FABRICATION OF SHAPE MEMORY POLYMER FOAMS WITH

SURFACE-MODIFIED NANOPARTICLE FILLERS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Fabrication of Shape Memory Polymer Foams with Surface-Modified Nanoparticle Fillers

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Every year, 30,000 individuals in the United States will suffer from a ruptured cerebral aneurysm. The Biomedical Device Laboratory seeks to improve on current aneurysm treatment by using a low-density, high-volume shape memory polymer (SMP) polyurethane foam-over-coil device to fully occlude aneurysms via minimally invasive surgery using a microcatheter. Due to the SMP foam's low density, it is susceptible to tearing, which would be a serious adverse event during aneurysm treatment. The potential for tearing can be reduced by improving the foam's mechanical properties. Incorporating aluminum oxide nanoparticle filler into the foam has been previously shown to improve mechanical properties, but the limited bonding between the nanoparticles and the polymer may cause excessive particulate leaching. Bonding between the nanoparticles and foam can be improved by altering the surface chemistry of the nanoparticles by applying a silane coupling agent. Nanoparticles modified with a silane coupling agent can form a strong urea linkage with the polyurethane foam that improves upon the secondary bonding of unmodified nanoparticles with the polyurethane foam.   This increased bonding is hypothesized to improve the foam's mechanical properties and decrease the potential for excessive particulate leaching as compared to foams loaded with unmodified nanoparticles.

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like to thank Marziya Hasan for her invaluable guidance and advice as my graduate student

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NOMENCLATURE

APS   3-Aminopropyltrimethoxysilane

BDL   Biomedical Device Laboratory

SMP   Shape Memory Polymer

CHAPTER I

INTRODUCTION

Clinical need: cerebral aneurysms

A cerebral aneurysm is a weak spot on a blood vessel in the brain that balloons out and fills with blood. The bulging aneurysm can put pressure on a nerve or surrounding brain tissue, or it may rupture and leak blood into the subarachnoid space, which could lead to permanent brain damage or even death[1]. Every year in the United States, 30,000 individuals suffer from a ruptured cerebral aneurysm, and up to 6 percent of the population may have an un-ruptured cerebral aneurysm[2]. There are currently two options for treating cerebral aneurysms: surgical clipping or endovascular embolization. Surgical clipping is a well-researched and effective treatment method. Clipping involves placing small clips around the aneurysm neck to prevent blood from entering the aneurysm sac so that it may no longer pose a risk for rupturing[3]. The clipping procedure is highly invasive, usually requiring the surgeon to perform a craniotomy so that they may access the aneurysm in the brain[3]. Endovascular embolization provides a less invasive treatment option. Current endovascular embolization treatment aims to deposit platinum coils in the aneurysm to occlude blood flow and promote thrombogenesis. The procedure for depositing the platinum coils uses a catheter inserted into a vessel over the hip and guided up to the brain, which is much less invasive and generally has a shorter recovery period than surgical clipping[4]. However, compared with surgical clipping, there is an increased risk of recurrent bleeding due to coil compaction and irregular thrombus formation, particularly with larger aneurysms[5].

Previous research

The Biomedical Device Laboratory's (BDL's) foam-over-coil device seeks to improve the current endovascular embolization technique by placing low-density, high-volume shape memory polymer (SMP) foam over coils to achieve greater aneurysm occlusion. SMPs have the unique ability to switch between a primary and secondary shape with the application of an external stimulus, such as heat[6]. These foams must have a very low density to enable tight crimping onto the coil for their delivery via microcatheter. Due to this low density, the foam is susceptible to tears and micro-fractures. If the foam were to tear while in use, the effect would be highly detrimental to aneurysm treatment. The potential for tears and microfractures in the foam can be reduced by improving the foam's mechanical properties. Preliminary research from the BDL has shown that incorporating metal oxide nanoparticles into the foam results in improved mechanical properties. However, chemical bonding between the nanoparticles and the polymer matrix is limited. The chemical interactions between the nanoparticles and the polymer foam can be increased by altering the surface chemistry of the nanoparticles before incorporating them into the foam.

