IBP1094_11

ADVANTAGES OF POLYPROPYLENE BASED COATINGS FOR BURIED OR SUBMERGED PIPELINES OPERATING IN AGGRESSIVE ENVIRONMENTS

André Koebsch [1], André L. Lemuchi[2], Renata R. de Oliveira[3], Robert Buchanan[4]

Abstract

The use of polypropylene based coatings for steel pipelines operating at high temperatures or exposed to severe mechanical stresses has increased considerably over the years. Examples of this kind of application are: offshore pipelines laid in deep water, oil flow lines operating at high temperatures and projects in harsh environments where the type of construction or the soil and terrain conditions are extremely aggressive. Polypropylene based coatings present important advantages when compared to other types of coatings. Polypropylene has superior resistance to impact, indentation, abrasion and soil stress, excellent chemical resistance and low water vapor transmission. Finally, these coatings are more resistant to high operating temperatures. This paper presents the reasons why polypropylene performs better than other polyolefins in terms of thermal, mechanical and chemical resistance when used as pipeline coating systems in combination with epoxy primers. It also describes how the industry has been taking advantage of these attributes to develop polypropylene coating systems to be applied either in coating plants or at field for girth welds and repairs. It concludes by showing the several mainline and field joint coating systems commercially available and establishing a comparison between them.

1. Introduction

The objective of this paper is to carry out a bibliographic review of polyolefins, highlighting their main chemical, thermal and mechanical properties in consideration of their functionality as an outer layer in multi-layer anticorrosion pipeline coatings. It includes the different grades of polyethylene and polypropylenes and establishes a comparison between them.

Following, the most used polypropylene multi-layer coating systems are described for both plant and field joint application. Comparisons between the systems including performance properties, installation characteristics, equipment and manpower involved, cycle time of installation and economics are also established.

2. Polyolefin Coatings

The use of three-layer polyolefin coatings rather than thin film coatings such as fusion bonded epoxy (FBE) is a wide practice in some regions as South America, Europe and the Middle East due to several reasons as described below. Before engaging in discussions of the advantages and benefits of each of the pipeline coating systems, we introduce a brief review of polymers, concepts and characteristics for a better understanding of the subsequent discussions.

2.1. Polyolefin

Polyolefin are polymers, macromolecules composed by the repetition of simpler molecules called monomers, where the only atoms present are hydrogen (H) and carbon (C). They are thermoplastic materials processed by different methods which, for pipe coating, being longitudinal or a concentrically oriented extrusion process to apply on to pipe.

[1] Mechanical Engineer – Petróleo Brasileiro SA - Petrobras
[2] Technical Support Manager – South America - Canusa-CPS
[3] Sales Manager – IEC Engenharia
[4] Global Marketing Manager – Canusa-CPS

These polyolefins can also be chemically processed or electronically irradiated in order to crosslink the structure to enhance mechanical properties and allow for the manufacture of heat-shrinkable sleeve systems that facilitate field installation onto pipeline girth weld joints and repairs.

Polyolefins are used as external layer in multilayer pipeline coating systems because they provide excellent barrier to water ingress and impart superior mechanical resistance to the system. These materials are combined with anticorrosion layers such as epoxy primers and anticorrosion adhesives.

Epoxy primers are commonly Fusion Bonded Epoxy (FBE) electrostatically applied at pipe coating plants, or two-component liquid epoxy which is generally used in field-applied systems. The epoxy primers provide corrosion resistant properties because they are excellent barriers to oxygen, carbon dioxide and other gases, but they are not as resistant to water. They do provide high adhesion to steel substrates and improved cathodic disbondment resistance.

Anticorrosion adhesives act as an intermediate layer that is needed to bond the low energy non-polar surface of the polyolefin to the polar structure of the epoxy. The adhesives for 3-layer polyolefin systems are commonly a copolymer with functional sites that bond to both the non-polar polyolefin and polar epoxy, as shown on Figure 1.

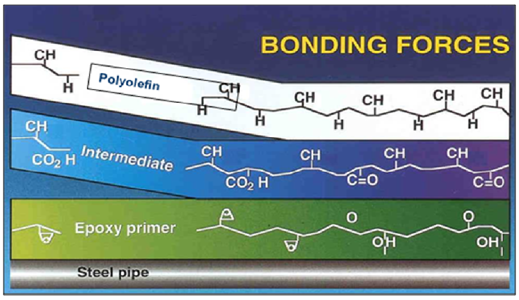


Figure 1. Three layer polyolefin coating system structure

2.2. Polymers Concepts

Homopolymers and copolymers are used as raw-materials for pipeline coatings, being the first ones, polymers composed by the repetition of only one monomer and the second one presents a different co-monomer in smaller quantities. The number of repetition of the monomer in the polymer chain is called polymerization degree. Increase in the degree of polymerization also increases the molecular weight (MW) which, in general, gives better physical properties for the final product. Construction materials in general have the molecular weight above 10,000 and for superior mechanical resistance, polymers with much higher molecular weight called high polymers have been used in several applications.

More over than the polymer molecular weight, the types of interactions between the macromolecules of the polymer are quite important to define its physical properties. As an example, even materials with different chemical structures as high density polyethylene and copolymer polypropylene can show similar physical properties.

2.3. Polyolefin Synthesis

Polyethylene (PE) and Polypropylene (PP) are polymers synthesized by the polymerization of ethylene and propylene respectively under defined conditions of temperature and pressure.

Most recent process to produce both polyethylene and polypropylene use a stereo specific catalyst that will determine how the basic units (monomers) will link. The variety of catalysts basically defines the wide variety of polyethylenes.

Most traditional methods as the Ziegler-Nata, when developed allowed for the use of lower pressures in the chemical reactor still resulting in less ramified polyethylenes than the ones obtained in older type of processes.

