Effects of Marine Environments on the Mechanical Response of Polymeric Coatings

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EFFECTS OF MARINE ENVIRONMENTS ON THE MECHANICAL RESPONSE OF
POLYMERIC COATINGS

BY

JULIANNA MARTINEZ

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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2022
ABSTRACT

Polymeric materials are an important part to marine structures as they provide protection from the harsh underwater environment. While they can be used in many other applications, they can be found as a coating on propellers, boat and ship hulls, and even protective coatings for electronics. Given the service environment of these polymers, it is important to understand how they are affected by their surroundings. Three polymers were studied in different conditions; two polyurethanes and a polyurea. Each polymer underwent different experiments to determine how they would be affected by the environmental factors they would be exposed to.

Polyurea is a very durable polymer with excellent mechanical and chemical properties. It is wear and corrosion resistant which makes it an optimal choice for naval applications. The US Navy uses polyurea as a protective coating on marine structures which expose it to aggressive marine environments, i.e. low temperatures, sea water, and possible high strain rate loadings. This work investigates the effects of low temperature coupled with saline water weathering at multiple strain rates. For this study, a range of tests were conducted: low temperature (-2°C) and room temperature, virgin and weathered specimens, low and high strain rates, and a combination of those mentioned. Specimens which were weathered were exposed to saline water for 2 weeks in an accelerated weathering facility. This simulates 4.4 months in real life time at 17°C and 12 months at -2°C. An insulated box with cold flowing air was used to obtain the low temperature. A universal testing machine and a modified Split Hopkinson Pressure Bar were used to obtain strain rates of $10^{-3}$ to $10^3$. Results show polyurea’s response in highly sensitive to the given parameters, where weathering has the dominant effect.
In the marine industry, polyurethanes are a well-known material for use as they are water and tear resistant. Their properties allow the material to be an excellent choice for encapsulants for cable connectors and circuitry which during its service life may come in contact with sea water. In order to better understand how this material changes over time when exposed to sea water, a polyether-based polyurethane was studied after long term exposure to saline water using accelerated weathering techniques. The specimens were weathered in 3.5 % saline water at 70°C for 10, 48, 85, and 129 days simulating 1 month, 4.5, 8 and 12 months in real life service time, respectively. The quasi-static (2 x 10\(^{-3}\) /s) tensile and compressive behavior and the dynamic (2 x 10\(^{3}\) /s) compressive behavior was studied. It was found that the exposure to saline water caused softening in the material which decreased mechanical properties. Under quasi-static conditions the Young’s modulus and strain energy decreased by a maximum of 57% in compression and 51% and 50% in tension. The dynamic strain energy also decreased by 83% after 129 weathering days.

Cable connectors are an integral part of submarine communication systems. Some of these cables can be found on the exterior of ship hulls exposing them to the aggressive marine environment. The sea water along with of factors, such as the cable weight, may accelerate the failure of these cables. In this study, a polyurethane and primer subject to peel tests using a static load of 2.27 kg (5 lbs) while submerged in saline water and in air at two temperatures of 20 and 55°C. The contact angles of the Monel, primer and polyurethane surface were taken to understand the mode of failure when comparing the underwater to air experiments. Conventional peel tests were conducted to determine the peel strength of the system while in air at room temperature. When submerged under
saline water, it was found that the average time to peel significantly increased when they were placed in air at room temperature when compared to the other conditions.
ACKNOWLEDGMENTS

The author would like to kindly thank her mentor Dr. Arun Shukla for his guidance, patience, and wisdom throughout her time as a student. It helped to push her to not only grow as an engineer, but as a person and voice. She would also like to thank Dr. Irine Chenwi who supported and guided her while completing her own degree. She would also like to thank Dr. Thomas Ramotowski who was always helpful and willing to discuss important aspects of this project and also provided supplies. She would also like to thank her family for the never-ending support. Finally, she would like to thank her colleagues at the DPML.
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Chapter 1

Effects of Arctic Marine Environment on the Mechanical Behavior of Polyurea

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Abstract

Polyurea is a very durable polymer with excellent mechanical and chemical properties. It is wear and corrosion resistant which makes it an optimal choice for naval applications. The US Navy uses polyurea as a protective coating on marine structures which expose it to aggressive marine environments, i.e. low temperatures, sea water, and possible high strain rate loadings. This work investigates the effects of low temperature coupled with saline water weathering at multiple strain rates. For this study, a range of tests were conducted: low temperature (-2°C) and room temperature, virgin and weathered specimens, low and high strain rates, and a combination of those mentioned. Specimens which were weathered were exposed to saline water for 2 weeks in an accelerated weathering facility. This simulates 4.4 months in real life time at 17°C and 12 months at -2°C. An insulated box with cold flowing air was used to obtain the low temperature. A universal testing machine and a modified Split Hopkinson Pressure Bar were used to obtain strain rates of $10^{-3}$ to $10^3$. Results show polyurea’s response in highly sensitive to the given parameters, where weathering has the dominant effect.
1. Introduction

Polyurea is an amorphous polymer made artificially from a combination of amines and isocyanates. It is known to exhibit exceptional mechanical properties, proving itself useful in many military fields as an abrasion resistant coating, an impact and blast mitigating layer in structures and composites materials, and in vibration dampening systems. Studies have been conducted that explore the effects of the presence of polyurea coatings on structures loaded dynamically. Iqbal found that tiles coated in 6mm of polyurea could resist fragmenting in shock tube experiments with loading pressures up to 90 psi [1]. Further sources suggest that composites generally improve their response during dynamic loading [2-4]. Studies have also been conducted on how the location of the polyurea coating affects dynamic response. Pinto has found that under hydrostatic pressure a carbon fiber/epoxy tube externally and internally coated with polyurea was found to reduce the energy released during an implosion event when compared to those which were not coated with polyurea [3]. Thick internal coatings were found to mitigate the energy better than exterior and thin coatings. Gardner found that the configuration of a foam composite with a polyurea interlayer determines the effectiveness of blast response; arranging the polyurea on the side away from the blast loading reduced the particle velocity during the event. Similarly, Mohotti et al. found that a thick polyurea coating on the back side of a steel plate decreased the displacement during an explosion event by 20% when compared to front face coated plates [5]. The polyurea coating on the back face also reduced the chance of melting during an explosion. The constitutive stress-strain behavior has been studied for both polyurea and polyurethanes [6]. It is known that amorphous polymers may exhibit strain rate
dependence when approaching higher strain rates, which both polymers demonstrate. As the strain rate increases, the yield stress increases which causes the polymer to behave in a brittle manner. When the cross-link density of a polyurea was varied to increase the damping factor, the strain rate sensitivity was also shown to increase [7]. Recently, the effects of saline water and UV radiation on a polyurea coating were studied utilizing accelerated life testing [8]. Mforsoh et al. found that with increased exposure to saline water, the quasi-static and dynamic strain energy decreased by 69% and 52%, respectively at 25% strain after 84 days of exposure. However, exposure to UV radiation caused an increase in strain energy by 29% and 45% after 30 days of exposure, for the quasi-static and dynamic cases.

