Power Cable Manufacturing

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1 Preface

This course presents a basic overview of wire and cable manufacturing, expanding on the principles, materials, and processes involved in transforming raw materials into finished electrical cables. It also highlights some of the factory testing requirements along with quality assurance methods. The intent is to provide both technical grounding and a practical understanding of how cables are designed, manufactured, and validated.

2 Introduction

Power cables are among the most critical components of modern electrical infrastructure, forming the physical backbone that enables electricity to flow from generation sources to substations, industrial facilities, commercial buildings, and residential communities. They serve as the lifelines of energy transmission and distribution systems, carrying power safely and efficiently across vast distances. Without reliable power cables, modern society would struggle to function, as every aspect of daily life, from transportation and healthcare to communication, manufacturing, and digital technologies, relies on the continuous delivery of electrical energy. The performance, reliability, and safety of power cables are therefore of paramount importance. Even minor defects or weaknesses can result in severe consequences, including unexpected power outages, operational disruptions, financial losses, safety hazards, and in extreme cases, injury or loss of life. Understanding how power cables are manufactured provides engineers, designers, inspectors, installers, and maintenance professionals with essential insight into the factors that influence the behavior of these products in service. It allows them to make informed decisions regarding cable selection, installation practices, and maintenance strategies, ensuring that each cable performs reliably over its intended lifespan.

The manufacturing lifecycle of power cables is a complex, multi-stage process that transforms raw materials into highly engineered products. This lifecycle begins with the careful selection of conductor materials, typically copper or aluminum, each chosen for their unique properties and suitability for the intended application. Copper is highly valued for its superior electrical conductivity, mechanical strength, and corrosion resistance, making it ideal for building wiring, industrial installations, and medium-voltage applications. Its relatively high cost and density are offset by its performance, as copper conductors carry current efficiently while maintaining structural integrity under mechanical and thermal stresses. Aluminum, on the other hand, offers reduced weight and cost advantages, which makes it particularly suitable for large-diameter power cables and long-distance transmission. Although aluminum has lower electrical conductivity than copper, appropriate sizing and alloy selection allow it to meet stringent performance requirements. Regardless of the material chosen, the conductor must be processed carefully to achieve the desired electrical and mechanical characteristics.

Once the raw conductor material is procured, it is typically formed into strands and assembled into a final conductor structure through various stranding techniques. Stranding improves both flexibility and mechanical performance while maintaining the necessary electrical capacity. Conductor strands can be arranged concentrically, bunched, sector-shaped for multi-core cables, or compacted to reduce air gaps between strands. Compaction is a particularly important step, as it ensures that the strands make good electrical contact, creates a smooth surface for insulation, and allows for a more uniform conductor diameter. Proper stranding and compaction enhance the cable's ability to withstand mechanical stresses during installation and service, including bending, pulling, and vibration, and help ensure consistent electrical performance throughout the cable's lifespan.

The next stage in the manufacturing process involves the preparation of polymer compounds used for insulation and jacketing. The insulation system serves as the electrical barrier, containing the conductor's electric field and preventing current leakage, while also providing thermal and mechanical protection. Common insulation materials include polyvinyl chloride (PVC), cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), and polyethylene (PE), each chosen for their combination of electrical performance, thermal stability, and mechanical durability. Jacketing compounds are applied over the insulation or armoring layers and are designed primarily to protect the cable from environmental and mechanical stress. Jackets may incorporate flame-retardant additives, ultraviolet stabilizers, moisture barriers, and chemical resistance enhancers depending on the cable's intended environment and service conditions. The selection and formulation of these polymer compounds are critical, as they influence the cable's flexibility, lifespan, and ability to withstand heat, abrasion, chemicals, and extreme weather conditions.

Extrusion is one of the most critical stages of power cable manufacturing, during which heated polymer compounds are applied around the conductor to form the insulation layer. This process requires precise control of temperature, line speed, pressure, and cooling rate to ensure uniform thickness and consistent electrical properties. Proper centering of the conductor within the insulation is essential to avoid uneven wall thickness, which can create points of high electrical stress that may lead to premature failure. In medium- and high-voltage cables, extrusion may be performed in multiple layers that include a conductor screen, the primary insulation, and an insulation screen applied in a continuous sequence. This multi-layer approach ensures optimal dielectric performance and reduces the likelihood of partial discharge or breakdown under operating voltages. Throughout extrusion, careful monitoring and adjustments are made to maintain consistent quality and to prevent defects such as voids, bubbles, or contamination, which can compromise the cable's reliability.

Once insulation is applied, many cables incorporate shielding and metallic layers to manage the electric field and provide additional protection. Shielding systems may consist of semi-conductive screens, copper tape or wire shields, or aluminum laminated tapes. These layers serve to control electromagnetic interference, provide a return path for fault currents, and improve overall electrical performance. In some applications, metallic sheaths are added to protect against moisture ingress or to provide additional mechanical strength, particularly in underground or direct-burial installations. The application of shielding and metallic layers requires precise control to ensure uniform coverage and consistent contact with the conductor, as gaps or overlaps can negatively affect the cable's electrical performance.

For multi-core cables, individual insulated conductors are carefully twisted together in a controlled cabling process. This ensures balanced mechanical forces, uniform stress distribution, and consistent geometry across the assembly. Fillers and binding tapes are often added to maintain the cable's round shape and to secure the assembly before further layers are applied. Proper cabling is crucial for preventing conductor movement during installation or service, which can cause localized stress and lead to premature insulation failure. Following cabling, additional layers such as bedding, armoring, and outer jackets are applied. The bedding layer provides a smooth surface for armoring, which is added when cables must resist impact, crushing, rodent damage, or high tensile forces during installation. Common armoring types include steel wire armor and aluminum wire armor. The outer jacket is the final protective layer and is formulated to resist mechanical damage, ultraviolet radiation, chemical exposure, moisture, and other environmental stresses.

Quality control is embedded at every stage of the manufacturing process, rather than being limited to final inspection. Dimensional checks, surface inspections, spark testing, and process monitoring are continuously performed to prevent defects from progressing through the production line. Dimensional control ensures that conductor diameters, insulation thicknesses, and cable diameters remain within strict tolerances. Surface inspections detect contamination, scratches, or inclusions that could compromise electrical performance. Spark testing identifies pinholes or insulation weaknesses during extrusion, allowing corrective action before the cable is completed. Process parameters such as extrusion temperature, line speed, tension, and curing conditions are closely monitored to maintain consistent quality and prevent deviations that could affect the cable's long-term reliability. By integrating quality assurance throughout production, manufacturers minimize scrap, reduce rework, and ensure that the final product consistently meets performance expectations.