More recently, processing with metallocene catalysts have been widely used giving significant advantages because they are more economical and efficient, more active and specific relative to how the monomers will link, resulting in polymers with special properties.

The metallocene are called catalysts of single site (all equivalent in reactivity) allowing for better control of the final product properties. Metallocene catalysts, combination of various mono- and bis-metallocene, in particular ansa- (or bridged) metallocene complexes of Ti. Zr or Hf are used. They are usually used in polymerization reactions in combination with a different organoaluminum cocatalyst, methylaluminoxane (or methylalumoxane, MAO).

Importance for pipeline coatings is that the polyolefins made from metallocenic process are between 2 and 4 times more tear resistant and about 4 times impact resistant.

Several peroxides can be used in the pressurized heated reactor containing the monomers, solvents and catalysts to initiate the polymerization, being oxygen (O_2) the most widely used. On the other hand, Hydrogen (H_2) is used as the element that finishes the polymerization, thus defining the length of the molecules and consequently the molecular weight. The final product in form of powder or flakes precipitates in the reactor. It is then washed and dried in order to eliminate solvent and catalysts residues. After that, the polymers receive specific additives and pigments depending on the application and are processed in an extruder that makes pellets.

Different grades of polymers with different final properties are achieved by varying pressure, temperature, catalysts or monomers quantities.

The methods most used to manufacture Low Density Polyethylene (LDPE) are called ICI and Carbide. They use high pressures of about 2,000 Bar and temperatures between 100 and 300°C, avoiding higher temperatures that could degrade the polymer. High Density Polyethylene (HDPE) commonly uses the Ziegler method as mentioned above that involves low pressure, between 3 and 4 Bars, and temperatures between 50 and 75°C or the Philips method with higher pressures and temperatures (30 to 40 Bar and 120 to 175°C). The second method results in a less ramified polyethylene with higher density because it is more crystalline.

Linear Low Density Polyethylene (LLDPE) is manufactured using transition metals catalysts under a pressure of 145 MPa, temperatures up to 200°C and hydrocarbon solvents in different types of reactors. It results in a more crystalline product than LDPE (more ordered and thicker lamellae) presenting better mechanical properties and higher fusion temperatures, being better materials for pipeline coating than LDPE. Though, it is more difficult to process due to the higher shear strength and its melt fracture susceptibility.

Grades of HDPE highly crystalline, achieving up to 90% of crystallinity, presenting less than one lateral ramification for each 200 carbon atoms can also be manufactured. It has a melting point of about 132°C, density between 0.95 and 0.97 g/cm^3 and numeric molecular weight between 50,000 and 250,000.

As linear as the polyolefin is, its density increases due to the more efficient orientation, alignment and packaging of the chains. In these cases, the Van der Waals intermolecular forces action is more intense resulting in more crystallinity and higher melting points. It is because the lateral ramifications and the length of the chains difficult the crystallization and so interfere on the final properties. When the polyolefins cool down, they don’t crystallize in a perfect manner leaving amorphous material in the interstices of the crystallites as can be seen on Figure 2.

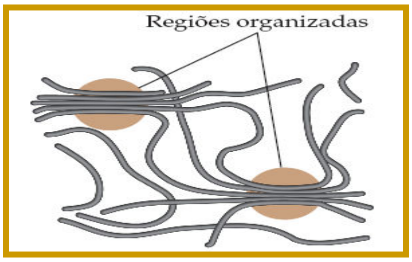


Figure 2. Scheme of a Polyolefin structure showing amorphous regions and crystallites.

The crystallinity with higher density gives strength to the material while the amorphous regions impart elasticity, softness and flexibility.

The aggregated crystallites form structures called spherolytes that when oriented at the same direction produces better creep resistance but reduces resistance to other directions. Polymer properties are very influenced by the relative quantities of the crystalline and amorphous phases.

2.4. Polyethylene classification and properties

Polyethylenes are generally classified according to the density, as per Table 1.

Table 1. Polyethylene classification according to density (British Standard)

Classification	Density	Crystallization Degree	Ramifications
HDPE	> 0.945	60 – 80%	Few and short
MDPE	0.931 – 0.944	50 – 60%	More than HDPE but also short
LDPE	0.910 – 0.930	35 – 50%	Several and lengthily

The classification according to the British Standard is also widely used in the Brazilian industry. The polyethylene chains orientation also considerably influence the mechanical properties of the polymer. A highly oriented HDPE can achieve about 10 times more resistance than non-oriented ones due to the chains packaging increase.

Even though the classification according to the density is important, the molecular weight shall also be considered when defining the properties needed for each application. Table 2 shows how density and molecular weight affects on the polymer properties.

In general terms, increase in the polyolefin molecular weight results in better mechanical properties as impact, tear and abrasion resistance but also makes it more difficult to process and extrude. In some cases, it is virtually impossible to extrude them in common extruders.

On the other hand, the permeability to gas and water vapor depends more on the density than the molecular weight. Other mechanical properties as flexibility, stiffness and hardness also depends more on the density.