Silane coupling

One technique for surface modifying nanoparticles prior to filler loading in polymers is the application of a silane coupling agent, a common method of promoting adhesion between two chemically incompatible materials[7]. In particular, amine-functional silanes have the ability to foam strong urea linkages with isocyanates, a desirable characteristic for loading nanoparticles into SMP polyurethane foams. The coupling agent is first applied to the nanoparticles, and then the modified nanoparticles are incorporated into the polymer. It is hypothesized that applying a

silane coupling agent to the nanoparticles will introduce stronger bonds between the

nanoparticles and the SMP foam to further improve the mechanical properties and decrease the

potential for the nanoparticles to leach out of the foam.

Research objectives

The first objective of this project is to modify the surface of aluminum oxide nanoparticles using

a silane coupling agent. The success of this modification will be based on the grafting

percentage of coupling agent to nanoparticle, with a goal of at least 10%[8]. The next objective is

to evaluate the effect of the modified nanoparticles on the SMP foams. A number of the foam's

characteristics will be tested, including mechanical properties, density, pore size, and thermal

behavior. The success of the modified filler loading will be based on improving the SMP foam

mechanical properties (tensile strength and toughness) without negatively affecting the other

basic foam characteristics (density, pore size, glass transition temperature).

CHAPTER II

METHODS

Materials

Aluminum oxide nanopowder (99+%, US Research Nanomaterials) with average particle size of 80 nm was selected as the nanofiller for this study. Sulfuric acid (Sigma-Aldrich), (3-aminopropyl)trimethoxysilane (APS) (97%, VWR Scientific), trimethylamine (Sigma-Aldrich), and toluene (anhydrous, Sigma-Aldrich) were used in surface modification as reducing agent, silane coupling agent, catalyst, and solvent, respectively.

The monomers used in fabrication of the polyurethane foams were *N,N,N',N'*-tetrakis(2-hydroxypropyl)ethylenediamine (HPED) (Sigma-Aldrich), triethanolamine (TEA) (Sigma-Aldrich), and trimethyl-hexamethylene diisocyanate (TMHDI) (TCI America).

Surface modification and characterization of nanoparticles

Two grams of nanoparticles were placed in sulfuric acid and sonicated for 60 minutes. The acid was removed, and the nanoparticles were dried at 60 °C for 24 hours. Next, the nanoparticles were placed in 100 mL of toluene and sonicated for 30 minutes. This mixture was then stirred at 800 rpm for 60 minutes under N_2 atmosphere. A solution with APS (100 wt.% to the nanoparticles) and catalyst (300 microliters) in toluene (100 mL) was added dropwise to the nanoparticle-toluene mixture under N_2 atmosphere. This mixture was stirred at 800 rpm at approximately 120 °C for 24 hours. The nanoparticles were then filtered out of solution, rinsed with ethanol, and dried under vacuum at 80 °C for 24 hours[8].

The surface hydroxyl content of the nanoparticles was evaluated after acid treatment using titration. A suspension of 0.5 g of nanoparticles in 10 mL of deionized water was prepared, and 5 drops of phenolphthalein indicator solution was added to the suspension to indicate a basic solution. Sodium hydroxide (0.5 N) was added dropwise to the suspension until a pink endpoint (pH range 8.2-10) was reached.

Grafting of the APS onto the nanoparticles was evaluated by Fourier transform infrared (FTIR) spectroscopy and thermal gravimetric analysis (TGA). FTIR spectroscopy was performed on a Bruker Alpha FTIR spectrometer (Bruker Corp.) collecting 32 scans in the 200-4000 cm^{-1} range with 4 cm^{-1} resolution. The thermal behavior of the nanoparticles was evaluated by a Q50 TGA (TA Instruments) by performing a ramp of 10 °C/min from room temperature up to 1000 °C under N_2 atmosphere.

Fabrication and characterization of SMP polyurethane foams

SMP polyurethane foams were fabricated using HPED, TEA, and TMHDI. Each foam was loaded with a different type of nanoparticle at a concentration of 1 wt.%.

