA fibers: untreated (left), after monotonic loading (middle), after cyclic loading (right).

SEM studies performed on lateral surfaces (near fracture) of virgin fibers after monotonic loading tensile test reveal that pore shape becomes more elliptical close to fracture point which indicates that elliptical pore shape is more prone to rupturing. This is due to the fact that stress concentration increases on the long axis of the ellipse, which in turn leads to easy crack initiation and easy crack propagation. This situation is also revealed by XRD studies of virgin fibers without being stressing and monotonically loaded virgin fibers. Monotonically loaded fibers become more crystalline or in other words they become more brittle.

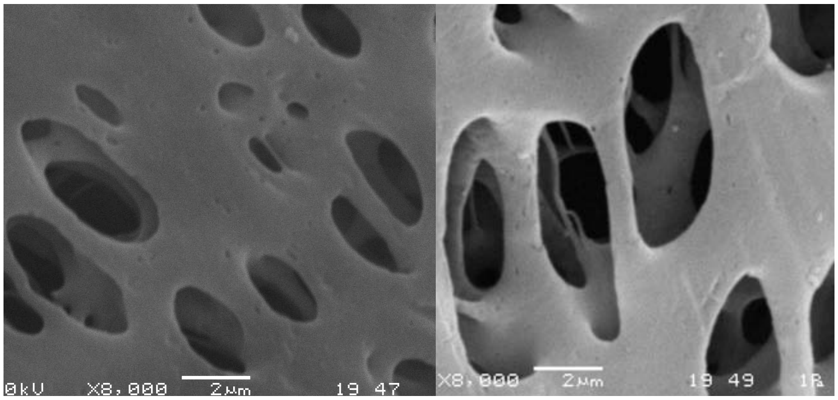

**Figure 6.2** SEM pictures of virgin PA fibers after monotonic loading: near fracture (left), far from fracture (right).

SEM studies performed on fracture surfaces of virgin fibers after tensile tests reveal that rupturing of ligaments, which in turn results in merging of pores and also formation of big cracks. Although both of the monotonically and cyclically loaded fibers have merging of pores on the fracture surfaces, more merged and bigger cracks are seen in cyclically loaded fibers. The original structure of polyamide hemodialyzer fibers have channel like big pores however after cyclic loading stressing induces the rupturing of these structures.

SEM studies performed on used-processed fibers after tensile tests reveal that chemical attacks together with stressing cause more merging of pores and bigger and more cracks and than that of the monotonically or cyclically stressing alone. Merging of pores which are the beginnings of crack propagations are seen not only close to fracture surface but also throughout the lateral surface of used-processed fibers. Tensile tests experiments also reveal this situation that used-processed fibers even monotonically loaded rupture earlier than the virgin fibers loaded cyclically.

AFM studies performed on virgin and used-processed fibers also reveal that used-processed fibers have rough and wavy surface structure although virgin fibers have a smoother surface structure. More defects and damages were seen in used-processed fibers which are also revealed by tensile test experiments. Used -processed fibers rupture earlier than the virgin ones.

XRD studies performed on virgin fibers before and after tensile tests experiments reveal that monotonically loaded fibers become more crystalline than the fibers without stressing. Monotonic loading together with the chemical attack increase the crystallinity of used-processed fibers. Due to the chemical attacks, the degree of increase in crystallinity is higher in used-processed fibers with respect to virgin fibers. This situation is also revealed by tensile test experiments. Cyclic loading is also responsible for new nucleation and new orientations on virgin polyamide membranes. Chemical attacks together with the cyclic loading also cause new orientations and growth of new phases with respect to virgin fibers without stressing. New phases observed on both the virgin and used-processed fibers created by cyclic loading can be the reason of earlier rupture of the material than those of the monotonically loaded.

SEM, tensile test and XRD experiments reveal that monotonically and cyclically stressing alters the structure of the polyamide membrane. Cyclically loaded fibers become weaker. It is also revealed by AFM studies that reuse germicides cause deformation on surface structure. SEM, XRD and tensile test experiments reveal that chemical attacks together with the hemodialysis environment superposes the change in structure of the material. Used-processed fibers become weaker even after monotonic loading than the virgin one cyclically loaded.

When taking all of these consisting experimental results into consideration, it is concluded that the used-processed polyamide membrane is no longer the same membrane as the original membrane from engineering point of view.

It is known that membrane material and pore morphology are one of the most important parameters in determining the dialysis efficiency. Thus, altering in pore morphology and the structure of the material will affect the dialysis efficiency from healthcare point of view.

Albumin loss and pyrogenity reactions are the known disadvantages of high flux dialyzers because of their bigger pore sizes than the conventional dialyzers.

In this study, it is revealed that merging of pores result in bigger pores in high flux used-processed fiber than that of virgin high flux fibers which can in turn cause the undesired passage of useful substances such as albumin. These deficiencies can lead to different types of illnesses.

Although the dialyzer is tested to make sure there are no broken fibers and it is still working before reusing, a mechanical break can occur during dialysis session which can cause bacterimia. It is clear that reuse of high flux dialyzers superposes the complications of single use high flux dialyzers.

Although reuse of dialyzers seems to be an effective cost saving procedure, in 2002 Mann et al reported that the cost savings that could be expected by switching from single-use dialysis to heated citric acid reuse were small, ranging from CAN $0–739 per patient per year [46]. When the costs of accompanying diseases associated with dialyzer reuse stated above are taken into consideration, reuse idea should also be revised from economical point of view.

## 7. CONCLUSION

Mechanical tests reveal that the effect of reuse solution on the mechanical parameters; ultimate tensile strength, yield stress and toughness of polyamide membrane are changed. Generally reuse solution decreases the toughness of the material so that crack initiation and propagation become easier.

The chemical attacks by reuse solutions cause nucleation and growth of new phases and /or growth of available ones.

Cyclic stressing decreases toughness more than that of monotonic loading so that the change of pressure during hemodialysis session should be taken into account from the stability point of view of the membrane.

Pores on the surface due to hemodialysis and reuse solution together with mechanical effect are merging each other. This is also another reason to obtain easy crack propagation.

AFM results that has mesh analysis revealed that surface roughness is increased because of used conditions and reuse solution. This condition also increases the possibility of crack initiation on the surface addition to the contribution of the geometrical changes of the pores.

The number of dialysis patients is growing rapidly all over the world. Polyamide membranes, which are used extensively, have many materials problem which may result in failure thus it is imperative to make new programs in order to obtain new stable materials which decrease economical cost and increase health and wealth condition.

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