Table 2. Impact from the Density and Molecular Weight increase on Polyethylene properties

Properties	Increase on Density (Crystallization)	Increase on Molecular Weight (Molecules length)
Processability	Do not affect considerably	Decreases
Extrusion Speed	Do not affect considerably	Decreases
Permeability to Gases and Solvents	Decreases	Decreases less
Resistance to bending, stiffness	Considerably Increases	Increases less
Superficial Hardness	Increases	Increases less
Tensile Strength	Decreases	Increases
Impact Resistance	Decreases	Considerably Increases
Tear Resistance	Decreases	Increases
Chemical Resistance	Increases	Increases
Creep Resistance	Increases	Increases

Other grades of polyethylene developed, includes the following:

1. Linear Low Density Polyethylene (LLDPE) that is less ramified than LDPE, very flexible, more mechanical resistant and less susceptible to fatigue stress. It is a good material for pipeline coatings in cold environmental.
2. Ultra High Molecular Weight Polyethylene (UHMWPE) that is a derivation of the HDPE with better mechanical and high temperatures resistance but very difficult to process due to its rheological properties.
3. Bimodal PE that presents a Molecular Weight distribution curve with two concentrations or peaks. It generates excellent mechanical properties while keeping the processability easy. Also keeps up the tensile strength and creep resistance. Bimodal polyethylenes are widely used on composite pipes with dry fiberglass or steel reinforcement for high pressures operations.

Table 3, shows the main properties for homopolymer polypropylene and polyethylenes with different densities for comparison.

Table 3. Typical Properties for Homolymer PP (PP-H) and Polyethylenes

Properties	PP-H	HDPE	MDPE	LDPE	LLDPE
Melting Point (°C)	160-165	126-135	120-125	105-118	126
Tensile Strength (Kgf/cm^2)	300-390	210-380	80-240	40-140	
Ultimate Elongation (%)	200-700	90-800	50-600	90-800	
Vicat Melting Point (ºC)	90-95	60-80		45-60	
Thermal Conductivity (W/(mK))	0.21-0.22	0.38-0.51		0.32-0.40	
Density (g/cm^3)	0.90-0.92	0.94-0.96	0.925-0.935	0.915-0.92	0.935
Shore D Hardness	62-70	58-63	45-60	45-51	38-60
Rockwell Hardness	75-92	65	15	10	
Volume Resistivity (Ω.m)	$>10^{16}$	$>10^{15}$	$>10^{15}$	$>10^{15}$	$>10^{15}$
Dielectric Strength (kV/mm)	50-70	30-40	30-40	30-40	30-40
Water Vapor Permeability (g/m^2 d)	0.92-1.0	0.9		1.2	
Water Absorption, 24 h (%)	<0.01	<0.01	<0.01	<0.01	<0.01

HDPE is the grade of polyethylene most used as external layer for three layer anticorrosion systems due to its higher melting point and VICAT, hardness, impact and indentation resistance and lower gas and water vapor permeability.

LDPE combines unique tenacity, flexibility, stability and electrical properties more over than the easy processability. It has several industrial applications but for pipeline coatings it presents disadvantages as lower hardness and indentation resistance as well as higher gas and water vapor permeability than LLDPE and HDPE.

Finally polypropylene presents better mechanical properties maintained even at higher temperatures. It also has better thermal properties being widely used as external layer in three or multiple layers coatings operating at temperatures higher than 80°C or as thermal insulation barrier, mainly for offshore pipelines.

2.5. Polypropylene

As mentioned above and can be seen on Table 3, polypropylene has lower density than HDPE, and even than other grades of PE, and is slightly more permeable to water vapor than HDPE. But due to its better mechanical and thermal properties it has been used extensively for pipeline coatings in applications where aggressive construction conditions exist, where the pipeline will be buried in aggressive soils, where high operating temperatures are, or where thermal insulation is needed.

Polypropylene presents a linear structure with crystallization typically between 60% and 70%. The Isotactic structure shown on Figure 2 is the one typically used for commercial applications, including for pipeline coatings.

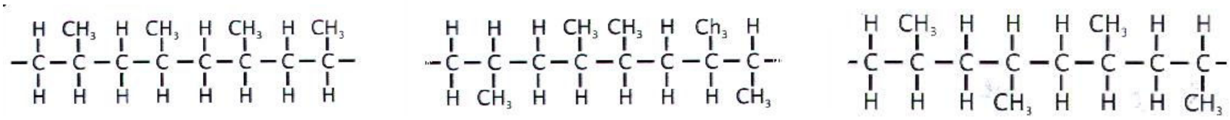


Figure 3. Polypropylene stereo specific structures.

2.6. Polypropylene classification and properties

Polypropylenes are classified depending on the presence or not of co-monomers in the chains and how these co-monomers are linked to the main chain:

1. Homopolymer Polypropylene (PP-H): It is only composed by propylene monomers. It is stiffer and more resistant to higher temperatures but less resistant to impact than the other grades and presents density between 0.90 and 0.92 g/cm^3. It is translucent and crystalline, being the main component to manufacture biaxially oriented PP films (BOPP).
2. Copolymer Polypropylene: It has also ethylene co-monomers, being subdivided in:
    a. Block Copolymer – Presents repetitive continuous C_3H_6 groups interspersed with one or more C_2H_4 groups and has excellent resistance to impact but not as good as PP-H for higher temperatures operation. It is also translucent and crystalline.
    b. Random Copolymer – Presents random links between the groups. It is semi-crystalline, in general not translucent but clear aspect.
3. Impact Copolymer: Composed with the addition of EPR, EPDM, polyethylene or plastomers to the PP-H, being very widely used in the industry because of the better properties achieved. For example, Basell Adstif can be added to the PP-H to provide better performance as water and oxygen barrier.

2.7. Polyethylene versus Polypropylene Properties

This section compares the chemical, thermal and mechanical properties of HDPE and PP for the purpose of pipeline coatings.

2.7.1. Chemical Properties Comparison

Basically both HDPE and PP are not attacked by the chemicals present in sea water or in most soils that pipelines are exposed to while in service. The exception would be pipelines in chemical plants or refineries where leakages of the types of chemicals as shown on Table 4 occurred and may attack the pipeline coating.

