A compilation on
High Modulus Polyethylene Fibers
(HMPE)

May 2010
Different Names

- HMPE (High modulus polyethylene)
- UHMWPE (Ultra high molecular weight polyethylene)
- UHMPE (Ultra high modulus polyethylene)
- HPPE (High performance polyethylene)

SEM image of HMPE

PE Chemical Formula

![Polyethylene structural formula](image-url)
PE molecular chains

Molecular structure compared to p-Aramids

- Aramid molecules have straight rod-like structure even before polymer spinning into fiber;
- PE molecules are forced to have straight orientation in the fiber direction during spinning/stretching.

Normal PE vs. HMPE

<table>
<thead>
<tr>
<th>Normal PE</th>
<th>HMPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low molecular weight</td>
<td>• Ultra-high molecular weight</td>
</tr>
<tr>
<td>• Shorter molecular chains</td>
<td>• Longer molecular chains</td>
</tr>
<tr>
<td>• The molecules are not well-orientated and</td>
<td>• To make strong fibers, the molecular</td>
</tr>
<tr>
<td>are easily torn apart</td>
<td>chains are stretched, oriented</td>
</tr>
<tr>
<td></td>
<td>and crystallised in the direction of the</td>
</tr>
<tr>
<td></td>
<td>fiber</td>
</tr>
</tbody>
</table>

Unsuitability of melt spinning of HMPE

- Spinning is difficult because of extremely high melt viscosity
- Drawing is not efficient due to high entanglement of molecular chains

HMPE feedstock polymer for spinning

- Flexible PE polymer has a very weak interaction between the molecular chains
- Only the Van der Waals forces are active
- This interaction is so weak that for strong fibers, ultra-long chains with a high overlap lengths are required.
- Thus starting material for the high-performance polyethylene fibers is polyethylene with an average molecular weight of one million or more

Gel Spinning

- The molecules are dissolved in a solvent and spun through a spinneret.
- In the solution the molecules become disentangled and remain in that state after the solution is spun and cooled to give filaments.
- The term ‘gel spinning’ derives its name from the gel-like appearance of the dissolved polymer/solidified filament
- Because of its low degree of entanglement, the gelspun material can be drawn to a very high extent
- As the fibre is superdrawn, a very high level of macromolecular orientation is attained
Gel spinning

HMPE is dissolved in a solvent and then spun through small orifices (spinneret). Successively, the spun solution is solidified by cooling, which fixes a molecular structure which contains a very low entanglement density of molecular chain. This structure gives an extremely high draw ratio and results in extremely high strength. The gel-like appearance of the solidified fiber is the origin of the name of this technology. The highly drawn fiber contains an almost 100% crystalline structure with perfectly arranged molecules, which promotes its extremely high strength, modulus and other excellent properties.
Key HMPE Properties

- High strength and high modulus with low density (<1, floats in water)
- Extremely high specific strength and specific modulus because of low density
- Low melting point
- Hydrophobicity
- Biological inertness

Chemical Name: Polyethylene
Short Form: PE
Density [g/cm³]: 0.97
Melting Point (°C): 150
Main Trade Names: Dyneema (DSM), Spectra (Honeywell)

Reasons for high strength

- Ultra high molecular weight (> 1 million) polymer
- Ultra high spinning draw ratio (50-100 times)
- High molecular chain orientation
- High crystallinity

Tenacity
Stress-Strain Curve

Tenacity vs. Modulus
Specific Gravity

Density of Some Fibers

HMPE is the only high performance fiber that floats on water (density below 1.0 g/cm³)

Weight and volume saving

Specific modulus
The high specific modulus is also relevant in ballistic protection. The **sonic velocity** in the fiber determines the **speed of spreading energy** on ballistic impact and the sonic velocity is calculated as the square root of the specific modulus.

**Free breaking length**

Free breaking length is the theoretical length at which a rope breaks under its own weight.