The foams were characterized using density measurements (g cm^{-3}), scanning electron microscopy (SEM), differential scanning calorimetry (DSC), and mechanical property measurements (toughness (J m^{-3}), ultimate tensile strength (kPa), and strain at break (%)). Density was calculated by removing three samples from the foam and finding the mass and volume of each. Samples for SEM imaging were obtained from the foam in both the axial and

transverse directions. The samples were coated with gold using a Cressington Sputter Coater 108 (Cressington Scientific) and imaged with a Neoscope JCM-5000 (JEOL Ltd.). Glass transition temperature (T_g) was measured using a Q200 DSC (TA Instruments). Mechanical properties of the foam were evaluated according to ASTM standard tensile testing. Ten dog-bone specimens (3 mm x 6 mm x 120 mm) were prepared by cutting the specimens to shape. Tensile testing was performed using an MTS Synergie 400 testing machine (MTS Systems Corporation).

Surface modification of aluminum oxide

Three batches of surface-modified Al_2O_3 nanoparticles were prepared with varying molarities of

acid (0.5, 1, and 3 M sulfuric acid) for pre-treatment. After acid pre-treatment, the nanoparticles

were reacted with a silane coupling agent. A schematic representation of the final surface-

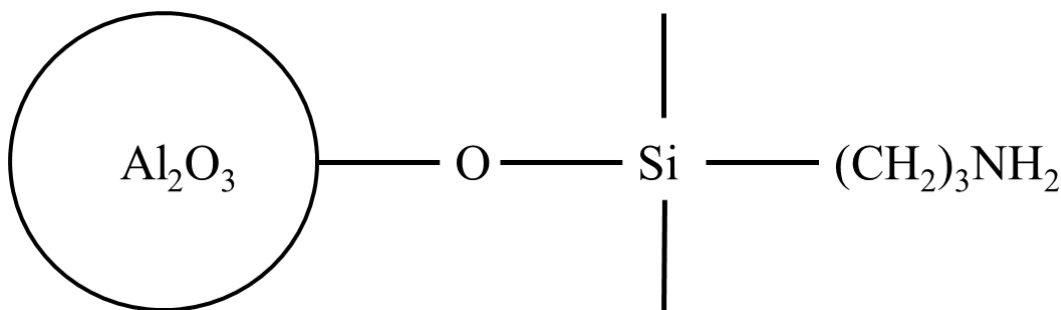modified aluminum oxide nanoparticle bonded to the silane coupling agent can be seen in Figure

1.

Figure 1. Schematic representation of a surface-modified Al_2O_3 nanoparticle.

The surface hydroxyl content of the nanoparticles after acid treatment but before addition of the

silane coupling agent was evaluated using a titration method. The moles of NaOH per gram of

Al_2O_3 needed to titrate the nanoparticle suspension can be found in Table 1. By increasing the

molarity of the acid used in pretreatment of the nanoparticles, the number of moles of NaOH

needed to titrate the suspension increases. Therefore, increasing the concentration of the acid

used in treating the nanoparticles increases the acidity of the nanoparticles. The increase in

acidity of the nanoparticles is likely due to an increase in the concentration of hydroxyl groups

on the surface of the Al_2O_3 nanoparticles, as the surface hydroxyls act as Bronstead acid sites[9].

The control Al_2O_3 nanoparticles in suspension immediately turned pink upon addition of the

indicator solution and required no NaOH, indicating that they lacked a significant concentration

of surface hydroxyl groups. Surface hydroxyls on the Al_2O_3 nanoparticles are vital to the

success of the surface modification, as they provide a bonding site for the silane coupling agent

molecules to attach to the nanoparticles. The titration experiment illustrates the importance of

first treating the nanoparticles with acid before applying the silane coupling agent.