Table 4. Chemical Resistance – PP and HDPE

Agent	HDPE	PP
Dilute Acid Solutions	Resistant	Resistant
Oxidizing Agents and Strong Acids	Resistant but suffers very slow attack	Slightly more susceptible than HDPE
Aliphatic Hydrocarbons	Swelling/ permeability	Swelling/ permeability
Aromatic and Chlorinated Hydrocarbons	Suffers attack, swelling, permeability	Not resistant
Detergents, Surfactants	Stress cracking	Resistant
Alcohols	Resistant	Resistant

Dilute solutions in general do not affect the polyolefins while oxidizing agents or strong acids slowly attacks them, with oxidizing agents more aggressive to PP.

The interaction with aromatic, aliphatic and chlorinated solvents causes swelling, partial dissolution, color changes and degradation to the polyolefins when exposed for longer period.

Polyethylenes in contact with surfactants suffer reduction on the mechanical resistance due to superficial cracking while PP resists to them. Thus, polyethylenes are more susceptible to environmental stress cracking which can be minimized by using bimodal PE.

Also, as described on previous sections, the polyolefins are poor barriers to gases such as O_2 and CO_2 and this is one of the reasons they are combined with epoxies in three layer coating systems. Additives such as Basel Adstif can be used on PP formulations to decrease PP permeability to gases and water vapor. Still, relative to the water impermeability, in general, as higher the density, lower the permeability. Thus, PP is about 20-25% less permeable to water than LDPE but slightly more permeable than HDPE.

2.7.2. Cathodic disbondment resistance

For most pipelines, a cathodic protection system is combined with the protective coating in order to provide a complete corrosion protection system.

In the event of damages to the coating during pipeline installation or operation, cathodic protection is used to prevent corrosion from occurring at the "holiday" in the coating. The protective coating must resist disbondment at the holiday which can be caused by the cathodic reaction, releasing hydroxyl groups, that tends to disbond coatings from the steel surface.

Three layer polyolefin systems provides the benefits of having a thick, low permeability layer of PE or PP avoiding the ingress of electrolyte to the steel surface, combined with an epoxy layer (fusion bonded or liquid applied epoxy) that has intrinsic resistance to cathodic disbondment. Obviously the installation process of the epoxy, including the surface preparation, surface temperature during application, the thickness and curing degree of the epoxy, is quite important and can affect on the coating ability to resist to the cathodic disbondment.

2.7.3. Thermal properties comparison

The thermal properties as shown on Table 5 and the mechanical properties of polypropylene at high temperature, make it as a better choice for using as external layer on multi-layer coating systems for pipelines operating at temperatures above 80°C or when thermal insulation is needed.

Table 5. Typical thermal properties for homopolymer PP and polyethylenes

Properties	PP-H	HDPE	LDPE
Typical Melting Point (°C)	165	132	110
Thermal Conductivity (W/m.K)	0.22	0.38-0.51	0.32-0.40

Due to its low water vapor permeability and temperature resistance, an external polypropylene layer gives the anticorrosion system long term performance at higher operation temperatures.

On the other hand, polypropylene is more susceptible to thermal oxidation than HDPE due to the tertiary carbons (more susceptible to oxidation). When polypropylene is heated up in presence of air, it tends to cross-link, increase the embrittlement temperature on the molten viscosity and discolors. Thus, polypropylene mainline coatings require some additional care when installing field joint coatings or repairs. Commonly, indirect pre-heating is needed and the most commonly used methods are induction heating or hot air for minor repairs.

For HDPE, chemical processes under high temperatures results in polymer chain rupture and cross-linking. Oxygen attacks the macromolecules decreasing the molecular weight. Under lower and ordinary temperatures, photo-oxidation can happen but specific additives are used to avoid that. HDPE is resistant to heat during installation or application of the coatings under normal conditions as less pre-heating is needed for the type of adhesives used.

2.7.4. Mechanical properties comparison

All thermoplastic materials when stressed suffer creeping effect and will collapse after time. Collapsing time, though, varies inversely with tensile value. Thus, plastic materials to be used for each application shall be selected according to the designed life time and the stresses expected for the application.

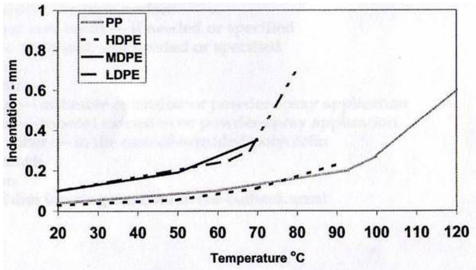
Polyolefins in general practicality do not suffer with the soil, axial or other stresses imparted during regular pipeline operation due to its very low roughness, intrinsic strength and tenacity.

Mechanical properties, as seen above, depend on the polymer density, molecular weight and molecular weight distribution as well as on the operation temperature, applied stresses and its duration.

Polypropylene chemical structure results in better mechanical properties than the most grades of polyethylene, including HDPE, and keeps superior mechanical properties, including indentation, impact, abrasion and soil stress resistance, even at temperatures above 80°C.

Pipeline coatings based on polypropylene materials are considerably more resistant to indentation than HDPE materials. The French norm used for three layer polypropylene coatings (3LPP) NF A 49-711 presents an indentation resistance test allowing for maximum of 0.1 mm of indentation at 20°C and 0.4 mm at 110°C, while the corresponding

French Norm for three layer polyethylene coatings (3LPE) NF A 49-710, allows for a maximum of 0.3 mm of indentation at 20°C and the maximum temperature it is tested is 70°C with a requirement of maximum 1.0 mm indentation. Figure 4 shows polypropylene and different grades of polyethylene indentation resistance.