An area of interest for the US Navy is understanding the effects that low temperature environments have on polyurea. The US Navy performs exercises in the Arctic Circle to study the performance of acoustic equipment under the ice, known as IceX or Ice Exercise. This environment exposes ship and submarine hull coatings to both arctic temperatures and sea water, which may negatively impact their behavior. It is known that low temperatures increase the stiffness and yield stress of amorphous polymers due to the decrease in movement of the chain segments [9]. Shahi et al. studied the effects of chain length on the thermo-mechanical properties of polyurea variants [10]. They found that low temperatures affected the ability for the chains to move. Water absorption also has an effect on the polymers at low temperatures [11]. This study found that after the intake of water, some polymers such as Polyethersulphone (PES) and Polyetherimide (PEI), had an increase in shear modulus at low temperatures, while the damping factor decreased at low temperatures. This demonstrated the effects water
ingressed in polymers can have at low temperatures. The previous works demonstrate that environmental factors influence the mechanical properties of the polymers, however it is important to understand any effects that may occur in the service environment. To the knowledge of the author, there has not been much done to study the changes in mechanical behavior of polyurea when exposed to saline water and low temperature, and study aims to bridge that gap. This study uses accelerated weathering facilities and low temperature chambers to observe the changes in mechanical behavior in polyurea before and after exposure to saline water weathering coupled with exposure to a low temperature environment at a high and low strain rate.

2. Specimen Preparation and Methodologies

2.1. Specimen Preparation

The material used is Specialty Products HM-VK™ Ultra High Strength Hand-Mix Polyurea. The two-part mixture is thoroughly mixed by hand, degassed, then poured into a mold and set to harden for 24 hours at room temperatures as according to manufacturer instructions. After removing from the mold, the specimens are cured in an oven at 70°C for 16 hours to ensure complete polymerization; 70°C was chosen because this was within the service temperature. Each specimen is then machined to the approximate thickness and polished to create a smooth surface. The final dimensions of the specimens prepared for quasi-static experiments are 28.57 ± 0.15 mm in diameter and 12.45 ± 0.51 mm in thickness, in accordance with ASTM D575. Specimens cast for dynamic experimentation had a final diameter of 12.70 ± 0.13 mm and a thickness of
7.62 ± 0.25 mm. The thickness of the dynamic specimens was determined by the equation given below,

\[
\frac{l}{d} = \sqrt{\frac{3}{4\nu}}
\]

Where \( d \) is the diameter, \( l \) is the thickness of the specimen, and \( \nu \) is Poisson’s ratio of the material. This is an important parameter as this thickness allows enough reverberations within the material to pass through to promote force equilibrium on each face.

### 2.2. Ageing Methodology

A 65-gallon steel drum was filled with water with an insulated blanket heater secured around it for the quasi-static specimens. The water was monitored for at least 3 days to verify the water had reached 70°C. Before placing specimens into the weathering chamber, they are separated into their testing group and are double bagged in polyethylene bags with 3.5% saline water. The bags are sealed with an induction sealer. When specimens are removed from the weathering chamber, the salinity of the water is measured to verify if any leaking had occurred during the two-week period. The smaller specimens were placed in a beaker with 3.5% saline water solution that was heated to 70°C. The water was monitored daily to adjust for any evaporated water or change in salinity.

Mforsoh et al [8] performed an Arrhenius diffusion study and determined the activation energy of this polyurea. This study uses those results alongside a MATLAB code to determine time to saturation for each size of specimen. The larger specimens used for quasi-static experimentation required 6.8 days to saturation, while the smaller
specimens only required 2.3 days to saturation. To ensure all specimens were completely saturated before experimentation, all specimens were weathered for a total of 14 days, equivalent to approximately 4.4 months of service life at 17°C (average ocean temperature) or 12 months at -2°C (average arctic ocean temperature).

2.3. Experimental Setup

A Shimadzu Universal Testing Machine was used to obtain a strain rate of 0.005 /s. Each experiment was conducted at a crosshead speed of 3.81 mm/min. A modified Split Hopkinson Pressure Bar (SHPB) setup was used to obtain the dynamic response of the polyurea. An SHPB consists of an incident bar and a transmitter bar typically made of the same metal, and a striker bar whose properties are variable depending on desired input. Strain gauges are mounted to the incident and transmitter bars, two on each bar on opposite sides from one another, and are connected to a Wheatstone bridge, amplifier and oscilloscope for data acquisition. Figure 1 shows the setup of an SHPB. As the striker impacts the incident bar, a compressive pulse is generated and travels down the bar to the specimen. Due to the change in impedance from the specimen, some of the pulse is reflected as a tensile pulse and the rest is transmitted. Soft materials have a high impedance difference from metals, resulting in much of the signal becoming reflected. To overcome this, modifications to the SHPB can be made for soft materials. Decreasing the elastic modulus for the bars and the cross-sectional area of the transmitter bar can be done to amplify the low transmitted pulse that is generated. The SHPB used in this study consists of a 1.83 m incident and hollow transmitter bar of diameter 19.05 mm made of aluminum. The internal diameter of the hollow bar is 15.75 mm. Pulse shaping is an important technique for soft materials. Proper pulse shaping will increase the rise
time of the incident pulse allowing the specimen to reach equilibrium. A copper disk of 5.77 mm diameter and 0.813 mm thickness was used as a pulse shaper as well as a 330.2 mm aluminum striker bar.

Figure 1: Setup of the Split Hopkinson Pressure Bar.