Table 1. Titration of acid-treated Al_2O_3 nanoparticles

Molarity of Pre-Treatment Acid	Moles NaOH/mg Al_2O_3 Required to Titrate
0	0
0.5	0.984
1	1.809
3	6.107

The degree of surface modification of the aluminum oxide nanoparticles after applying the silane

coupling agent was estimated using TGA. TGA curves for each batch of aluminum oxide

nanoparticles can be found in Figure 2. The unmodified control aluminum oxide nanoparticles

experienced minimal mass loss through the entire heat ramp up to 1000 °C. Each batch of

modified aluminum oxide nanoparticles experienced significant weight loss (10-13% reduction

from the starting weight) throughout the heat ramp up to 1000 °C. The initial weight loss of the

modified nanoparticles seen in the TGA curves around 100 °C is likely due to desorption of

physisorbed water[8]. The drastic weight loss of the nanoparticles that begins around 300 °C can

be attributed to the oxidative thermal decomposition of the APS chains bonded to the surface of

the aluminum oxide nanoparticles. This significant weight loss of the modified aluminum oxide

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nanoparticles confirms successful grafting of the silane coupling agent APS onto the surface of the nanoparticles.
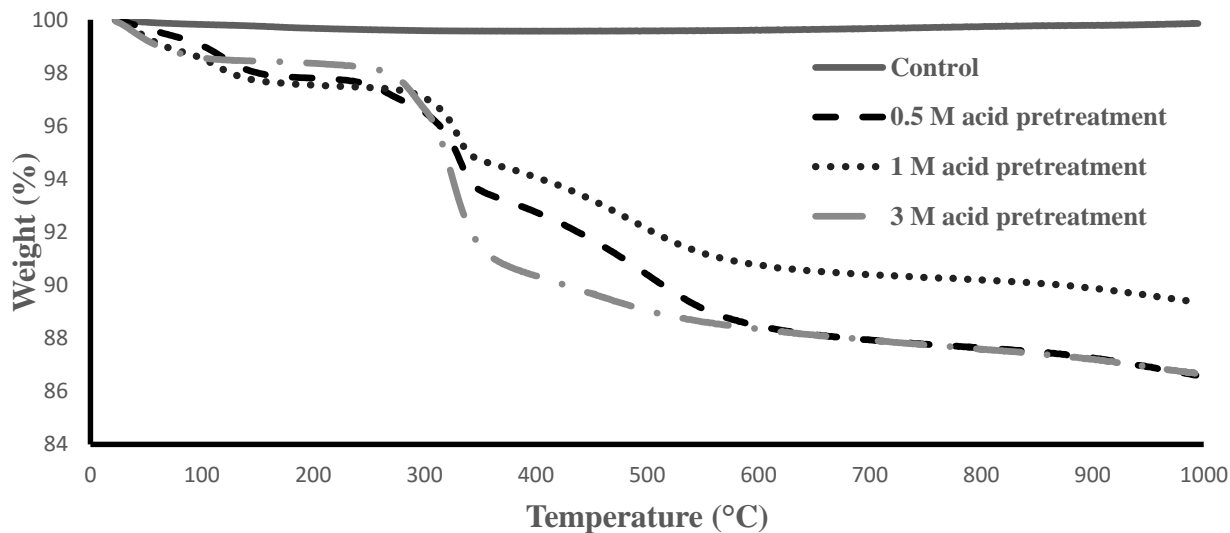

Figure 2. TGA curves of unmodified and modified Al_2O_3 nanoparticles.