Thickness < 2 mm
Indentor of 1.8 mm diameter
Mass of 2.5 Kg)

Figure 4. Polyolefin Indentation vs. Temperature. Requirements from DIN 30670

The impact resistance from 3LPP systems are also much higher than 3LPE systems with typical requirements of 10 J/mm, means twice the impact energy required for 3LPE.

2.8. The use of three layer polyolefin systems

Three layer polyolefin coating systems, independently if using HDPE or PP, are very high dielectric strength systems with excellent mechanical properties. They are extensively used as protective coating system for pipelines where the pipeline transportation, handling, type construction and operation are very aggressive. They also minimize the operating costs of cathodic protection systems due to lower current requirements versus other pipeline coatings such as FBE, dual layer FBE or coal tar coatings.

Additionally, there is positive historical data for multi-layer polyolefin coatings, in South America, Europe and the Middle Easr where they are the dominant type of pipeline coating used. Three layer field joint coating systems (field applied) developed to mirror the three-layer polyolefin mainline coating systems (plant applied) with proven performance, as we will see in the next sessions, are commercially available and provide continuity to the mainline coating.

Summarizing, polypropylene coatings present superior thermal and mechanical properties when compared to polyethylene coatings. Disadvantages are in terms of oxidizing agents attack and thermal oxidation when heated up in presence of air, thus demanding extra care for the field joint coating installations.

Polypropylene coatings are also excellent for high operating temperature pipelines due to low water vapor permeability, even at higher temperatures, its higher melting point and better mechanical properties at higher temperatures.

Polypropylene external layers combined with novolac-epoxy primers highly cross-linked and complemented with a suitable copolymer adhesive, provides three layer systems that can operate at temperatures as high as 140°C in offshore applications.

2.9. Cross-linked polyolefins

As above explained, thermoplastic materials have their strength depending upon the distance between the molecules, and the crystalline nature of the molecular structure, being these crystals which provide most of the strength of the material.

The exposure of polyolefin materials such as polyethylene and polypropylene to high-energy irradiation can cause the permanent cross-linking, or intermolecular joining, of molecules. This linking results in the chemical bonding of the plastic structure into a new three-dimensional structure.

These cross-linked structures resist to melt or flow and are known as partial thermoset. When the material is heated, the crystals still disappear as before, but it will no longer flow or change shape because the cross-links act as ties between the molecules. The cross-linked structure, however, is elastic. That means that when it is heated to a temperature where the crystals have melted, the material behaves like plastic (versus elastic). The chemical and mechanical properties are improved from the initial thermoplastic polyolefin and it allows the manufacture of user friendly field joint coatings, such as heat-shrinkable sleeve systems.

Between other improved properties are abrasion, impact, indentation resistance, flexibility (even at low temperatures) and improved impermeability to water vapor. For higher temperature operations, coatings composed by cross-linked polyolefin materials also present other important improved characteristics as stress cracking resistance, slow crack growing resistance and superficial hardness.

These cross-linked products are supplied in an expanded condition and have a perfect elastic memory. When heated up, they will shrink and tightly encapsulate the object over which they have been placed, being ideal for

protecting pipe joints and a variety of unusual configurations and pipe fittings.
The basic steps to manufacture polyethylene based heat-shrinkable backings can be seen on Figure 5.

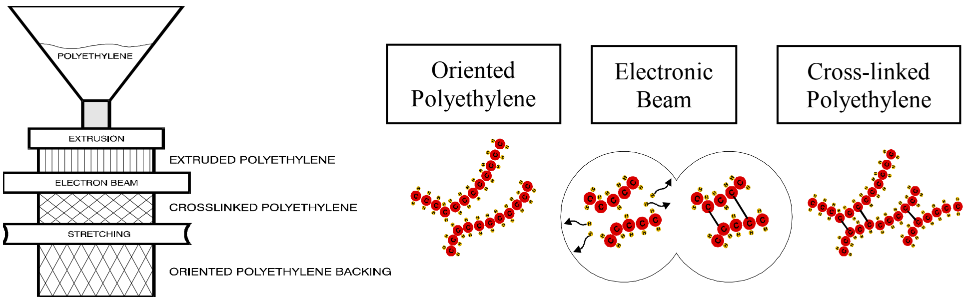


Figure 5. Cross-Linked Polyethylene Backing Manufacturing Process.

Basically, thermoplastic polyolefins in pellets and the required additives are fed to an extruder and laminated to a thick oriented thermoplastic sheet. This sheet is submitted to an irradiation process where electrons with very high kinetic energy are beamed through the polyolefin sheet. The polyolefin chains are changed and intermolecular bonds results after hydrogen release. The final three-dimensional structure is a partially thermoset cross-linked polyolefin.

3. Plant Applied Polypropylene Systems

Due to the characteristics of polyolefins highlighted in section 2, the three-layer polypropylene systems are widely used as pipeline coating for high operating temperatures or when superior mechanical resistance is important. These are the cases of gathering and flow lines onshore in oil and gas fields where operation temperatures can be as high as 135°C or pipelines crossing very aggressive terrain in mountainous regions combined with rocky conditions. Polypropylene coatings are also used on many offshore applications when the construction campaign involves stalks welded together on land and reeled into Reel Lay barges to lay the pipelines offshore. The handling and reeling of these stalks are very aggressive and the type of construction does not allow for much time for coating repair. Finally for deep water applications, for both anticorrosion and thermal insulation purposes (flow efficiency), multi-layer polypropylene coatings are used due to their mechanical and thermal properties. This section intends to present the different type of polypropylene systems used for the above mentioned applications.

3.1. Three-Layer Polypropylene (3LPP)

This system consists of an initial layer of Fusion Bonded Epoxy (FBE) that provides excellent adhesion to the steel, low gas permeation rate and works very well when combined with the cathodic protection impressed currents. It is coupled with a thick external layer of thermoplastic polypropylene used as mechanical protection and as a water barrier resulting on prolonged anticorrosion resistance. An intermediate layer of copolymer adhesive is required as an intermediate layer to adhere the external to the internal layers, as can be seen on Figure 6.