Finished cables undergo a comprehensive set of electrical, mechanical, and dimensional tests to verify compliance with design specifications and industry standards. Electrical tests include insulation resistance measurements, voltage withstand tests, and, for medium- and high-voltage cables, high-voltage AC or DC testing to confirm dielectric integrity. Mechanical tests such as tensile, elongation, bending, and impact assessments ensure that the cable can withstand installation and operational stresses. Dimensional verification confirms that the cable meets specified tolerances for overall diameter, layer thicknesses, and ovality. In addition to standard tests, specialized tests may be performed depending on the cable's application, such as fire resistance, smoke and toxicity measurements, chemical or oil resistance, water penetration tests, or rodent resistance evaluations. Proper marking and labeling are also inspected to ensure that the cable can be traced to its production batch and that essential information, such as voltage rating, manufacturer identification, and standard references, is clearly displayed. Only after passing these rigorous inspections is the cable released for packaging and shipment.

Understanding the intricacies of power cable manufacturing provides several key benefits for engineers, designers, and technicians. Knowledge of the conductor, insulation, shielding, and armoring processes allows for more informed cable selection based on electrical load, environmental exposure, installation constraints, and mechanical requirements. It enables professionals to anticipate potential failure modes and to implement preventative measures during design, installation, or maintenance. For example, awareness of how insulation can degrade under thermal cycling, mechanical stress, or moisture ingress can guide the specification of materials and installation practices that prolong service life. Moreover, understanding manufacturing processes fosters stronger collaboration across the supply chain, as designers, manufacturers, and end-users can communicate more effectively regarding material selection, tolerances, and application requirements, reducing misunderstandings and enhancing the overall quality of the power system.

In addition to these practical benefits, knowledge of cable manufacturing contributes to safety and cost optimization. Professionals who understand the relationship between material properties, processing conditions, and final performance can make decisions that balance cost-effectiveness with reliability, avoiding over-specification or under-specification that could compromise safety or increase lifecycle costs. Installation teams equipped with this knowledge are more likely to respect bending radius limits, avoid excessive pulling tensions, prevent mechanical damage, and ensure proper terminations, directly impacting the cable's operational lifespan. Maintenance teams can diagnose issues more accurately by tracing failures to their root cause, whether it be a conductor defect, insulation compromise, or environmental exposure, enabling timely corrective actions before problems escalate.

Modern cable manufacturing also emphasizes sustainability, with efforts focused on energy-efficient production, environmentally friendly materials, and compliance with environmental regulations. Understanding manufacturing processes allows professionals to make choices that support these goals without compromising performance or reliability. By viewing the cable as an engineered system in which each layer interacts with the others, from the conductor to the outer jacket, professionals gain insight into how mechanical, electrical, and environmental factors interplay to influence performance. Thermal aging can affect insulation strength, moisture can impact dielectric properties, and mechanical stress can alter conductor geometry, all of which can be traced back to design and manufacturing decisions. This systems perspective underscores the critical importance of understanding manufacturing processes to ensure optimal cable performance throughout its service life.

Power cables are not simply conductors surrounded by insulation; they are carefully engineered assemblies designed to perform under specific electrical, mechanical, thermal, and environmental conditions. Every step of the manufacturing process, from material selection and conductor stranding to extrusion, shielding, armoring, and final testing, influences the cable's ability to meet its intended performance criteria.

3 A Brief History

The use of wire and cable dates back more than 200 years, to the early 1800s, when scientists first began systematically studying electricity and its behavior. This period marked the foundation of electrical engineering as a discipline.

Several key scientists made ground breaking contributions during this era, including Humphry Davy, Hans Christian Ørsted, Georg Simon Ohm, Joseph Henry, Michael Faraday, and Thomas Edison, among others. Their discoveries in electromagnetism, electrical resistance, and power generation laid the groundwork for the development of practical electrical conductors, insulation systems, and ultimately modern cable technology.

A particularly important milestone in materials science was Charles Goodyear's patent in 1844, which introduced the process of **vulcanization**. Vulcanization fundamentally changed the way rubber could be used in industrial applications, including cable insulation and jacketing.

Shown in **Figure 1** is a gutta-percha tree, from which a natural thermoplastic material was historically derived. Gutta-percha forms a rubber-like elastomer and was widely used in early cable insulation, especially for underwater telegraph cables, due to its excellent electrical insulating properties and resistance to moisture.

Prior to vulcanization, early rubber products such as boots and clothing performed poorly in real-world environments. In hot conditions, rubber would soften and deform, while in cold temperatures it would become brittle and crack. These limitations made rubber unsuitable for long-term or industrial use.

Figure 1 – Gutta-percha tree

Determined to overcome these challenges, Charles Goodyear relocated his family to Massachusetts, where the first rubber factories in the United States were established. After years of failed experiments and personal financial hardship, Goodyear finally discovered a successful formula in the winter of 1839. Although the discovery was ground breaking, it took another five years to refine the process and secure the patent in 1844.

The vulcanization process produced rubber that was **stable, durable, elastic, and resistant to temperature extremes**, making it suitable for a wide range of applications. As a result, vulcanized rubber quickly became an essential and unremarkable part of everyday life, from footwear to industrial products—and eventually to wire and cable insulation.
We will discuss vulcanization in further detail later in this course, including why it is so important to cable performance, safety, and longevity.

The name **Goodyear** may sound familiar today. With the rise of the automobile industry, two brothers from Ohio named their tire company **"Goodyear"** in honor of Charles Goodyear, recognizing his lasting contribution to rubber technology—particularly in applications where durability, flexibility, and reliability are critical.

4 The Manufacturing Process

Cable manufacturing can be broadly divided into two fundamental buckets: **pre-processes** and **processes**.

The pre-processes focus on the **materials** that ultimately define a cable's electrical, mechanical, and environmental performance. This includes:

1. **Metallurgy,** where conductive materials such as copper and aluminum are refined, alloyed, and conditioned to achieve the required conductivity, strength, and flexibility; and

2. **Polymer Compounding**, where insulation and jacket materials are engineered to meet specific requirements such as thermal rating, dielectric strength, flame resistance, chemical resistance, and durability.

Decisions made at this stage, such as conductor purity, grain structure, or compound formulation, set the performance limits of the finished cable long before manufacturing begins.

The second bucket consists of the **manufacturing processes** that transform these raw materials into a finished cable. These processes include wire drawing to reduce conductor size while maintaining mechanical integrity, stranding to improve flexibility and current distribution, and extrusion to apply insulation and semiconductive layers.

Subsequent steps such as cabling, shielding, armouring, and jacketing build up the cable structure, providing electrical protection, mechanical strength, and environmental resistance. While these processes add functionality and ensure consistency, they rely heavily on the quality and design of the pre-processed materials. In practice, successful cable manufacturing depends on a careful balance between material science and process control, as weaknesses in either bucket can directly impact reliability, safety, and service life.

4.1 Pre-processes (Materials)

4.1.1 Metallurgy

The four (4) best conductors of electricity are silver, copper, gold and aluminum, in that order. See **Figure 2** below.

Figure 2 – The four best conductors electricity

Conductor material selection is a critical decision in cable design, as it directly affects electrical performance, mechanical behavior, cost, and manufacturability. From a purely electrical standpoint, the four most conductive metals are silver, copper, gold, and aluminum, in that order. However, conductivity alone does not determine suitability for cable applications. Practical considerations such as material availability, cost, weight, and ease of processing ultimately drive material selection in real-world designs.