In order to obtain the low temperature of -2°C, two boxes (one the universal testing machine and the other for the SHPB) insulated with fiberglass were constructed. A diagram of the insulated box can be seen in figure 2.
One end of a copper tube is set inside of the insulated box, with the other end connected to compressed air. The compressed air is passed through a desiccator before a methanol and dry ice bath to ensure the air is dry and blockages do not occur within the copper tube. A thermocouple was placed inside of the insulated box to verify the temperature. Once the box reached and maintained -2°C for 15 minutes for both the quasi-static specimens and dynamic specimens, then the experiment was started.

3. Results and Discussion

3.1. Quasi-static Response

3.1.1. Effect of Weathering

The true stress-strain response of the polyurea at \( 5 \times 10^{-3} \) /s can be seen in figure 3. In this figure, one can see the effects of the low temperature, weathering, and a combination of the two effects. The error bars represent the standard error of the sample
of at least six specimens. It can be seen in the figure that there was a loss in hardness of the material. The Young’s modulus decreased by 62% after the duration of weathering. Other properties such as strain energy and yield strength also exhibited a similar decrease, which can be seen in the table 1. This material does not exhibit the typical yielding behavior therefore the yield strength was calculated by the offset yield method with the offset percentage set at 0.5. This number was chosen as the yield does not appear to occur until after that point. This decrease in properties can be attributed to the water ingression in the material causing change in the material properties. There are two processes which can occur during water ingression, plasticization and hydrolysis. Plasticization is a temporary change in material properties due to the water molecules adjusting themselves within the polymer chain. This can be reversed by removing the water from the system. Hydrolysis is a chemical process which causes permanent change in the polymer change, resulting in a decrease in material properties.

Table 1: Material properties under quasi-static loading before and after exposure to saline water and low temperature environment.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Weathered (W) or Unweathered (UW)</th>
<th>Elastic Modulus (MPa)</th>
<th>Strain Energy Density at 20% strain (MJ/m³)</th>
<th>Yield Strain (%)</th>
<th>Yield Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>UW</td>
<td>96.09 ± 4.22</td>
<td>1.02 ± 0.03</td>
<td>4.75 ± 0.46</td>
<td>3.93 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>36.27 ± 1.32</td>
<td>0.44 ± 0.01</td>
<td>4.92 ± 0.17</td>
<td>1.61 ± 0.03</td>
</tr>
<tr>
<td>-2°C</td>
<td>UW</td>
<td>96.76 ± 2.65</td>
<td>1.10 ± 0.03</td>
<td>4.92 ± 0.75</td>
<td>4.27 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>39.13 ± 2.00</td>
<td>0.47 ± 0.01</td>
<td>5.02 ± 0.22</td>
<td>1.70 ± 0.07</td>
</tr>
</tbody>
</table>
3.1.2. Effect of Low Temperature and Weathering

Low temperatures are known to have an effect on amorphous polymers. Polyurea is also affected by this change in temperature. It can be seen in figure 3 that the low temperatures increase the stress response. At 20% strain the unweathered specimens saw an 8% increase in stress after testing at a low temperature. Similarly, the weathered specimens also saw a 7% increase in stress after exposure to the low temperature at 20% strain. This resulted in an increase of the Young’s Modulus from 96.09 to 96.76 MPa and 36.27 to 39.13 MPa, resulting in a 0.7% and 8% increase in unweathered and weather specimens, respectively. The change in Young’s modulus in the unweathered case is negligible as it is within the standard error range seen in the table. The yield stress and strain energy also increased with exposure to the low temperature before and after weathering. It can be seen in the figure that when unweathered specimens were exposed to the low temperature, after approximately 25% strain, the stress response appears to diverge. This may indicate strain hardening at the lower temperature that is not observed when the specimens are weathered.
3.2. Dynamic Response

The force equilibrium is an important part of dynamic experimentation. It is the first step in a SHPB experiment. The force equilibrium can be seen in the figure 5. The force equilibrium can be improved in the case of this polyurea. The discussion can be found in Appendix 1. Figure 4 shows the pulses obtained during the experiments which were of approximately 150 µs in duration.

Figure 3: True stress-strain diagram of the polyurea in the case of unweathered (UW) and weathered (W) at temperatures of 20° and -2°C.
Figure 4: Incident and transmitted pulses captured during an SHPB experiment.
3.2.1 Coupled Effects of Low Temperature and Weathering at a High Strain Rate

Similar to quasi-static conditions, exposure to saline water decreases the stress-strain response and the strain energy of the polyurea. The strain energy density under dynamic loading can be found in table 2. The strain energy decreased by 58% at 20% strain after weathering at room temperature. It also decreased by 32% when tested at the low temperature and exposed to saline water. When comparing the two weathered conditions, the strain energy increased by 30% when tested at the low temperature. However, between 10% and 20% strain, the stress does not continue to increase during
loading, but this does not occur at room temperature. In unweathered conditions, there is no significant change in response.

Figure 6: Stress-strain response of polyurea unweathered (UW) and weathered (W), at 20 and -2°C.
Table 2: Strain energy density of the polyurea at $2 \times 10^3 /s$ at 20% strain.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Weathered (W) or Unweathered (UW)</th>
<th>Strain Energy Density (MJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>UW</td>
<td>2.99 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>1.24 ± 0.09</td>
</tr>
<tr>
<td>-2°C</td>
<td>UW</td>
<td>2.37 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>1.62 ± 0.25</td>
</tr>
</tbody>
</table>

4. Conclusion

Polyureas are an important class of polymer as they are used in a wide range of applications. They are widely used in many applications and can be found in military and marine applications due to their properties. While previous studies have determined the effects weathering and temperature have on polyurea separately, this work determined the coupled effects of weathering, low temperature, and strain rate. In this study the following conclusions were made,

- Under quasi-static conditions weathering is the primary form of degradation in the material. It was found that Young’s modulus decreased by 62% from unweathered to weathered conditions at room temperature, but only increased by 0.7% when tested at the low temperature, when comparing the unweathered conditions.

- In unweathered, quasi-static conditions, the low temperature increased the Young’s modulus of the material. It can also be seen after 25% strain, there is
strain hardening. This is not seen in the polyurea when it was weathered when tested at room temperature and a low temperature.

- Under dynamic loading, weathering is also the primary mode of degradation. When specimens are unweathered, exposure to the low temperature does not cause a significant change in behavior. Weathered specimens saw an increase in stress response and increase in strain energy when exposed to the low temperature.