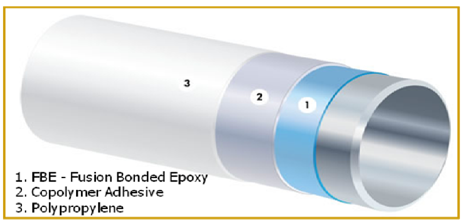


Figure 6. Three layer polypropylene

Three-layer polypropylene systems have excellent impact, indentation and abrasion resistance to protect the pipeline during transportation and construction handling, minimizing repairs. They can also be installed with thicker external polypropylene layer to enhance on mechanical resistance (typical 3LPP thickness ranging from 3 to 4 mm). In onshore projects the use of selected backfilling material can be avoided by using thicker PP.

3LPP can be used from small diameter flow lines to very large diameters transmission lines at temperatures ranging from -40°C to up to 140°C depending on the formulation. The main international norms for this type of coating are the CSA Z245.21-02, the DIN 30678 and NF A 49-711.

3.2. Thermal Insulation with Multilayer Polypropylene Systems

Polypropylene coating systems are effective as thermal insulation for offshore pipelines. Depending on the water depth and thermal characteristics required, they may be designed using various configurations as described in this section.

3.2.1. Polypropylene Foam Multilayer Systems

This system basically uses polypropylene foam layers between the anticorrosion three layer coating (3LPP) and an external PP outer shield as can be seen on Figure 7. The system can be installed with up to 9 layers. More dense PP foam layers can be installed as internal layers for better mechanical performance while less dense PP foam are used as external layers for better thermal efficiency.

The polypropylene foam is made by extruding a polypropylene matrix with blow agents to obtain foam cells that are more or less closed depending on the water depths the pipeline will be laid down.

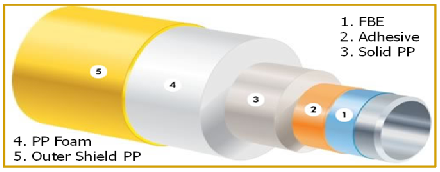


Figure 7. Polypropylene foam multilayer system

For shallow waters, the PP foam used has larger cells that yield better thermal efficiency (lower thermal conductivity). For deeper waters, more closed cells with better compression resistance are needed due to the hydrostatic pressure that could collapse a weaker foam structure. Still, the polypropylene foam layer thickness varies depending on the thermal efficiency needed for each type of PP foam system.

The polypropylene coating still requires stability at the seabed, excellent performance for use with tensioners, shall resist to the axial loads imparted during the offshore pipe laying and to the stress caused by fatigue. Polypropylene foam systems for water depths of up to 700 meters withstand operating temperatures to 155°C while deep water systems at depths to 2200 meters can resist temperatures to 140°C.

3.2.2. Syntactic Polypropylene Five-Layer Systems

Five layer syntactic polypropylene systems are manufactured by incorporating a thermal insulation layer of syntactic polypropylene between the 3LPP and an outer shield of solid PP as shown on Figure 8.

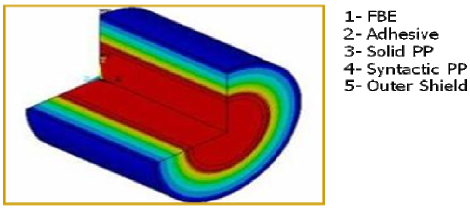


Figure 8. Syntactic polypropylene system

Syntactic PP uses a matrix composed by a special polypropylene with glass microspheres resulting on excellent thermal properties while keeping better resistance to the hydrostatic pressure than the PP foams.

3.2.3. Solid Polypropylene Five-Layer Systems

Five layer solid polypropylene systems are made by incorporating a thick thermal insulation layer of solid polypropylene between the 3LPP and an outer shield of solid PP.

Solid PP maximizes the mechanical performance being more compression resistant due to the hydrostatic pressure than the other systems and meets the requirements for the pipelines at the seabed for very deep water. However, the thermal efficiency of these polypropylene materials is inferior to the PP foams and syntactic polypropylene. The table 6 compares the thermal conductivity, operating temperatures and water depths for the different types of PP thermal insulation system described above.

Table 6. Typical thermal properties for multilayer PP thermal insulation coating systems

Properties	Solid PP System	Syntactic PP System	Shallow Water PP Foam System	Deep Water PP Foam System
*Density (Kg/m^3)	890 to 900	630 to 670	550 to 650	650 to 850
Thermal Conductivity (W/m.k)	0.210 to 0.220	0.140 to 0.160	0.125 to 0.185	0.160 to 0.190
Operation Temperatures (°C)	Up to 140	Up to 140	Up to 155	Up to 140
Water Depth (m)	Up to 3,000	Up to 3,000	Up to 700	Up to 2,200

Obs.: * Density for the thermal insulation layers.

4. Field Applied Polypropylene Systems – Field Joint Coating and Repair

The field applied polypropylene systems can be divided into three groups depending on how they are presented and installed at field:

a. Field applied polypropylene system– Powder raw materials (FBE, adhesives and sometimes the outer layer) are field installed through flame spray or flocking units. The outer mechanical protection layer may be a polypropylene hot applied tape or flame sprayed powder polypropylene.
b. Injection molded polypropylene systems (IMPP) - Molten Polypropylene is injected into a molding to build up the external mechanical protection layer over FBE anticorrosion and intermediate adhesive layers.
c. Polypropylene heat-shrinkable sleeves (PP HSS) – Prefabricated system in which the polypropylene based adhesive is laminated to an external cross-linked polypropylene backing installed over a liquid epoxy primer.