When comparing conductors on an equivalent electrical basis, useful insight can be gained by evaluating materials relative to a copper conductor 1 mm in diameter and 1 km in length. Silver, while the best electrical conductor, offers only a marginal improvement over copper—requiring approximately 3% less diameter to achieve the same resistance, which translates to only about 6% less volume. This small performance gain is rarely enough to justify silver's significantly higher cost, restricting its use to specialized or high-performance applications. Gold performs noticeably worse electrically, requiring roughly 20% greater diameter to match copper's resistance, making it impractical for most power applications despite its excellent corrosion resistance.

Aluminum requires an even larger increase in size, approximately 30% greater diameter than copper, to achieve equivalent conductivity. However, aluminum offers important advantages that offset this drawback. It is significantly lighter, less expensive, and easier to source in large quantities, making it the preferred choice for overhead transmission lines and weight-sensitive applications. The increased conductor size also results in a larger surface area, which can aid in heat dissipation, partially compensating for its lower conductivity.

Beyond these primary conductors, many other metals—such as steel—are electrically conductive but are not selected for their conductivity. Instead, they are used to provide mechanical strength, tensile support, or structural reinforcement, often in combination with conductive materials. Examples include steel-reinforced aluminum conductors, where each material is chosen for the property it contributes. Ultimately, conductor material selection is a balance between electrical efficiency, mechanical requirements, cost constraints, and manufacturing considerations, all of which must align with the intended application and service environment.

In summary, there are several advantages and disadvantages that should be considered, including price, availability, weight, processability, and durability. See **Figure 3** for another comparison of some of these characteristics.

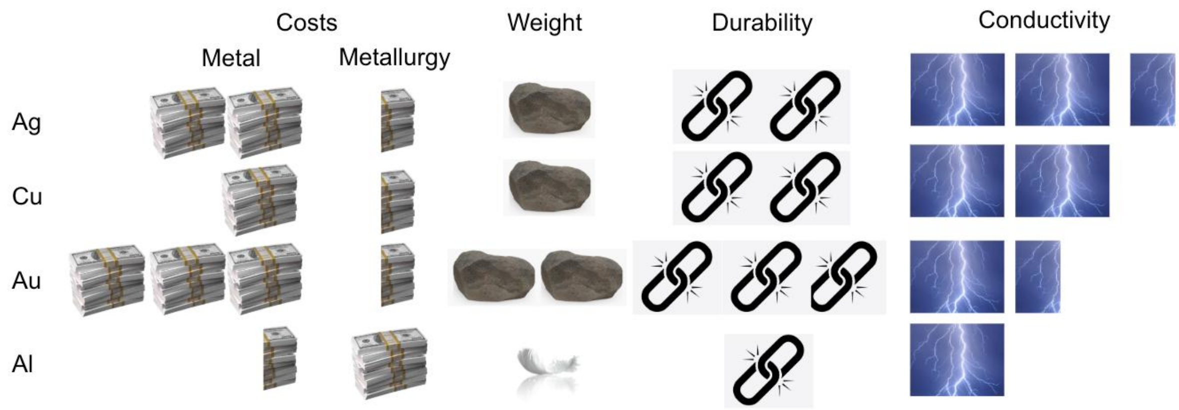


Figure 3 – More comparisons between silver, copper, gold, and aluminum

Silver is easy to work with, has reasonable weight, excellent durability, and great conductivity since silver oxide is also conducting. However, it is very expensive. It is

used in surface plating for RF applications and use in specialized electronics.

Copper is also an excellent conductor, easy to work with, has a reasonable weight and durability. It can also be expensive, but as much as silver. It is the workhorse of the cable industry.

Gold is a good conductor and extremely easy to work with, it has excellent durability, but is heavy. However, it can be rather expensive. It is used for ultrafine wires and plating for connectors and switches, mostly in aerospace and electronics applications.

Aluminum has acceptable conductivity, a reasonable price, is lightweight, but is somewhat difficult to process. It also generates a layer of insulating oxide (alumina) making connections slightly more challenging.

The two most common conductor materials are **copper and aluminum**. Copper has a density of 3.3 times that of aluminum and has a lower resistance (and subsequently, higher conductivity). For an equivalent conductivity, aluminum is:

1. 50% lighter than copper;
2. 30% larger in diameter; and
3. Less expensive.

The drawbacks include:

1. Requires more insulation material, screening and jacketing due to the larger diameter;
2. Special techniques for connections/terminations due to the oxide film; and
3. Cold flow can cause high resistance joints and leads to overheating.

Before conductors can be drawn into wire, copper and aluminum must first be converted from raw materials into solid rod, a form that provides consistent chemistry, controlled grain structure, and suitable mechanical properties for downstream processing.

Copper typically begins as mined ore that is concentrated, smelted, and turned into refined cathodes (Figure 4) with a very high purity, often exceeding 99.9%. Resistivity increases with the impurity content. After refining, the cathodes are cast into continuous rod using processes such as continuous casting and rolling (CCR). In this process, liquid copper is solidified into a bar and immediately hot-rolled through a series of mills to achieve a uniform rod diameter, commonly 8 mm. This approach minimizes defects, refines grain structure, and produces a rod optimized for efficient and consistent wire drawing.

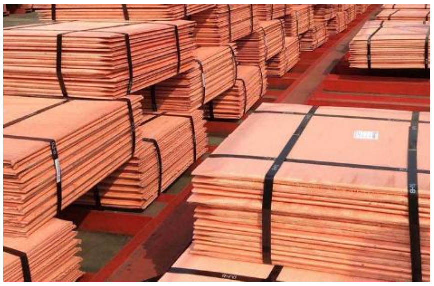


Figure 4 – Copper cathodes

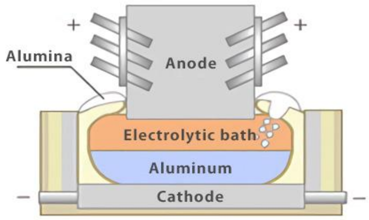


Figure 5 – Electrolytic Process

Aluminum follows a similar but distinct path. Bauxite ore is first refined into alumina, which is then reduced to metallic aluminum through an electrolytic process. The molten aluminum is alloyed as required and cast into rod using continuous casting systems, often producing rod diameters in the range of 9.5 mm.

As with copper, the casting and rolling stages are carefully controlled to ensure uniform composition, surface quality, and mechanical properties. Proper rod preparation is especially critical for aluminum, as its oxide layer and lower tensile strength can influence drawability and final conductor performance.

For both materials, the rod-making stage serves as the critical bridge between metallurgy and manufacturing. Any inconsistencies in purity, grain size, surface condition, or internal defects introduced at this stage can lead to drawing breaks, poor surface finish, or reduced electrical performance.

By producing high-quality, well-controlled copper and aluminum rod, manufacturers ensure that the subsequent wire drawing process can achieve tight dimensional tolerances, high conductivity, and the mechanical flexibility required for modern cable applications.