- As seen in previous studies, the polyurea exhibits strain rate dependence. The strain rate dependence is also seen after weathering and at the low temperature.
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The authors of this manuscript would like to kindly thank the Naval Engineering Education Consortium (NEEC) for the financial support in completing this project. They would like to thank Dr. Thomas Ramotowski and Dr. Irine Chenwi for their discussion and support with this project. They would also like to thank their colleagues at the Dynamic PhotoMechanics Laboratory for their insightful discussion and never-ending support especially Piyush Wanchoo and Tyler Chu.

References


Chapter 2

Mechanical Response of Polyurethane after Long Term Exposure to Marine Environment

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Abstract

In the marine industry, polyurethanes are a well-known material for use as they are water and tear resistant. Their properties allow the material to be an excellent choice for encapsulants for cable connectors and circuitry which during its service life may come in contact with sea water. In order to better understand how this material changes over time when exposed to sea water, a polyether based polyurethane was studied after long term exposure to saline water using accelerated weathering techniques. The specimens were weathered for 10, 48, 85, and 129 days simulating 1 month, 4.5, 8 and 12 months in real life service time, respectively. The quasi-static (2 x 10^{-3} /s) tensile and compressive behavior and the dynamic (2 x 10^3 /s) compressive behavior was studied. It was found that the exposure to saline water caused softening in the material which decreased mechanical properties. Under quasi-static conditions the Young’s modulus and strain energy decreased by a maximum of 57% in compression and 51% and 50% in tension. The dynamic strain energy also decreased by 83% after a 129 weathering days.
1. Introduction

Polyurethanes are an important and integral part of today’s society as it is used in a wide range of applications. It is an artificially made polymer, synthesized from a combination of isocyanates and polyols. It can be found commercially as a rigid or soft rubber in shoes, electronic encapsulants, over molds for cable connectors and circuitry, and as a foam in refrigerators and mattresses. It can also be found as an encapsulants for acoustic electronics on marine vessels and coatings on US Navy ships. Its durability and water resistance makes polyurethanes an ideal choice for some underwater applications. Many have studied the mechanical properties of thermoplastic and thermoset polyurethanes [1-4]. Qi studied the hysteresis and softening effects of polyurethane of a thermoplastic polyurethane [1]. The findings agreed with the known behavior of polyurethanes, exhibiting hysteresis, rate dependence and softening during cyclic tests. The stress-strain behavior of polyurethane has been studied with varying hard and soft segments of the polymeric chain [2]. Cho found that with increasing hard segment in the polyurethane, the yield behavior became more visible along with the dispersion of the material. The polyurethane with lower hard segments exhibited rubbery behavior, while that with the highest percentage of hard segments was glassy. The acoustic properties and dynamic mechanical properties of polyurethanes were also of interest [3]. Using the time-temperature superposition, it was found that both the shear modulus and loss tangent increased with increasing frequency.

While many have studied the mechanical response of polyurethanes ranging from low to high strain rates and the dynamic mechanical behavior, it is important to understand how the material will behave in its service environment after long term
exposure. Studies have shown how water ingestion or humid environments have on the behavior of polyurethane foams and rubbers [5,6,7-10]. When polyurethane foam was exposed to humid environments ranging from 40% to 100% relative humidity, the tensile failure stress behavior was found to decrease by a maximum of 30-40% as a result of plasticization [5]. The glass transition temperature also shifted from 67° to 5°C after the water absorption. Similarly, after exposure to sea water, the properties of a composite with polyurethane foam core were also degraded [6]. This study found that the flexural modulus and strength were decreased by the extended exposure, but the compressive properties were not affected. While previous works have investigated the chemical and physical changes of polyurethanes after exposure to different environments, this work seeks to understand the change in mechanical response of a polyether-based thermoset polyurethane rubber. Polyether-based urethanes are more resistant to water than ester-based urethanes and understanding their behavior after long term exposure to sea water is important to understand how it will affect the service life of components. In this study, accelerated life testing is used to observe the change in mechanical response of the polyurethane after long term exposure to saline water. Quasi-static compression and tensile tests were performed at a strain rate of $2 \times 10^{-3}$ and dynamic compression tests were conducted at a strain rate of $2 \times 10^{3}$ after exposure to 3.5% saline water at 70°C for 10, 48, 85, and 129 days.
2. Materials and Methods

2.1. Material Preparation

The polyurethane used was Conathane EN-1556 distributed by Ellsworth Adhesives. The polyurethane was mixed by a weight ratio of 100A:33B and degassed to remove bubbles introduced when stirring. The polyurethane was poured into the molds resulting in specimens which conform to ASTM D638 and D575. After gelling for 24 hours at room temperature, they were placed in the oven to cure for 10 hours at 100°C. After removing from the mold, each specimen was machined to the approximate thickness then sanded to a smooth finish. Once completed, they were moved to a desiccator to remove excess moisture before being prepared for weathering. The final specimen dimensions for quasi-static and dynamic compression specimens are 28.57 ± 0.15 mm in diameter and 12.45 ± 0.51 mm in thickness and diameter of 12.70 ± 0.13 mm and a thickness of 7.62 ± 0.25 mm, respectively.
2.2. Weathering Facility

The weathering facility, as seen in Figure 1, is 14-gallon stainless steel drum with a blanket heater and insulation wrapped around the outside. The pressure release valve releases any pressure that builds in the tank due to water evaporation or heat. Before placing the specimens in the tank, the specimen samples were separated into double polyethylene bags filled with 3.5% saline water, then sealed using an electric bag sealer.

![Figure 1: Weathering facility](image)

The duration of weathering time was determined by the acceleration factor found by equation 1,

\[ A = e^{\frac{E_a}{RT}} \left( \frac{T_2 - T_1}{T_1 T_2} \right) \]  

(1)

Where \( A \) is the acceleration factor, \( E_a \) is the activation energy, \( R \) is the ideal gas constant, \( T_1 \) is the service temperature, and \( T_2 \) is the accelerated aging temperature. The activation energy was known to be 16.32 kJ/mol (3.9 kcal/mol) and using equation 1 at 70°C, the
acceleration factor was found to be 2.84 which results in the service life equivalents that can be found in Table 1.

Table 1: Accelerated weathering time and service life equivalents of the polyurethane at 70°C.