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMPE</td>
<td>400</td>
</tr>
<tr>
<td>Aramid</td>
<td>235</td>
</tr>
<tr>
<td>Carbon fibre</td>
<td>195</td>
</tr>
<tr>
<td>Glass</td>
<td>135</td>
</tr>
<tr>
<td>Polyester/Nylon</td>
<td>85</td>
</tr>
<tr>
<td>Steel</td>
<td>25</td>
</tr>
</tbody>
</table>
Chemical Stability

Table Resistance of fibres to various chemicals: 6 months immersed at ambient temperature

<table>
<thead>
<tr>
<th></th>
<th>HPPE</th>
<th>Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Sea water</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>10% detergent</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Hydrochloric acid (pH = 0)</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Nitric acid (pH = 1)</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Glacial acetic acid</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Ammonium hydroxide</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Sodium hydroxide (pH &gt; 14)</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td>Petrol</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Kerosene</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Toluene</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Trichloromethane</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

*** Unaffected  ** slightly affected  * seriously affected.

Resistance to acids and alkalis

![Graph showing resistance of HPPE and Aramid in acids and alkalis over time]

pH Stability

HMPE is sensitive to oxidizing media. In strongly oxidizing media, fibres will lose strength very fast.
Hydrophobicity

- HMPE is not hygroscopic
- It does not absorb water

Light Stability
UV Resistance

![Graph showing UV resistance over time for different materials: HPPE, PES, PA, Aramid, and LCP (Vectran).](image)

Contraction with Temp.

![Graph showing thermal contraction vs. temperature for various FRP materials.](image)

Toshio Kajima et al. Summary of lecture at Cryogenics - Superconductivity Society 245 (1991)
Heat Conductivity

![Graph of Heat Conductivity](image)


Electrical Properties

Polyethylene is an insulator and has no groups with dipole character.

**Volume Resistivity** > $10^{14}$ Ωm

Very Low dielectric loss factor ($2 \times 10^{-4}$)

- Low dielectric constant (2.2-2.5)
- As spun yarns contain a small fraction of spin oil of a hydrophilic nature. So, for applications where the electrical properties are important, the spin finish should be removed.
The lower the value of the dielectric constant, the greater its resistance to the flow of an electrical current.

### Dielectric Constant of different materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Min.</th>
<th>Max.</th>
<th>Material</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>1</td>
<td>Nylon</td>
<td>3.4</td>
<td>22.4</td>
</tr>
<tr>
<td>Amber</td>
<td>2.6</td>
<td>2.7</td>
<td>Paper</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Asbestos fiber</td>
<td>3.1</td>
<td>4.8</td>
<td>Paraffin</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Balleite</td>
<td>5</td>
<td>22</td>
<td>Plexiglass</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Barium Titanate</td>
<td>100</td>
<td>1250</td>
<td>Polycarbonate</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Beeswax</td>
<td>2.4</td>
<td>2.8</td>
<td>Polyethylene</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Cambric</td>
<td>4</td>
<td>4</td>
<td>Polymide</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Carbon Tetrachloride</td>
<td>2.17</td>
<td>2.17</td>
<td>Polystyrene</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>Cellubid</td>
<td>4</td>
<td>4</td>
<td>Porcelain</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>Cellubse Acetate</td>
<td>2.9</td>
<td>4.5</td>
<td>Quartz</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Dunita</td>
<td>4.7</td>
<td>5.1</td>
<td>Rubber</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ebonite</td>
<td>2.7</td>
<td>2.7</td>
<td>Ruby Mica</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>3.4</td>
<td>3.7</td>
<td>Selenium</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Ethyl Alcohol</td>
<td>6.5</td>
<td>25</td>
<td>Shellac</td>
<td>2.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Fiber</td>
<td>5</td>
<td>5</td>
<td>Silicone</td>
<td>3.2</td>
<td>4.7</td>
</tr>
<tr>
<td>Formica</td>
<td>3.6</td>
<td>6</td>
<td>Slate</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Glass</td>
<td>3.0</td>
<td>14.5</td>
<td>Sol dry</td>
<td>2.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Glass Pyrex</td>
<td>4.0</td>
<td>5</td>
<td>Steatite</td>
<td>5.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Gutta Percha</td>
<td>2.4</td>
<td>2.8</td>
<td>Styrofoam</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>Isolantite</td>
<td>3.1</td>
<td>6.1</td>
<td>Teflon</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Kevlar</td>
<td>3.5</td>
<td>4.5</td>
<td>Titanium Dioxide</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Lucite</td>
<td>2.5</td>
<td>2.5</td>
<td>Vaseline</td>
<td>2.16</td>
<td>2.16</td>
</tr>
<tr>
<td>Mica</td>
<td>4</td>
<td>9</td>
<td>Vinylt</td>
<td>2.7</td>
<td>7.5</td>
</tr>
<tr>
<td>Micarta</td>
<td>3.2</td>
<td>5.5</td>
<td>Water distilled</td>
<td>34</td>
<td>78</td>
</tr>
</tbody>
</table>