4.1.2 Compounds

Polymer Compounding

Polymer material compounding is a critical step in cable manufacturing, as it is the process by which raw ingredients are transformed into a consistent, processable material suitable for extrusion.

During compounding, base polymers, fillers, and additives are carefully combined to produce uniform granules, commonly referred to as compounds, which are later used as the raw material for cable insulation and jacketing. Additives are typically present in relatively small amounts, often just a few percent, but play an essential role in providing properties such as thermal stability, flame retardancy, UV resistance, and processing aid.

Fillers, which can make up as much as 60% of the formulation, are used to modify mechanical properties, reduce cost, or enhance specific performance characteristics, while the polymer itself makes up the balance and provides the fundamental structure of the material.

Although the exact layout and equipment may vary from one compounding facility to another, the overall process follows the same basic principles. Raw materials are typically delivered to the plant in semi-trailer tankers and unloaded using compressed air, which conveys the powders or pellets into large storage silos. This closed, pneumatic handling system helps maintain material cleanliness, prevents contamination, and allows for efficient bulk handling of large volumes of material.

From the main storage silos, materials are again transported by compressed air through a network of pipes—often visible throughout the facility—to smaller day silos located near the production lines.

These smaller silos feed the compounding equipment directly. From there, the materials flow by gravity into precision dosing machines, which accurately measure and dispense the exact quantity of each component required for the formulation. Accurate dosing is essential, as even small deviations in additive or filler content can significantly affect the compound's processing behavior and final cable performance.

Once measured, the materials are mixed and processed to form homogeneous granules, ensuring consistent quality and reliable performance in subsequent cable manufacturing operations.

Once the raw materials have been accurately dosed, they fall into the compounder itself, where the compounding process takes place. Inside the compounder, the materials are heated and mechanically kneaded, allowing the polymers to melt while the fillers and additives are thoroughly dispersed. This combination of heat and shear transforms the individual ingredients into a homogeneous molten paste, ensuring uniform composition and consistent material properties throughout the batch.
The molten compound is then conveyed downstream into a small extruder, typically located at the discharge end of the compounder. The extruder applies controlled pressure to push the material forward and force it through a perforated die plate, similar in function to a meat grinder. As the material exits the die, it forms continuous strands—often referred to as "spaghetti"—which represent the compound in its newly formed shape. These strands are immediately cut by a rotating knife into small, uniform granules or pellets. The granules fall through a collection tray to the level below, where they are cooled, collected, and prepared for packaging or direct use in cable extrusion.

Throughout this entire process, computerized control systems continuously monitor temperatures, pressures, screw speeds, and material flow rates, ensuring repeatability, quality consistency, and traceability of the finished compound.

Polymer Compounds

Polymer compounds are materials made up of long, repeating chains of molecules, which give them versatile and tunable properties. In cable manufacturing, these compounds are essential for providing insulation and mechanical protection, shielding conductors from electrical stress, environmental factors, and physical damage.

Depending on the manufacturer's needs, polymer compounds can either be purchased ready-for-use from specialized suppliers or produced in-house through compounding processes, allowing for tailored formulations that meet specific performance requirements.

An important related process is master-batching, which involves the addition and thorough mixing of functional ingredients directly on the extrusion line. Master-batching allows manufacturers to enhance or modify compound properties such as flexibility, longevity, flame resistance, and overall cost efficiency, without the need to produce a completely new compound batch. This approach provides versatility and rapid adaptation to changing performance or regulatory requirements.

While polymer compounds dominate modern cable insulation, there are some honorable mentions. For example, air is the cheapest natural insulator used primarily in overhead lines, and paper insulation has been used successfully for over a century.

Polymer Types

All conventional polymers used in cable manufacturing are derived from petrochemical feedstocks, produced by the oil industry through well-established chemical processes.

While bio-polymers, made from renewable vegetable sources, are slowly emerging, they remain relatively expensive and generally do not yet meet the performance standards required for most cable applications.

The choice of polymer depends heavily on the required electrical, mechanical, thermal, and fire-resistant properties of the finished cable. Broadly, four main types of polymer materials are commonly used and are discussed below.

1. Polyethylene (PE) – Electrical Properties

Polyethylene is the material of choice for electrical insulation due to its excellent dielectric properties. It is widely used in power and communication cables where high electrical performance is essential. However, polyethylene has some limitations: it softens at relatively low temperatures and is highly flammable, which restricts its use in applications with stringent fire performance requirements unless specially modified.

2. Polyvinyl Chloride (PVC) – Limited Flame Spread Properties

PVC is frequently used where fire performance and cost are important considerations. It offers reasonable electrical insulation and good resistance to flame, making it suitable for low-cost, general-purpose cable applications. High-performance alternatives, such as HFFR (halogen-free, flame-retardant) materials, are used when stricter fire performance is required. The main drawback of PVC is that, if it burns, it can release toxic fumes, although it remains popular due to its versatility, affordability, and broad application range.

3. Elastomers (Rubbers) – Flexibility

Elastomeric polymers are chosen primarily for flexibility and mechanical resilience, such as in crane cables or other applications requiring repeated bending and winding. This category includes a family of rubbers, with silicone rubber being notable for its ability to withstand high temperatures and produce cohesive ash during combustion, which aids in fire resistance. Rubbers also often provide excellent chemical resistance, making them suitable for harsh environments or flexible power cables.

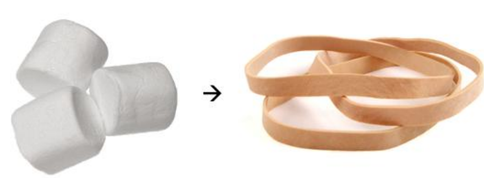
4. Specialty Polymers – High-Performance or Unique Applications

A wide variety of specialized polymers are used for extreme or niche requirements. For example, PTFE (Teflon) and its derivatives (like FEP) are used in very high-temperature cables, aerospace applications, and where specific regulatory standards must be met, such as plenum-rated data cables in the US. Other advanced polymers, such as Kevlar (aramid fiber), provide exceptional tensile strength and are used to reinforce cables that must resist high traction forces.

Polyimides, including Kapton, offer outstanding thermal resistance (up to 400°C) for specialized industrial applications. These high-performance polymers are more expensive and require precise processing but are indispensable for cables operating in demanding environments.

Crosslinking

Crosslinking is a key process in wire and cable manufacturing, particularly during extrusion, because it allows the modification of polymer properties to meet specific mechanical, thermal, and electrical requirements.



The process essentially creates chemical bonds between polymer chains, transforming soft, easily deformable materials into more stable, elastic, and resilient products. For example, natural or synthetic rubber—originally soft and marshmallow-like—can be crosslinked to achieve elasticity, strength, and dimensional stability, making it suitable for cable insulation or jacketing.

It is important to note that not all polymers can be crosslinked, but materials like polyethylene (PE) are particularly suitable for this process.