<table>
<thead>
<tr>
<th>Weathering Time (days)</th>
<th>Service Life (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>48</td>
<td>4.5</td>
</tr>
<tr>
<td>85</td>
<td>8</td>
</tr>
<tr>
<td>129</td>
<td>12</td>
</tr>
</tbody>
</table>

2.3. Experimental Setup

Quasi-static experiments were conducted using a universal testing machine and dynamic material characterization done using a split Hopkinson Pressure Bar (SHPB). As seen in figure 2, there were two setups for each test during quasi-static testing. The compression setup is comprised of two plattens, one stationary and the other mobile and connected to the load cell. Similarly, the tensile setup had one stationary grip and one moving grip connected to the load cell. Sandpaper was placed between each grip face for additional support on the specimen. The Instron was set to displacement control at a crosshead speed of 1.72 mm/min for compression and set to 3.99 mm/min in tension in order to obtain a strain rate of 0.002 /s for each test type.
The setup for the SHPB can be seen in figure 3. A 1.828 m (6 ft) solid incident bar and 1.828 m (6 ft) hollow transmitter bar, of outer diameter of 19.05 mm (0.75 in) and inner diameter of 15.875 mm (0.625 in) made of aluminum 6061 were used. An aluminum striker bar of 330.2 mm (13 in) and 12.7 mm diameter was used. The gas gun was pressurized to 0.414 MPa (60 psi) and fired using a switch connected to a solenoid valve. This releases the striker bar which strikes the incident bar sending a compressive pulse through the bar and into the specimen. At the interface of the bar and the specimen,
due to impedance mismatch, much of the incident pulse is reflected back into the incident bar, while some is transmitted into the transmitter bar.

3. Results and Discussion

3.1. Percent Mass Change

Each specimen and test type was subject to an increasing number of weathering days at 70°C. Mass measurements were taken to observe the change in mass.

Table 2: Average percent mass change in percent for each specimen type and weathering time.
Table 2 shows that average percent mass change from each sample. It can be seen in the table that the percent mass change decreased by 19%, 30%, and 42% for the specimens used for compression, tension and dynamic compression, respectively. The decrease in percent mass implies that there is a loss of mass from each sample. This could be due to leaching of material during weathering over the duration of weathering.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.77 ± 0.43</td>
<td>1.86 ± 0.05</td>
<td>1.55 ± 0.04</td>
</tr>
<tr>
<td>48</td>
<td>1.60 ± 0.04</td>
<td>1.72 ± 0.16</td>
<td>1.25 ± 0.07</td>
</tr>
<tr>
<td>85</td>
<td>1.63 ± 0.12</td>
<td>1.53 ± 0.11</td>
<td>0.94 ± 0.08</td>
</tr>
<tr>
<td>129</td>
<td>1.42 ± 0.16</td>
<td>1.28 ± 0.05</td>
<td>0.42 ± 0.06</td>
</tr>
</tbody>
</table>
3.2. Quasi-Static Response

The polyurethane was tested in compression and tension at a strain rate of $2 \times 10^{-3}$/s. Figure 4 and figure 5 show the true stress-strain plot in compression and tension, respectively. In both compression and tension, the stress needed to deform the specimen decreased with an increasing number of weathering days. At 40% strain the stress decreased by 46.2% in compression and 45.6% in tension after 129 weathering days. It can be seen clearly in compression that the maximum decrease in stress was after 85 weathering days, which was a total of 55% change. This may be cause by many reasons, such as plasticization caused by the water and hydrogen within the polyurethane interacting. In tension, there is no significant change after 85 weathering days. The elastic modulus also decreased by a maximum of 57% after 85 days of weathering.

Figure 4: True stress-strain in compression at a strain rate of 0.002 /s.
Table 3 shows the elastic modulus in compression and tension for these experiments. There was a similar trend in compression at 85 weathering days, the elastic modulus was at a minimum of 3.783 MPa, then increased again after 129 weathering days to 4.551 MPa. Similarly, there is no significant change in elastic modulus after 85 weathering days in tension.

Figure 5: True stress-strain in tension at a strain rate of 0.002 /s.
Table 3: Elastic modulus in compression and tension over the weathering period.

<table>
<thead>
<tr>
<th>Weathering Time (days)</th>
<th>Elastic Modulus (MPa)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression</td>
<td>Tension</td>
</tr>
<tr>
<td>0</td>
<td>8.907 ± 0.515</td>
<td>7.110 ± 0.956</td>
</tr>
<tr>
<td>10</td>
<td>7.343 ± 0.329</td>
<td>5.299 ± 0.704</td>
</tr>
<tr>
<td>48</td>
<td>6.153 ± 0.367</td>
<td>4.193 ± 0.235</td>
</tr>
<tr>
<td>85</td>
<td>3.783 ± 0.403</td>
<td>3.452 ± 0.472</td>
</tr>
<tr>
<td>129</td>
<td>4.551 ± 0.317</td>
<td>3.578 ± 0.359</td>
</tr>
</tbody>
</table>

3.3. Dynamic Response

Obtaining good SHPB results first begins with equilibrium on both sides of the specimen face. Figure 6 shows the force on the incident side of the specimen compared to the transmitted side of the specimen. It can be seen in the figure that the force on the incident side follows the force on the transmitted side for the duration of the experiment.
The polyurethane exhibits a strain rate dependence at 2000 /s. It can be seen in Figure 6, the stress at 20% strain is 5.21 MPa at 2000 /s, while at 0.002 /s it is 1.47 MPa. It can also be seen in the figure that the stress continuously decreased with an increasing amount of weathering days, similar to the quasi-static cases. At 20% strain the maximum stress occurred with zero weathering time. The minimum stress occurred after 129 weathering days at 2.25 MPa, equating to a 57% decrease in stress after the total weathering time. The strain energy similarly decreases with an increasing amount of weathering days. After the total amount of weathering days, the strain energy
decreased by 57%, 50%, and 50% at 20% strain for compression, tensile, and dynamic compression tests, respectively.