4.1. Flame Sprayed Polypropylene Systems

This consists of field installing the same raw materials as for the 3LPP plant applied as shown on Figure 9. A first layer of FBE with thickness depending on the project specification is electrostatically applied to the joint surface previously pre-heated to the 220-240°C range by an induction heating equipment. Subsequently a copolymer adhesive is sprayed onto the primer to a typical thickness of 150-200 microns. Finally an external layer of PP material is to be installed. It can be applied as a tape that is heated up while being helicoidally installed over the adhesive or as powder and sprayed as the first layers.

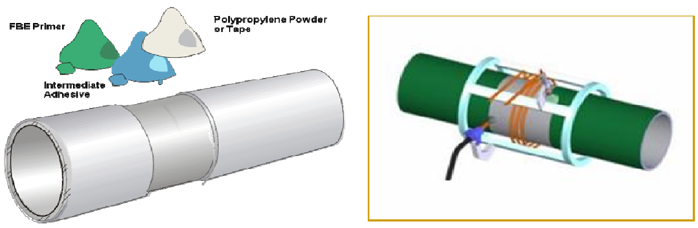


Figure 9. Flame sprayed polypropylene system

The system has to comply with the international norms for 3LPP as CSA Z245.21-02, the DIN 30678 and NF A 49-711 as is made of the same raw materials as the mainline coating but presents several disadvantages. It requires specialized heavy equipment including induction heating equipment, flame spray units, tape application equipment and specialized operators. Generally, this creates a need for a specialized subcontractor to assume the field joint coating scope that can be an obstacle in some projects. Storing, handling and installing three different components at field environmental are also a concern as it includes all the risks of handling powders particles in suspension. Another disadvantage is related to the loss of the powder raw materials at field environmental and the uncertainty of consumption for each raw material when compared to the other polypropylene field joint coating systems as the PP Heat Shrinkable Sleeves where one kit is provide/enough for each field joint.

Pre-heating field joints to very high temperatures as needed for the flame sprayed system also is a risk for the adjacent mainline coating as the high temperatures can affect the coating since the copolymer adhesive can melt and disbond the outer mechanical layer from the primer.

4.2. Injection Molding Polypropylene Systems (IMPP)

Injection molded polypropylene systems typically consists of an FBE primer layer, also installed to a 220-240°C heated surface by induction equipment, an adhesive layer and molten thermoplastic polypropylene injected to a molding, as can be seen on Figure 10, at controlled temperature, pressure and time to build PP thickness specified for the project. This typically results in a final thickness similar to the mainline coating. It is designed to present full compatibility with the mainline coating. In the case of thick multilayer thermal insulation coatings as described on section 3, it has also to provide similar thermal efficiency.

Figure 10. Injection molding polypropylene system

Its more common use is as field joint coating for anticorrosion protection and thermal insulation in offshore pipelines as also involves considerable heavy pieces of equipment which is difficult to handle in onshore construction. In addition, it is easier set up at a Spool Bases that are actually more similar to a coating plant facility. For offshore onboard applications, although it can be done at S-Lay and J-Lay type of barges, it is not often used due to the amount of equipment involved, the space onboard of the barge needed for that and as the flame sprayed PP system the need of specialized man power potentially involving subcontractor for the field joint coating installation.

4.3. Polypropylene Heat Shrinkable Sleeves (PP HSS)

The polypropylene field joint coating most user friendly and used worldwide that allows for fast and economic field installation is the three layer polypropylene heat shrinkable sleeve system. It is designed to mirror the three-layer polypropylene mainline coating systems (3LPP) and to fully comply with the international norms for the mainline coating as the CSA Z245.21-02, the DIN 30678 and the NF A 49-711 (as can be seen on Table 7). It also complies with field joint coating recommended practices as the DNV RP F-102 that presents a chapter for polypropylene field joint coating.

Either a high temperature 100% solids liquid epoxy or FBE can be used as primary anticorrosion layer. Liquid epoxy is the most widely used because it is easier to field install and does not need the same pre-heating temperature as FBE as shown on table 10. This minimizes the risk of adjacent mainline coating damage. In addition, it performs as well as the FBE in terms of providing excellent adhesion to the steel, cathodic disbondment resistance and gas barrier. An external cross-linked polypropylene backing provides similar mechanical resistance and water vapor barrier as the PP outer layer in the 3LPP and a PP based adhesive effectively bonds the backing to the primer and fuses with 3LPP mainline coating providing the continuity to the mainline coating anticorrosion and mechanical protection. Figure 11 shows a schematic and a photo of a three-layer PP HSS.

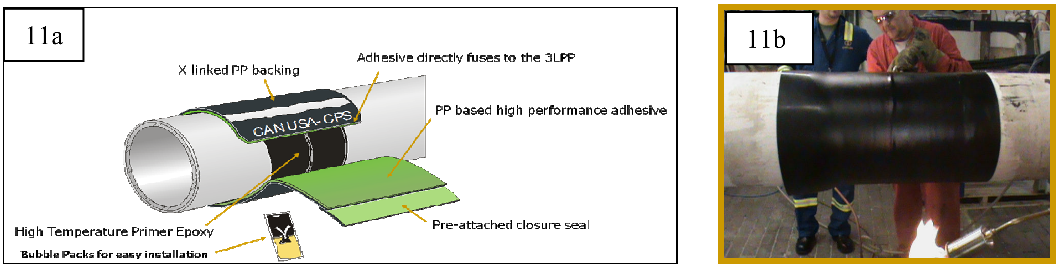


Figure 11. Polypropylene heat-shrinkable sleeve system.
a. Schematic. b. Photo from the Petrobras Tupi project. PP HSS being shrunk onto the field joint.