As mentioned earlier, the most well-known historical example of crosslinking is vulcanization, invented by Charles Goodyear in 1839. Working with natural latex rubber, Goodyear sought to create waterproof products, such as shoes and raincoats. While the untreated rubber worked reasonably well in cold, damp climates, it melted in hot weather and became sticky. Goodyear discovered that adding sulfur and applying heat produced a material that retained elasticity and stability across a wide range of temperatures. This process, which he called vulcanization, essentially crosslinked the rubber molecules, transforming them into a durable, elastic, and resilient material.
In modern cable manufacturing, similar crosslinking principles are applied during extrusion, particularly for polyethylene insulation, to enhance thermal performance, mechanical durability, and resistance to deformation under electrical stress.

Thermoplastic vs Thermosetting

The main purpose of a cable's insulation is to:

1. Withstand voltage stresses
2. Operate a wide temperature range
3. Withstand mechanical abuse (abrasion, crush, impact, and flexing)
4. Withstand chemical attack (oil, gases)

Insulation material is typically a non-conductive (dielectric) material having a specific voltage and temperature rating. The two most common insulation types are **thermoplastic** and **thermosetting**.

A **thermoplastic** material is a type of plastic polymer that softens and becomes moldable when heated and then hardens when cooled. This process can be repeated multiple times without altering the mate rial's chemical structure.

Thermoplastic

Thermoset

Examples include polyethylene (PE), Polypropylene, and PVC. A **thermoset** material is a polymer that, when heated or chemically treated during a process called curing, undergoes irreversible changes to form a rigid cross-linked network. This gives the material's molecular structure high strength, durability and heat resistance, but also means it cannot be remelted or reshaped once cured. Instead, if overheated, it will char or burn. See **Figure 6** which gives a relatable example/analogy to these two types of materials.

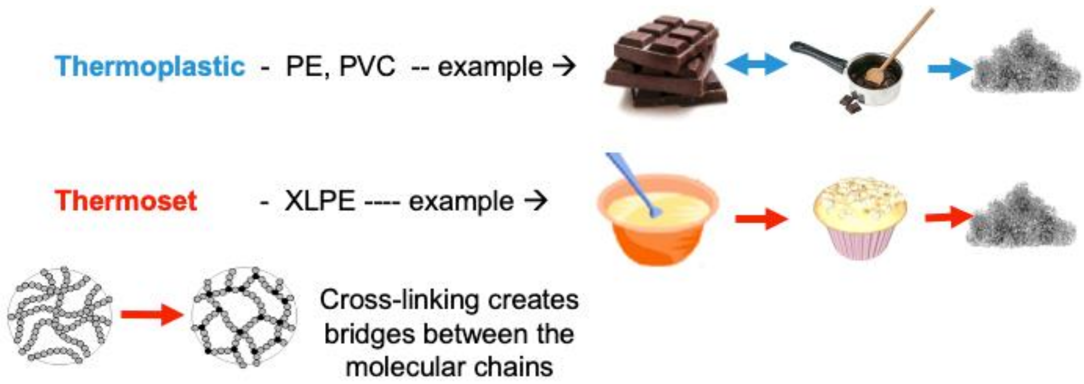


Figure 6 – Thermoplastic vs Thermoset

Thermoplastic Insulation Systems	Thermoset Insulation Systems
Have a lower maximum temperature typically 75°C	Have a higher maximum temperature typically 90°C or 105°C
Maximum short circuit temperature of 150°C	Maximum short circuit temperature of 250°C
When overheated, rapidly become liquid, allowing it to flow	When overheated, become somewhat moldable, but will not become liquid

Table 1 – Useful comparisons between thermoplastic and thermoset insulation systems

Other Materials

Before we move into the processing stages of cable manufacturing, it is important to highlight some of the additional materials that are commonly used in the construction of wires and cables. These materials, while not part of the conductor or primary polymer insulation, play critical roles in mechanical protection, water blocking, identification, and overall cable performance.

Paper remains an important material in certain cable types. It is used both as insulation paper around conductors and as filling paper (commonly craft paper) to occupy empty spaces in the cable core, helping maintain the cable's shape and integrity.

Wires, strings, and yarns are used for identification, binding, reinforcement, and protection. Examples include identification strings, binding strings, water-swellable yarns (impregnated with materials that swell on contact with water to block moisture ingress), jacket-opening strings, and reinforcement yarns such as aramid (Kevlar) for tensile strength. So me cables also use steel wires for armoring or protection.

Filling compounds serve to prevent water penetration, reduce friction, and enhance cable stability. Common compounds include grease, which blocks water ingress by capillarity; special filling compounds tailored to specific cable requirements; chalk to prevent the conductor or strands from sticking to the jacket during extrusion; tar or asphalt, typically for submarine cables; and swellable powders, which expand upon contact with water to seal the cable core.

These materials, while often overlooked, are essential for ensuring the reliability, durability, and performance of modern cables, particularly in challenging environments such as underground or submarine installations.

4.2 Processes

The manufacturing process of cables begins with careful handling of the bare wire, conductor or insulated conductor, and is supplied on a pay-off reel. From there, the material is guided through a series of capstans or tensioning devices that maintain precise control over the cable's tension throughout the process. Proper tension is critical to prevent stretching, deformation, or damage, especially during operations such as drawing, stranding, extrusion, or cabling.

The cable then passes through the main manufacturing operation, where it may be insulated, filled, shielded, armoured, jacketed or otherwise processed depending on the design. Finally, the finished product is collected on a take-up reel, ready for the next operation, inspection, testing, and/or shipment.

The basic set up for the various manufacturing processes that will be discussed in the following sub-sections is shown in **Figure 7.**

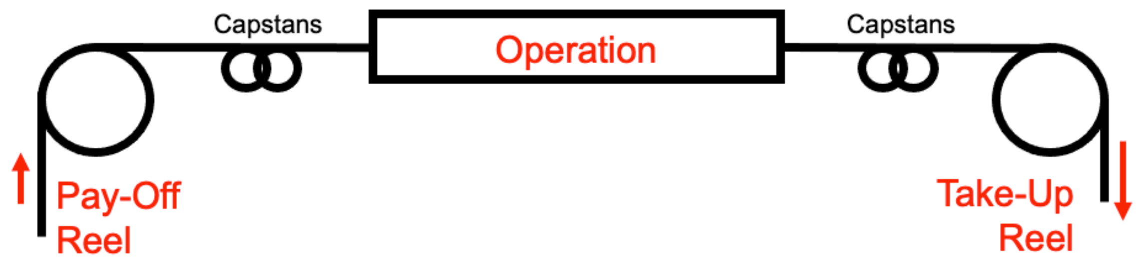


Figure 7 – The basic flow

This simple yet highly controlled flow, from pay-off to processing to take-up, forms the backbone of modern cable production and ensures consistent quality and reliability in the final product.

4.2.1 Drawing

One of the first key steps in conductor manufacturing is the drawing process, which is used to reduce the diameter of a metal rod to a size suitable for cable production while improving its mechanical properties. Drawing is a form of plastic deformation, in which a metal wire is pulled through a series of calibrated dies **(Figure 8)**, each with a progressively smaller opening.

This gradual reduction in diameter not only produces the desired conductor size but also enhances the strength, surface finish, and flexibility of the wire by refining its grain structure.