The modified aluminum oxide nanoparticles were further characterized by FTIR to confirm the presence of APS on the surface of the nanoparticles. FTIR spectra for APS, Al_2O_3, and modified Al_2O_3 can be seen in Figure 3. The top spectrum shows the absorbance of unmodified aluminum oxide nanoparticles, the middle spectrum shows the absorbance of the silane coupling agent APS, and the bottom spectrum shows the absorbance of the modified aluminum oxide nanoparticles. The modified aluminum oxide spectrum more closely resembles the spectrum of APS than the unmodified aluminum oxide, confirming the total surface modification of the modified aluminum oxide nanoparticles.
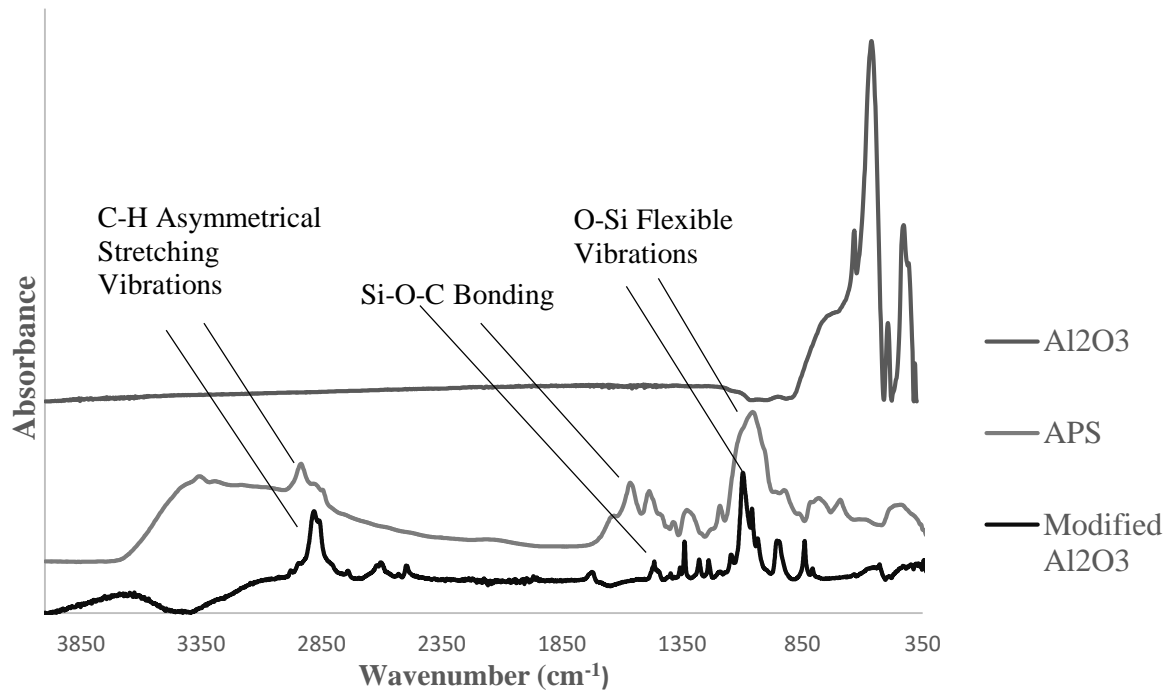
Figure 3. FTIR spectra of Al_2O_3 nanoparticles, APS, and modified Al_2O_3 nanoparticles[8].

Characterization of SMP foams loaded with aluminum oxide nanoparticles

Five SMP polyurethane foams were fabricated with the various aluminum oxide nanoparticles

added as fillers. The compositions of these foams and their densities can be found in Table 2.

The incorporation of both modified and unmodified nanoparticles into SMP foams has minimal

effect on foam density compared to the control foam with no fillers.

Table 2. SMP foam compositions and densities.

SMP Foam Filler Composition	Filler Acid Pretreatment (molarity)	Density (g cm^{-3})
0% control	N/A	0.015 ± 0.007
1 wt.% unmodified Al_2O_3	N/A	0.015 ± 0.001
1 wt.% modified Al_2O_3	0.5	0.018 ± 0.001
1 wt.% modified Al_2O_3	1	0.015 ± 0.001
1 wt.% modified Al_2O_3	3	0.015 ± 0.001

The pore sizes of the foams were measured using SEM. Two samples from each foam, one in the axial direction and one in the transverse direction, were removed for imaging. The results of the pore size measurements can be found in Table 3. The average pore sizes of the different foams vary, with all of the nanocomposite foams loaded with Al_2O_3 nanoparticles having smaller pore diameters than the control foam. The nanocomposite foams have smaller pores because the nanoparticles act as nucleating agents within the polymer foams to increase the number of nucleation sites and generate more, smaller pores[10]. However, the decrease in pore size due to the incorporation of nanoparticles is not detrimental to foam development for use in treating cerebral aneurysms, as pore diameters can easily be altered through minor changes in the foaming procedure.