Dielectric Strength

The maximum electric field strength that an insulating material can withstand intrinsically without breaking down, *i.e.*, without experiencing failure of its insulating properties

Miscellaneous

Vibration damping
Dyneema® has excellent vibration damping characteristics.

Insulation
Fundamentally a form of polyethylene, Dyneema® possesses the same chemical properties, making it an outstanding insulator.

Environment
As indicated by its chemical formula -(CH2-CH2)n- Dyneema® is formed from carbon(C) and hydrogen(H). Consequently, even if Dyneema® is burned all that remains is water (H2O) and carbon dioxide(CO2) and no harmful substances are released.
Coolness to Touch

Cut Resistance

Impact Strength & Energy Absorption

- Dyneema® SK60 has an extremely high impact strength.
- Extremely high amounts of energy absorption
- This property is utilized in products for:
  - ballistic protection,
  - cut-resistant gloves
  - helmets

Fatigue
• Good fatigue resistance properties
• Carbon fibers may have high modulus but are brittle whereas HPPE is flexible and has longer flex life
• In tension fatigue testing, a rope is repeatedly loaded in tension and relaxation cycles
• In bending fatigue or flex-life testing, a loaded rope is moving over two or three sheaves

Abraision Resistance and Flex Life

Dyneema® has excellent abrasion and fatigue resistance. Due to its ability to be processed easily (weaving, knitting etc.), this leads to wide applications for industrial use.
Biological Resistance & Toxicity

- HMPE is not sensitive to attach by micro-organisms
- HMPE is considered as biologically inert fiber
  - Suitable for medical applications

Thermal Properties

HMPE fiber has a melting point between 144°C and 152°C. The tenacity and modulus decrease at higher temperatures but increase at sub-zero temperatures. There is no brittle point found as low as -150°C, so the fiber can be used between this temperature and 70°C.
Flame Retardance

- LOI index lower than 20
- HMPE is thermoplastic, melts at about 150°C and decomposes over 300°C.
- Aramid fibres are thermosets, there is no melting point and gas emission starts at about 400°C.
- Polyethylene contains only carbon and hydrogen and no nitrogen or other hazardous chemical elements
  - Toxicity of the gases is relatively low

Compressive Yield Strength

In contrast to the high tensile strength, the gel-spun fibre has a low compressive yield strength, approximately 0.1 N/tex.

Viscoelasticity

- Polyethylene is a viscoelastic material, i.e.
- Its tenacity, tensile modulus and elongation at break depend on the temperature and the strain rate
- At high strain rates, or alternatively at low temperatures, both modulus and strength are significantly higher
  - Important in ballistic protection

Creep

- The fibre is prone to creep;
- The deformation increases with loading time, resulting both in a lower modulus and a higher strain at rupture
  - Important in ropes
- Creep is different in different fiber grades

Acoustic Properties

As with all mechanical properties, the acoustic properties are strongly anisotropic. In the fibre direction, the sound speed is much higher (10 – 12x10³ m/s) than in the transverse direction (2x10³m/s).
## Summary of HMPE Properties

### Water and chemicals
- **Moisture regain**: zero
- **Attack by water**: none
- **Resistance to acids**: excellent
- **Resistance to alkalis**: excellent
- **Resistance to most chemicals**: excellent
- **Resistance to UV light**: very good

### Thermal
- **Melting point**: 144–155 °C
- **Boiling water shrinkage**: <1%
- **Thermal conductivity (along fibre axis)**: 20 W/mK
- **Thermal expansion coefficient**: $-12 \times 10^{-6}$ per K

### Electrical
- **Resistance**: $>10^{14}$ Ohm
- **Dielectric strength**: 900 kV/cm
- **Dielectric constant (22 °C, 10 GHz)**: 2.25
- **Loss tangent**: $2 \times 10^{-4}$

### Mechanical
- **Axial tensile strength**: 3 GPa
- **Axial tensile modulus**: 100 GPa
- **Creep (22 °C, 20% load)**: $1 \times 10^{-2}$ % per day
- **Axial compressive strength**: 0.1 GPa
- **Axial compressive modulus**: 100 GPa
- **Transverse tensile strength**: 0.03 GPa
- **Transverse modulus**: 3 GPa
Applications: Ballistic Protection

Boats and Ships
- Dynexcel® is durable, resistant to UV exposure, and maintains ballistic integrity when wet.