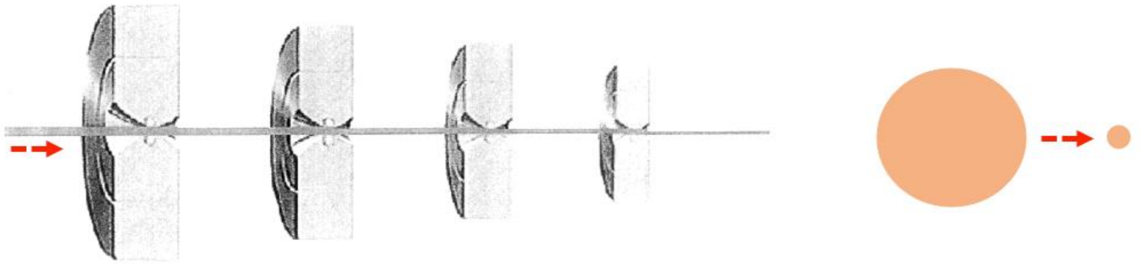


Figure 8 – Calibrated drawing dies

In practice, copper rods used for wire drawing typically start at a diameter of 5/16” (approximately 8 mm), while aluminum rods commonly begin at 3/8” (approximately 10 mm). These sizes are optimized for the standard wire drawing equipment and processes, providing a balance between material efficiency and ease of handling. For certain applications, such as solid conductors with relatively large final diameters, larger starting rods may be used. This allows manufacturers to achieve the desired conductor size in fewer drawing passes while maintaining the mechanical and electrical properties required for high-quality cable production.

Figure 9 – Lubricating fluid

The drawing process is critical not only for shaping the conductor but also for ensuring uniformity and consistency along the entire length of the wire. Properly drawn conductors exhibit smooth surfaces, predictable elongation characteristics, and minimal defects—all of which are essential for reliable cable performance. By carefully controlling the drawing speed, die geometry, and lubrication, manufacturers can produce conductors that meet stringent standards for electrical conductivity, mechanical strength, and flexibility.

During the wire drawing process, because the volume of metal remains constant, the linear speed of the wire increases as it passes through progressively smaller dies. This increase in speed can generate significant friction and heat, so a drawing lubricating fluid is applied to reduce friction, prevent surface defects, and make the operation smoother. Lubrication is essential not only for maintaining surface quality but also for prolonging the life of the dies and minimizing the force required to pull the wire through the dies.

Figure 10 – Drawing machine

Wire drawing requires careful handling, particularly on multiwire drawing machines, where multiple wires are drawn

simultaneously. If a wire breaks, it can be a time-consuming and labor-intensive task to re-thread the machine and restore proper tension and alignment. For this reason, operators must pay close attention to wire quality, die condition, and machine settings to minimize the risk of breakage.
The process of drawing produces important changes in the metal itself. Wire drawing increases the
hardness of the conductor due to work hardening, which improves its mechanical strength but can slightly reduce electrical conductivity. To manage these effects, manufacturers may select rods with a specific initial temper that allows the final drawing to achieve the desired mechanical properties. In cases where the drawn wire becomes too hard or brittle, a subsequent annealing process can be applied to restore ductility and improve conductivity, ensuring that the conductor meets both mechanical and electrical performance requirements.

A key sub-process within the drawing process is **annealing**.

Annealing is a critical heat treatment process in wire manufacturing, designed to modify the physical and mechanical properties of a metal to make it more ductile and reduce its hardness, thereby improving its workability. During annealing, the metal's internal structure is altered, relieving stresses introduced during processes such as drawing, and restoring properties that allow it to be shaped, bent, or coiled without cracking.

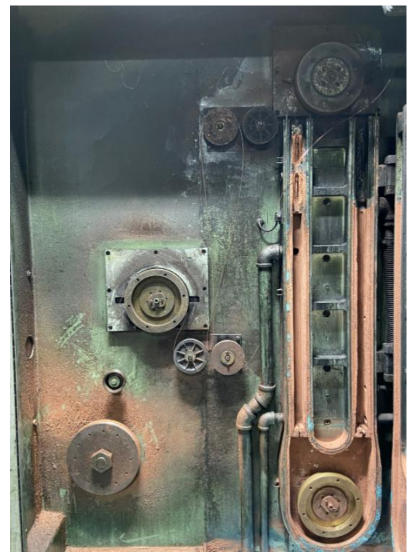


Figure 11 – Annealer

In continuous annealing systems, the wire passes through a series of sheaves or pulleys, which not only guide the wire but also help to apply electrical current that heats the wire as it moves. The heat softens the metal, restoring its flexibility, elongation, and ductility, while also increasing its electric al conductivity, which may have decreased during the work-hardening effects of drawing. After the heating stage, the wire is often quenched by immersion in a cooling liquid, which stabilizes the metal and locks in the desired properties.

Annealing can be performed in batch ovens, where coils of wire are heated for a set period, or in in-line, continuous systems—sometimes called "on-the-fly" annealing—especially for smaller conductors. Continuous systems are advantageous in high-volume production, as they allow the wire to be annealed without interruption, maintaining efficiency while ensuring consistent mechanical and electrical properties along the entire length of the conductor.

4.2.2 Stranding

Conductors are typically composed of a group of wires or any combination of groups of wires. Conductors are stranded to increase flexibility during installation and to increase mechanical strength in tension applications (i.e. overhead installations).

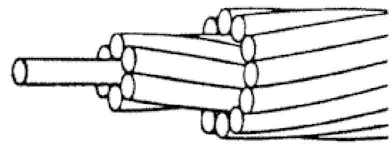


Figure 12 – Stranded conductor

Stranding is the application of subsequent layers of individual strands of wire around a center point. Each layer has 6 or more wires than the layer below it. This forms an almost natural construction.

1 wire = solid
7 wires = 1 center wire plus 6 around it
19 wires = 1 + 6 + 12
37 wires = 1 + 6 + 12 + 18
…

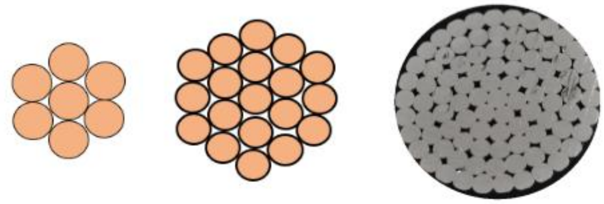


Figure 13 – Conductor strand layers

Some relevant terminology include:, regular round, compressed, compact, lay, concentric lay, unilay, rope lay, bunching, and strand block. They are explained in the following sub-sections.

Regular Round, Compressed, and Compact

Conductors can either be regular round, compressed, or compact stranded. **Figure 14** demonstrates the differences between each type of stranding for a 500 kcmil conductor. Important to note here that the metal volume remains constant, meaning that ampacity/resistance is the same regardless of stranding type.