One can also notice the increase in plateau region after the linear response. Interestingly, this stress-plateau behavior occurs with an increase in weathering time in the dynamic regime, but does not occur in the quasi-static regime. Unweathered specimens did not experience any plateau before 20% strain. At 10, 48, and 85 weathering days, the plateau region begins to form at 15% strain and remains constant for the remainder of strains. Finally, at 129 weathering days the plateau begins at 10% strain. Xu et al [7] studied the effects of water at 37°C on the tensile and dynamic mechanical behavior and structure of multiple polyurethane blends. This study discusses softening as a decrease in modulus. Similar to this work, their polyurethanes experienced softening in quasi-static experiments and yielding in dynamic experiments after exposure. They found that this was due to the water interacting with the hydrogen in the polyurethane structure. This may be the case as well, however since all specimens
experienced leaching it may also be possible that the rigid segments in the polymer chain were affected by the extended duration of weathering.

Figure 7: True stress-strain plot in dynamic compression at a strain rate of 2000 /s with varying weathering days (WD).
Table 4: Strain energy density of all experiment types over the weathering period.

<table>
<thead>
<tr>
<th>Weathering Time (days)</th>
<th>Strain Energy Density (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quasi-static Compression</td>
</tr>
<tr>
<td>0</td>
<td>0.150 ± 0.012</td>
</tr>
<tr>
<td>10</td>
<td>0.124 ± 0.002</td>
</tr>
<tr>
<td>48</td>
<td>0.106 ± 0.004</td>
</tr>
<tr>
<td>85</td>
<td>0.065 ± 0.005</td>
</tr>
<tr>
<td>129</td>
<td>0.081 ± 0.005</td>
</tr>
</tbody>
</table>

4. Conclusions

Polyurethanes have been a choice of polymer for many years due to its material properties. A polyether-based polyurethane was used in this study to observe the changes in mechanical behavior after long term exposure to saline water. The quasi-static compressive and tensile behavior was studied as well as the dynamic compressive behavior. The results found led to the following conclusions:

- The percent mass change decreased which implies leaching of material.
- Under quasi-static loading Young’s modulus and well as strain energy density decreased, in both compression and tension. There was no observed yielding behavior.
- Under dynamic loading the strain energy density also decreased. however, there was significant change in the stress behavior. With an increasing amount of weathering time, the stress needed for deformation decreased, resulting in a
stress-plateau region. This was due to the softening of the polyurethane and the water interaction in the polymer chains.
Acknowledgments

The authors would like to kindly thank the Naval Engineering Education Consortium for their financial support. They would like to thank Dr. Thomas Ramotowski and Dr. Irine Chenwi for their discussion and support with this project. They would also like to thank their colleagues at the DPML.

References


Chapter 3

Hanging Weight Peel Behavior of Primer/Polyurethane System

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Abstract

Cable connectors are an integral part of submarine communication systems. Some of these cables can be found on the exterior of ship hulls exposing them to the aggressive marine environment. The sea water along with factors, such as the cable weight, may accelerate the failure of these cables. In this study, a polyurethane and primer subject to peel tests using a static load of 2.27 kg (5 lbs) while submerged in saline water and in air at two temperatures of 20 and 55°C. The contact angles of the Monel, primer and polyurethane surface were taken to understand the mode of failure when comparing the underwater to air experiments. Conventional peel tests were conducted to determine the peel strength of the system while in air at room temperature. When submerged under saline water, it was found that the average time to peel significantly increased when they were placed in air at room temperature when compared to the other conditions.
1. Introduction

Underwater cable systems are a crucial part in fiber optic networks and submarine communications. Polymers have been the optimal choice for jackets and encapsulants of these systems as they are durable and water resistant. However, these cable systems are exposed to the aggressive marine environment, leading to damage, failure, and expensive repairs. These polymers are known to delaminate from the metal substrate they are bonded to for reasons including cathodic delamination and even the weight of the cable during use. Understanding the mechanism of these failures have been of interest for much time. Many have studied the effects of cathodic delamination on polymer and metal interfaces [1-6]. Ramotowski et al discuss the effects of long term exposure of two primers and polyurethanes to sea water in the presence of a zinc anode [1]. It was found that the exposure to this environment caused a “window frame” like delamination on the primer caused by the exposed areas on the interface. In another study, Ramotowski investigates multiple environmental effects, including concertation of salt, temperature and dissolved oxygen content, on the cathodic delamination of a primer and polyurethane [2]. Interestingly, it was found that the rate “window frame” grows increases with higher concentration of salt and also larger sized salt molecule. Similarly, Makama et al. also found the “window frame” of primer on a stainless steel and titanium substrate when subject to a similar corrosive environment [4].

The effects water and saline water exposure on polymer coatings have also been investigated [7-10]. Chenwi et al investigated how exposure to saline water changes the peel strength of polyurea bonded to a Monel 400 substrate [7]. It was found that
extended exposure to saline water decreased the strength by 83% in 180° peel test. When a polyurethane bonded to an aluminum substrate and pressure cycled in water, it was found that the fracture energy decreased after two weeks [8]. It was then found that the water may have decreased the strength of the polyurethane after two weeks of pressure cycling, resulting in only slight decrease in fracture energy. One study also investigated and developed a model on the thin film peel behavior when exposed to humid environments [9]. They found that the relative humidity, alongside the surface energy of the substrate and film can either improve or lower the force needed to peel off the thin film. These studies have demonstrated that water plays a significant role in the peel strength and adhesion energy of polymers bonded to metal substrates.

Many studies have also explored how the composition of polyurethanes, preparation of bonding surface and film thickness [11-16]. These studies have identified the many environmental factors which affect the adhesion behavior of polymers bonded to metal substrates, with cathodic delamination and water being two major factors. Considering the service environment of these polyurethanes, submarine cable jackets and connectors, it is important to investigate other factors which may play a role in delamination, namely the weight of the cable. This study uses a polyurethane and primer bonded to a metal substrate and subjects them to static load peel tests to simulate the weight of the cable on the polyurethane jacket. The tests are conducted both underwater and in air at two temperatures to compare how the two environment (air and underwater) effect the time to peel when loaded with a 2.27 kg weight. Contact angle measurements using deionized and saline water were performed on the surfaces of the system to infer
the wettability of each part of the system. The peel strength was determined using 90° peel tests in air at room temperature.

2. Materials and Methods

Monel 400 is an alloy primarily composed of nickel (63.0% minimum) and copper (28-34%), making it an optimal choice for seawater applications as it does not readily corrode. It is used as the metal substrate in this study. The polyurethane used is CPD-9130 distributed by Ellsworth Adhesives. PR-425 is the primer used in this study. It is found as an adhesion promoter for metals and polyurethanes used in underwater environments.