Aircraft
- Dynexcel® offers the highest strength-to-weight ratio available.

Land Vehicles
- When deploying tactical and utility vehicles, Dynexcel® is with you when it matters.

Inserts
- Inserts made with Dynexcel® offer enhanced stopping power at lighter weight.

Vests
- Vests made with Dynexcel® provide maximum strength with minimum weight.

Helmets
- Dynexcel® in helmets: Enhanced protection without the weight.

Ballistic Shields
- Shields made with Dynexcel® are lighter in weight, improving performance in the field.
Applications: Safety Gloves

![Comfort vs. cut resistance: Why compromise?](image)

Dyneema® Diamond Technology  Aramid

Relative Heat Conductivity (W/mK)

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyneema® Diamond Technology</td>
<td>4</td>
</tr>
<tr>
<td>Nylon</td>
<td>2</td>
</tr>
<tr>
<td>Aramid</td>
<td>1</td>
</tr>
</tbody>
</table>

Relative diameter of yarn required to achieve gloves that rated at EN388 cut level 3, ANSI cut level 2.

![Relative diameter of yarn](image)

Nylon  p-Aramid  HMPE  Dyneema® Diamond Technology

Applications: Ropes
Mooring ropes made with HMPE are used to secure ultra-large ships in the 250,000t and 300,000t class to the port, such as ore carriers, crude oil tankers, LNG tankers. Also, that’s the rope used by tug boats.

**Applications: Fishing line/Cord**

![Fishing line/Cord](image)

**Applications: Sail Cloth**

*Sail Cloth*

Delivering the perfect balance of strength and weight, Dyneema® fiber is the ideal material for today’s revolutionary new sail designs.

With low stretch characteristics that let sails retain an optimal shape and a pure white appearance that’s resistant to abrasion, as well as chemicals, salt and UV rays. And that’s why the sails’ useful service life exceeds that of other materials—exponentially.
Applications: Nets

Applications: Fiber-reinforced cement (FRC) and Fiber-reinforced plastic (FRP)

Applications: Unidirectional Laminates

Dyneema® Unidirectional (UD) technology is a composite laminate that provides excellent energy absorption and enhance protection at low weight.

The energy from an impact to be distributed along the fibers much faster and more evenly than conventional, woven fabrics Dyneema® UD is ideal for personal protection applications (vests, helmets, and inserts) and vehicle armor of all types (land, air, and sea).

Dyneema Purity® SGX fiber: in Medtech

• 15 times stronger than steel,
• 40% stronger than aramids on a weight-by-weight basis
• 3 times stronger than polyester on a volume basis
Dyneema Purity: Surgical Implants

- High strength and high modulus
- High pliability and softness
- Lower profile with equivalent strength
- Proven biocompatibility
- Non-hemolytic
- Cut resistant
- Low friction coefficient

Dyneema Purity in Cardiovascular Application

• Dyneema Purity fiber allows predictable diameter throughout the entire length of the balloon, ensuring complete inflation.
• Strongest fiber in the world with little to no elongation.
• Excellent biocompatibility, enforcing non-compliance at high pressures while maintaining a low profile for better navigation.
Dyneema Purity in Ligament Repair

Applications: Cargo Containers

**Air Cargo Containers**

Next-generation air containers made with Dyneema® are redefining air cargo operations for customers like Lufthansa and DoKaSch. Composite panels and fabrics made from our flexible and ultra-lightweight materials are contributing to super-strong, durable containers that are up to 50% lighter than metals - reducing fuel and carbon emissions even further.

**Air Cargo Nets**

Securing your investment

50% less damage

- Aluminium Air Cargo Container
- Air Cargo Container with Dyneema®
References

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