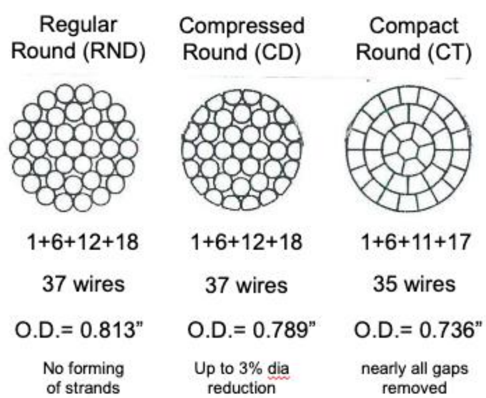


Figure 14 – Regular, Compressed, and Compact Stranding

Conventional strand designs force manufactures to draw a unique strand diameter for each conductor produces. The discussion on stranding is enhanced by mentioning of Single Input Wire (SIW) stranding to ASTM B836. This type of stranding allows manufactures to use the same strand diameter regardless of conductor size. An table comparing conventional conductors and SIW conductors is shown in **Figure 15**.

Conventional Conductor	Number of Wires	7	18	18	18	18
	Strand Diameter (inches)	0.1057	0.0735	0.0935	0.1050	0.1170
	Overall Diameter (inches)	0.268	0.336	0.376	0.423	0.475
	Conductor Size (AWG)	2	1/0	2/0	3/0	4/0
Single Input Wire (SIW) Conductor	Overall Diameter (inches)	0.268	0.336	0.376	0.423	0.475
	Strand Diameter (inches)	0.1160	0.1160	0.1160	0.1160	0.1160
	Number of Wires	6	10	12	16	19

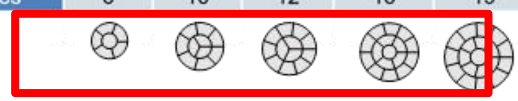


Figure 15 – Convention conductor stranding vs SIW conductor stranding

Conductor Lay

Each layer of strands in a conductor is typically laid in a specific direction. The lay direction defines the direction of twist of each layer. See **Figure 16**.

Right Hand (RH) – strands are twisted clockwise when looking down the axis of the conductor.

Left Hand (LH) – strands are twisted counter-clockwise when looking down the axis of the conductor
Industry convention:

- The outer layer on overhead conductors is always RH lay
- The outer layer on underground conductors is always LH lay

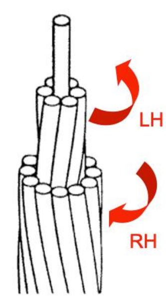


Figure 16 – Conductor Lay direction

Lay length is the measured distance, along the strand, between each of these twists. Cable design standards typically specify a minimum and maximum lay length. Lay length directly affects a conductor's flexibility, durability and overall performance. Shorter lay lengths increase flexibility and longer lay lengths may reduce production time, but also make the conductor stiffer. See **Figure 17**.

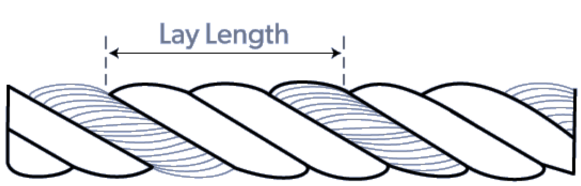


Figure 17 – Lay Length

Concentric Lay, Unilay, and Rope Lay

Concentric lay conductors have each layer of strands twisted in opposite directions with longer lay lengths on the subsequent layer. On the other hand, **unilay** conductors have each layer of strands twisted in the same direction with the same lay length. Unilay conductor are slightly more compact and flexible than concentric lay conductors, however they do not offer the same level of mechanical strength or crush resistance.

Rope lay conductors are conductors that are stranded in a more complex manner where each individual strand is a stranded conductor. See **Figure 18**. Rope lay conductors offer extreme flexibility making them suitable for applications like robotics, portable equipment, and welding leads and flexible connectors.

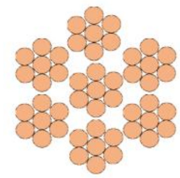


Figure 18 – Rope-lay conductor

4.2.3 Bunching

Some conductors may be bunched, meaning the individual strands are twisted together without control over the final strand location. See **Figure 19**. Conductor bunching is the lowest cost and fastest production method for stranding and results in a highly flexible conductor. The drawbacks are that it offers less precise dimensional control and a rougher surface which may impact the application of material in the subsequent layer of the cable.

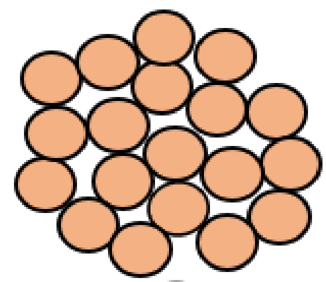


Figure 19 – Bunched conductor

Strand Block

Conductor water-blocking can be achieved using strand-blocking materials. The use of these materials is optional and typically only beneficial for medium or high voltage underground cables.

The traditional method of achieving this is by pumping a semi-conducting bitumen onto the surface of each layer to fill in the voids (air gaps) between strands. Other methods can include a combination of strand fill material, water swellable powders/tapes/yarns.

These materials prevent water that enters the conductor from travelling along its length in between the strands. The materials used must be qualified and tested for performance and compatibility for use in approved cables. See **Figure 20** for the methodology.

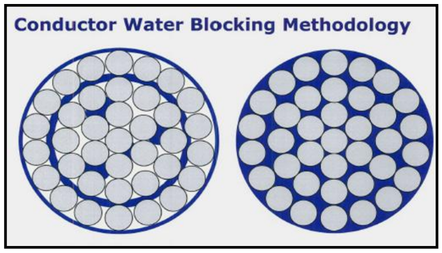


Figure 20 – Conductor water blocking (strand block) methodology

Tubular Stranders

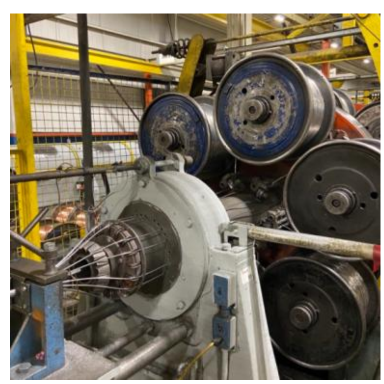
Tubular stranders **(Figure 21)** are widely used in cable manufacturing to produce multi-strand conductors, particularly those with 7 or 19 strands. This type of stranding machine is designed to lay individual wires together in a precise, controlled configuration, forming a compact and flexible conductor that can carry higher currents and resist mechanical stress better than a solid wire of equivalent size.
In a tubular strander, bobbins—small reels holding the individual wires—are positioned inside a long, rotating tube. As the tube spins, the wires are fed simultaneously and laid alongside each other in the desired pattern, forming a stranded conductor. This design ensures uniform tension on each wire, precise positioning within the strand, and consistent overall conductor geometry, which are critical for both electrical performance and mechanical reliability. Tubular stranders are particularly valued for their ability to produce high-quality, concentric, and balanced stranded conductors efficiently and consistently.