2.1. Material Fabrication and Specimen Geometry

The Monel 400 substrate is of dimensions 101.6 mm (4 in) in length, 25.4 mm (1 in) in width, and 3.175 mm (0.125 in) thick, was first sandblasted to an average surface roughness of 1.55 µm (61 µin) using silica beads at a pressure of 440 kPa. The metal substrate was then rinsed with warm water then thoroughly cleaned with acetone. An inch from each end of the metal substrate was taped off, leaving a 50.8 mm bare section for the primer to be bonded to. The primer was mixed then painted on the bare section of each substrate. After the primer was cured, the substrates are moved to the mold where they are coated in the polyurethane. They are left to cure overnight before removing from the mold. The final thickness of the polyurethane on the substrate is 6.35 mm (0.250 inches). The final specimen can be seen in figure 1.
2.2. Experimental Setup

2.2.1. 90° Peel Experiments

The 90° peel tests were conducted using screw driven universal testing machine, shown in figure 2. The substrate was carefully secured to the sliding rig and under the mandrel. The mandrel is used to ensure the polyurethane remains in 90° throughout the experiment. Then, the peel arm was fixed into the movable upper grip using sandpaper for additional support and to avoid any slipping. The loading rate was set to 50.8 mm/min.
2.2.2. Air and Underwater Hanging Weight Experiments

A sample rack was used to hold specimens in place in air and underwater. The sample rack and setup for the underwater peel experiments can be seen in figure 3. Experiments conducted underwater were held at constant temperatures of 20° and 55°C using two SousVide heaters and a salinity of 3.5% NaCl. Experiments conducted in air at 55°C were placed in an oven, while experiments conducted at 20°C were placed on table with a thermocouple monitoring the ambient temperature. A CCD camera was used to capture images at 2 frames per minute. Once specimens were placed on the rack, two minutes for final setup was taken before starting the image capture. The two-minute wait time was used in the final calculation of time to peel.
3. Experimental Results and Discussion

3.1. Contact Angle Measurements

The contact angle of the cured polyurethane surface, cured primer surface, and cleaned Monel surface were collected using deionized water and 3.5% saline water solution at 20°C. Each droplet was 2 µL. Using these measurements, one can infer the wettability or surface free energy of the surfaces. For example, if a water droplet on a surface has a contact angle greater than 90°, it has low surface energy and would be hydrophobic. A contact angle greater than 90° implies increased wettability and higher surface energy. Table 1 shows the contact angles for the different surfaces using the two types of water. These experiments were done to predict how the water would behave between each of the layers.
Table 1: Contact angles in degrees on the Monel, primer, and polyurethane surface using deionized water and 3.5% saline water.

<table>
<thead>
<tr>
<th></th>
<th>Deionized water</th>
<th>3.5% Saline Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monel</td>
<td>63.78</td>
<td>62.13</td>
</tr>
<tr>
<td>Primer</td>
<td>56.62</td>
<td>59.94</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>76.15</td>
<td>92.89</td>
</tr>
</tbody>
</table>

The polyurethane had the highest contact angle in each case supporting the hydrophobic nature of the polyurethane. The sodium chloride dissolved in the water increased the contact angle of the polyurethane. The 3.5% saline water solution is more hydrophobic on the polyurethane. Similarly, the contact angle of the saline water solution was higher than deionized water. The Monel surface had the opposite effect, where the contact angle at the Monel water interface was slightly lower when using saline water. Since the primer and Monel have similar contact angles, it can be implied that the two materials would have the better bond.

3.2. 90° Peel Experiments

The 90° peel tests were done to calculate the peel strength of the system. Figure 4 shows five trials of the test. The peel strength of this system was taken as an average of the five trials, which was 6.08 N/mm.
3.3. Hanging Weight Experiments

Static load experiments were conducted underwater and in air at both 55°C and 20°C. Figure 5 shows the time to peel for each experiment type. When specimens were placed under at 55°C, all specimens failed within one minute and fifteen seconds, all specimens were assumed to fail at that time. It can be seen in the figure that all underwater experiments had the shortest time to peel. This can be attributed to degradation of the exposed interface caused by the water. This is also seen in the figure, where the average...
time to peel increased to 133 minutes when placed in air at 20°C resulting in an approximate 96% decrease in time when place underwater at 20°C. It can also be seen in the figure that temperature also plays a role in the time to peel. When comparing the specimens tested in air, there is a significant increase in time to peel once they are tested at room temperature. This can be seen when specimens are tested underwater, but the change is not as substantial. Ramotowski [2] also saw the rate of window frame growth increase with increased temperature, however this is attributed to the increase in current density when specimens were weathered underwater with a zinc anode.

Figure 5: Average time to complete peel for each experiment type.
3.4. Coupon Surfaces

Images of the surfaces after experimentation can be seen in figure 6. It can be seen in the image that specimens tested at room temperature underwater and in air remained with the primer on the Monel coupon. It can be seen in the figure that at room temperature, the primer’s bond to the Monel was not affected by the saline water, but by the rate of the peel. This can be supported by the contact angle measurements which were taken at room temperature. On the other hand, specimens tested at 55°C failed with the majority of the primer on the polyurethane surface. In this case, the temperature played a significant role in the delamination of the primer from the Monel.

![Figure 6: Coupon and polyurethane surfaces after experiments (a) in 90° peel, (b) at 20°C in air, (c) at 20°C underwater, (d) 55°C in air, and (e) 55°C underwater.](image-url)
4. Conclusions

Polyurethanes bonded to metal substrates can be greatly affected the service environment. Previous studies demonstrated a decreased in peel strength and adhesion energy of polyurethane after exposure to aggressive marine environments. This was done to understand how the statically loaded peel behavior of a polyurethane bonded to a primer and Monel substrate would change when exposed to saline water and air and two temperatures, the following was found from this study:

- The peel strength of the polyurethane and primer was found to be 154.5 N/25 mm under 90° peel tests.
- When subject to static load tests, the presence of water caused the time to peel to decrease by 68% at 55°C and by 95% at 20°C. Water had a greater influence in the time to peel at room temperature.
- Contact angle measurements were taken at room temperature (20°C). The cleaned Monel surface had a similar contact angle to the primer with both deionized and 3.5% saline water. This implies that the Monel and primer have a better bond than the primer and polyurethane, this is supported by the surfaces post mortem. When subject to 90° peel test and the other tests at room temperature, the primer primarily stayed on the Monel surface.
Acknowledgments

The authors would like to kindly thank the Naval Engineering Education Consortium for their financial support. They would like to thank Dr. Thomas Ramotowski and Dr. Irine Chenwi for their discussion and support with this project. They would also like to thank their colleagues at the DPML.