Comparing to other PP field joint coating systems, more over than the reduced pre-heating temperatures involved, the PP HSS only requires induction heating for force curing the epoxy primer achieving temperature in the range of 170-190°C that is needed to activate the polypropylene based adhesive. It also allows for reduced cycle times that is very important for offshore applications, there is no need for any other heavy equipment as can be thermally shrunk by the conventional torch method reducing equipment and mobilization costs as well as the space needed onboard. Finally there is no need for specialized operators. With training and qualification given by the heat-shrinkable sleeves manufacturer the contractors personnel can install the system.

Table 10. Polypropylene field joint coating systems vs. three-layer polypropylene mainline coating system. Test method from NFA 49-711.

Properties	**PP HSS**	**IMPP/PP Tape Wrap**	**3LPP**
Peel at 23°C (N/cm)	> 250	> 250	> 250
Peel at 110°C (N/cm)	> 80	> 80	> 80
Shore D Hardness	> 65	> 65	> 65
Impact Resistance (J/mm)	> 10	> 10	> 10
Indentation Resistance at 110°C (mm)	< 0.4	< 0.4	< 0.4
Installation temperature (°C)	170-190	220-240	220-240

The polypropylene heat-shrinkable sleeve technology has been developed by ShawCor research and development group in 2001 and since then, several hundred thousand field joints have been coated worldwide with the system. This is a strong history of projects, from small to large diameter, onshore flow and gathering lines operating in high temperatures and offshore projects with different laying methods such as S, J and Reel-Lay.

Most recently, the same technology has been improved for use in deep water application with thickness of up to 8mm, details can be seen in the referenced paper Lemuchi et all. (2009). Equipment and install process related improvements have also occurred since then.

As detailed on section 2, the polypropylene when cross-linked has its mechanical resistance improved. It allows the PP HSS system to present superior impact, indentation and abrasion resistance, exceeding the requirements from the 3LPP norms for these mechanical properties. Figure 12a shows an impact test applied to a PP HSS while Figure 12b shows a bending test executed for the Petrobras PDET Shallow Water Project. Figure 12c shows a peel tested sleeve with cohesive type of failure that is one of the field checking to confirm the sleeves have been correctly installed.

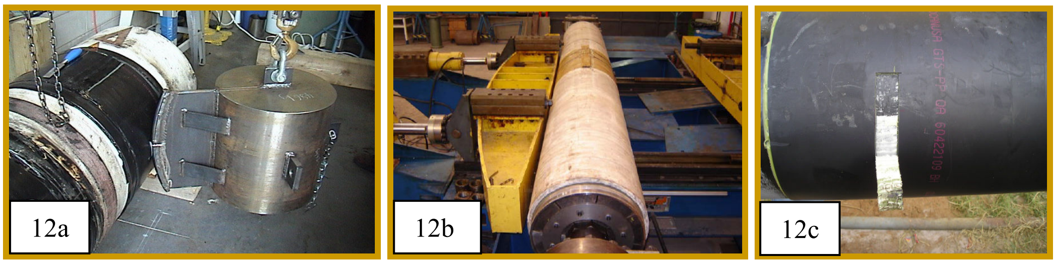


Figure 12. Polypropylene heat-shrinkable sleeve system
12a. Impact testing
12b. Bending testing - field joint coated with PP HSS plus solid polyurethane as thermal insulation layer
12c. Peel tested field joint

5. Conclusion

This paper shows that polyolefins are excellent materials to be used as external mechanical protection and water vapor barrier in pipeline coating systems, especially in the case of aggressive handling or operating parameters. They also allow for savings in the cathodic protection system versus thin film coatings. Polypropylene tends to be the preferred polyolefin for applications on pipelines operating in high temperatures, where thermal insulation properties are required or when outstanding mechanical resistance is needed.

There are many polypropylene plant applied systems for anticorrosion and mechanical purposes and multilayer thick PP systems that more over than that also provides thermal insulation, mainly for offshore pipelines where other kind of materials as polyurethane foam cannot be used because collapses with the hydrostatic pressures involved.

Currently, different types of polypropylene field joint coatings are commercially available and fully comply with the mainline coating requirements, being the preferred system the one based on polypropylene heat shrinkable sleeves due to its easier and faster install method, less equipment and specialized personnel involved, lower pre-heating temperatures reducing the risk to damage the adjacent mainline coating and the very extensive successful tracking record.

6. References

N.S Allen, M.E.D. Holdsworth, A. Rahman, F. Catalina, E. Fotan, A.M. Escalona, F.F. Sibon, “Ageing and spectroscopy properties of polyethylenes – comparison with metallocene polymer”

M. Ashby, H. Schercliff, D. Cebon, “Materials – Engineering science processing and design”

F.M.B. Coutinho, I.L. Mello, L.C. Santa Maria, “Polietileno – Principais tipos, propriedades e aplicações”, Chemical Institute, UERJ

M. Welander, “Effect of High Stress on the Ageing Behaviour of High Density Polyethylene”, Chalmers University of Technology, Dept of Polymeric Materials, Goteborg, Sweden

J.R.B. Danielleto, “Manual de Tubulações de Polietileno e Polipropileno”

Lemuchi A, Gudme C., Buchanan R, IBP 1335_09 – “Engineered Pipeline Field Joint Coating Solutions for Demanding Conditions”

Technical Catalogues Canusa-CPS, A ShawCor Company

Technical Catalogues Bredero Shaw, A ShawCor Company

Technical Catalogues Safplast – Polypropylene

Technical Catalogues Emco Plásticos Industriais – Homolymer and Copolymer Polypropylene