Table 3. Average pore sizes of SMP foams.

SMP Foam Filler Composition	Filler Acid Pretreatment (molarity)	Pore Size – Axial (µm)	Pore Size – Transverse (µm)
0% control	N/A	2515 ± 407	1613 ± 131
1 wt.% unmodified Al_2O_3	N/A	1812 ± 328	1274 ± 141
1 wt.% modified Al_2O_3	0.5	1555 ± 209	958 ± 162
1 wt.% modified Al_2O_3	1	2477 ± 385	1497 ± 297
1 wt.% modified Al_2O_3	3	1531 ± 284	1314 ± 183

Tensile testing was performed to evaluate the mechanical properties of the foams. Table 4 shows the results of the tensile tests for each foam composition. The nanocomposite foam loaded with 1 wt.% unmodified aluminum oxide exhibited a significant increase in ultimate tensile strength and toughness compared to the control foam. The nanocomposite foam loaded with 1 wt.% aluminum oxide pretreated with 0.5 molar acid showed an even greater improvement in ultimate tensile strength and toughness relative to the control foam, with a 43% increase in tensile

strength and a 99% increase in toughness. The nanocomposite foam loaded with 1 wt.%

modified aluminum oxide pretreated with 1 molar acid also exhibited a 43% increase in tensile

strength but only a modest increase in toughness. The nanocomposite foam loaded with 1 wt.%

modified aluminum oxide pretreated with 3 molar acid exhibited large increases in ultimate

tensile strength and toughness compared to the control. The foams loaded with modified Al_2O_3

pretreated with 0.5 molar and 3 molar acid have superior mechanical properties compared to

foams loaded with unmodified Al_2O_3 due to the strong urea linkage formed by the silane

coupling agent on the surface of the modified Al_2O_3 and the isocyantes in the polymer. The

foam loaded with modified Al_2O_3 pretreated with 1 molar acid did not exhibit as great of an

increase in toughness as the other foams loaded with modified Al_2O_3, most likely because the

modified Al_2O_3 pretreated with 1 molar acid was not dispersed as uniformly within the foam.

Table 4. Mechanical properties of SMP foams.

SMP Foam Filler Composition	Filler Acid Pretreatment (molarity)	Ultimate Tensile Strength (kPa)	Strain at Break (%)	Toughness (J m^{-3})
0% Control	N/A	135 ± 12	45 ± 6	443 ± 28
1 wt.% unmodified Al_2O_3	N/A	161 ± 17	52 ± 5	695 ± 34
1 wt.% modified Al_2O_3	0.5	193 ± 18	54 ± 9	844 ± 33
1 wt.% modified Al_2O_3	1	193 ± 21	46 ± 4	593 ± 61
1 wt.% modified Al_2O_3	3	183 ± 27	47 ± 9	821 ± 52

CHAPTER IV

CONCLUSION

A procedure for modifying the surface chemistry of aluminum oxide nanoparticles was developed. TGA and FTIR results confirmed the successful application of a silane coupling agent (APS) onto the surface of the aluminum oxide nanoparticles. The surface-modified nanoparticles were incorporated into SMP polyurethane foams. The results indicate that the Al_2O_3 nanoparticles have varying effects on the foam properties. Foam densities were mostly unaffected by the Al_2O_3 nanoparticles while the pore sizes of the foams slightly decreased. The mechanical properties of the foams are greatly improved by the addition of surface-modified Al_2O_3, with foam toughness of nanocomposite foams nearly doubled compared to the control. The extent of the increase in foam mechanical properties is highly dependent upon the dispersion of the nanoparticles within the foam.

The goals presented in the introduction were met successfully. The increased mechanical properties of the SMP foams loaded with surface-modified nanoparticles can potentially improve the safety and reliability of the foams for treating cerebral aneurysms.

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