References


**Future Work**

This work focused on the arctic marine environmental effects on polyurea; long-term exposure to saline water on a polyurethane; and finally, how saline water environment effects the peel behavior of a polyurethane bonded to a metal substrate using a primer. These studies will aid in the choice of materials as well as help understand how exposure to ocean water may affect the service life of these polymers. It was found that the behavior of these polymers was greatly influenced by their environment, and therefore it is important to further investigate the factors that may degrade their properties. The following studies are recommended,

- High strain rate behavior was investigated for two polymers after exposure to saline water. It would be interesting to see the dynamic mechanical behavior of these polymers after exposure to saline water to obtain other dynamic material properties, such as the elastic modulus. It would also be interesting to observe whether there is a change in glass transition temperature after exposure to saline water.

- Ramotowski studied the effects of environmental factor on the rate of cathodic delamination of a polyurethane bonded to a metal substrate. In his study, the salt content of the water bath was changed to observe the rate of cathodic delamination. It was seen that at the higher salinity, the rate increased. In a different sense, it would be interesting to see how the rate of diffusion in these polymers is affected by salt content, as well as other possible environmental factors.
Finally, the peel behavior of a primer and polyurethane system should be investigated further. Initially, the underwater hanging weight peel behavior was to be investigated in the presence of a zinc anode. However, due to limitations using the polyurethane and primer system, it was unable to be accomplished. This study would help to determine the role cathodic delamination plays in the debonding of a polyurethane coated cable connector under a static load.
APPENDICES

Appendix A – Calculating stress and strain for Split Hopkinson Pressure Bar

Due to the wave mechanics during the loading in a SHPB experiment, the stress, strain and strain rate values cannot be taken as the same under quasi-static loading. The equation for nominal stress, strain and strain rate under quasi-static loading can be seen in equations 1-3.

\[
\sigma = \frac{F}{A} \quad \text{(1)}
\]

\[
\varepsilon = \frac{\Delta L}{L} \quad \text{(2)}
\]

\[
\dot{\varepsilon} = \frac{\varepsilon}{t} \quad \text{(3)}
\]

The true stress and strain can then be found as,

\[
\sigma_T = \sigma (1 + \varepsilon) \quad \text{(4)}
\]

\[
\varepsilon_T = \ln(1 + \varepsilon) \quad \text{(5)}
\]

Under quasi-static conditions, it can be assumed that the specimen is deforming uniformly and the stress at each point of the specimen is equal. However, under dynamic loading it is assumed that the load is the average of the load at the incident and transmitted face. Therefore, the nominal stress, strain and strain rate within the specimen is given as,

\[
\sigma = \frac{E_b A_b}{2A_s} (\varepsilon_i + \varepsilon_r + \varepsilon_t) \quad \text{(6)}
\]

\[
\varepsilon = \frac{c}{l_s} \int_0^t (-\varepsilon_t + \varepsilon_i - \varepsilon_r)dt \quad \text{(7)}
\]
\[ \dot{\varepsilon} = \frac{c}{l_s} (-\varepsilon_t + \varepsilon_i - \varepsilon_r) \quad (8) \]

Where \( \varepsilon_i \) is the strains upon incident loading, \( \varepsilon_r \) is the strain upon reflected loading, and \( \varepsilon_t \) is the strain upon the transmitted loading. Also \( A_s \) is the cross-sectional area of the specimen and \( A_b \) being the cross-sectional area of the bar. If force equilibrium is established, one can assume the specimen deforms uniformly. Therefore, equation 9 is valid.

\[ \varepsilon_i + \varepsilon_r = \varepsilon_t \quad (9) \]

Equations 6-8 can be further simplified using equation 9. Given the SHPB used in the two studies had a hollow transmitter bar, the change in cross-sectional area needs to be accounted for and the equations need to be adjusted. If equilibrium is established, then equation 10 holds true,

\[ \varepsilon_t = \frac{A_i}{A_t} (\varepsilon_i + \varepsilon_r) \quad (10) \]

Where \( A_i \) is the cross-sectional area of the incident bar and \( A_t \) is the cross-sectional are of the transmitter bar. Equation 10 can then be substituted into equation 7 to give the following.

\[ \varepsilon = \frac{c}{l_s} (1 - \frac{A_i}{A_t}) \int_0^t \varepsilon_i \, dt - \frac{c}{l_s} (1 + \frac{A_i}{A_t}) \int_0^t \varepsilon_r \, dt \quad (11) \]

The nominal stress can also be found by substituting equation 9 into equation 6. The nominal stress becomes,

\[ \sigma = \frac{E_b A_t}{A_s} \varepsilon_t \quad (12) \]

And the strain rate remains as,
\[ \dot{\varepsilon} = -\frac{2c}{l_s} \varepsilon_r \quad (13) \]

Finally, the true stress, strain and strain rate can be found as equation 4 and 5.

The true strain rate is then,

\[ \dot{\varepsilon}_t = \frac{\varepsilon \cdot \sigma_T}{1 - \varepsilon \sigma_T} \quad (13) \]
Appendix B – Obtaining force equilibrium in polyurea

In an attempt to obtain lower strain rate response of this material, it was found that increasing the length of the pulse enhances the equilibrium. This was done by increasing the length of the incident bar on the SHPB. This modification, which is discussed in [Chen], is used to obtain lower strain rates than the original setup. A striker bar with a lower material wave speed is used, as it takes longer for the incident pulse generated in it on impact to travel to the incident bar, resulting in a longer incident pulse. In this case, a 304.8 mm PBT rod of 12.7 mm diameter was used as the striker bar fired at 448 kPa (65 psi). This resulted in a strain rate of 500 /s. The pulse length increase can also be seen in figure 2 when compared to Chapter 1 figure 4, where the pulse length from the short SHPB setup is approximately 150 µs, while the longer SHPB setup had a pulse length of almost 500 µs.
Figure 1: Force on incident and transmitted side of the specimens at 500 /s with an extended pulse length.
Figure 2: Incident and transmitted pulse obtained using polymer striker bar.
BIBLIOGRAPHY


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