Figure 21 – Tubular Strander

Rigid Stranders (Planetary Stranders)

For conductors with a larger number of strands, manufacturers typically use rigid-frame or planetary stranders **(Figure 22)**, which are capable of handling the complexity and size of multi-strand configurations. Unlike tubular stranders, which are better suited for smaller 7- or 19-strand conductors, planetary stranders can efficiently produce large, high-strand-count conductors while maintaining precise geometry and uniform tension across all wires.
In a planetary strander, the wire reels are mounted on a rotating "cage" that moves around a central core.

As the cage rotates, each individual wire is laid systematically onto the strand, following a helical path that ensures tight packing, concentric alignment, and balanced stress distribution. This planetary motion allows for the simultaneous twisting of multiple



wires without compromising tension or uniformity, producing a conductor that is both mechanically robust and electrically efficient. Planetary stranders are essential in applications such as large power cables, busbars, and high-capacity conductors, where consistent performance and flexibility are critical.

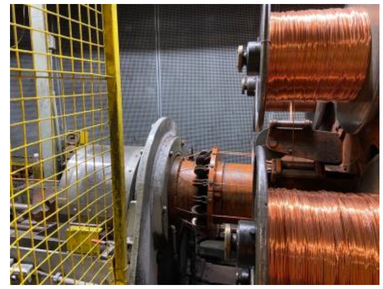


Figure 22 – Rigid Strander

Single- or Double-Twist Stranders

In addition to tubular and planetary stranders, single twist and double twist stranders are commonly used for certain conductor configurations, particularly where a simpler or more controlled twist pattern is required.

Figure 23 – Double Twist Strander

A single twist strander uses a flyer arm to twist the conductors as they are laid onto a reel. Each complete revolution of the flyer arm imparts one full twist to the conductor.

This method provides a straightforward and consistent way to produce stranded conductors with a defined lay length and uniform tension, suitable for small to medium-sized cables.

A double twist strander builds on the same principle but increases productivity by imparting two twists per revolution of the flyer arm. The first twist occurs as the wires are guided onto the arm (or bow), and the second twist is applied as the wires exit the arm onto the strand. This results in a conductor with the same twist per unit length as a single twist strander but produced more efficiently, which is particularly useful for high-volume production or larger conductors. Both single and double twist stranders are valued for their precision, simplicity, and ability to maintain consistent conductor geometry.

4.2.4 Extrusion

The extrusion stage is where the conductor and polymer compound meet to form the insulated or jacketing layer. Extrusion is a highly versatile process, and its basic principles remain largely the same regardless of the material being processed, whether it's polyethylene, PVC, rubber, or specialty polymers.

Figure 24 – Extruder head

The goal is to apply a uniform layer of polymer around the conductor or cable core with precise control over thickness, surface finish, and material properties.

The Extruder

A typical single-screw extruder consists of several key components **(Figure 25)**. Material is fed into the hopper on the left, which can accept pellets, strips, or powders depending on the polymer type. The screw and barrel assembly is the heart of the extruder **(Figure 24)** and is divided into functional zones. The feed zone conveys the raw material forward while beginning to compact it. In the melt zone, the material is heated and sheared, causing it to melt and become a homogeneous viscous fluid. Finally, the metering zone (or melt-pumping zone) ensures that the molten polymer is delivered at a controlled rate onto the conductor or core passing through the extrusion die.

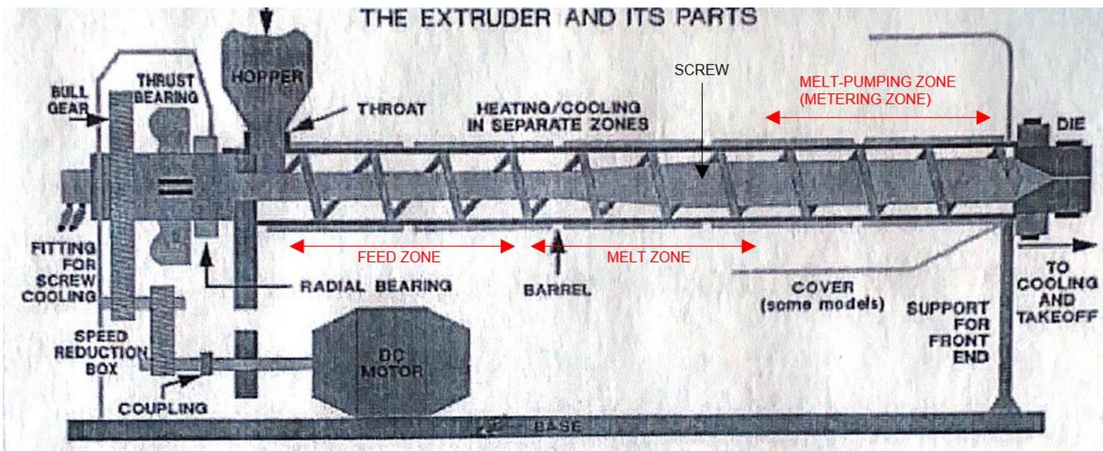


Figure 25 – The Extruder

Temperature control is critical throughout the extrusion process, with the barrel and screw being heated or cooled as required to suit the specific material. Different polymers are introduced in different forms: crystalline and semi-crystalline materials such as XLPE, TR-XLPE, PVC, and some EPRs are typically fed as pellets, while amorphous materials like CSPE, some EPRs, and Neoprene are supplied as strips.

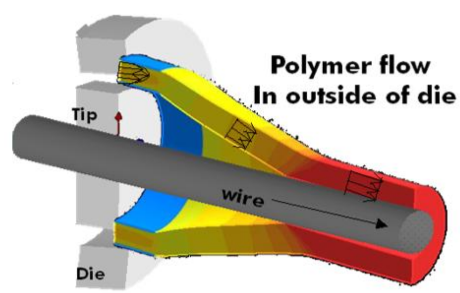


Figure 26 – Polymer flow

Specialized engineered plastics, including fluoropolymers, are generally fed as powders due to their unique handling and processing requirements. Proper control of material form, temperature, and screw design ensures consistent, high-quality extrusion and reliable insulation performance.

Extruder Heads

The extruder head **(Figure 24)** is the component that shapes and applies the molten polymer onto the conductor or cable core. After leaving the metering zone of the extruder, the melted compound flows through the head, which determines the thickness, profile, and uniformity of the insulation or jacket. The design of the head is critical, as it ensures that the polymer is applied evenly and smoothly, avoiding defects such as voids, uneven thickness, or surface irregularities. Because the extruder head is the final shaping point before the material solidifies, it plays a decisive role in both the electrical and mechanical performance of the finished cable.

Within the head, the polymer melt is redistributed from the circular outlet of the extruder barrel into an annular flow path that surrounds the conductor or cable core. This redistribution must be carefully engineered so that the flow velocity is uniform around the entire circumference. If the flow is unbalanced, the polymer will reach the die lip at different pressures and speeds, leading to eccentric insulation or jacket thickness. Over long production runs, even small imbalances can result in measurable dimensional variation, which may cause a product to fall outside of specification.

The internal geometry of the head, including the flow channels, mandrel supports, and distributor design, is therefore optimized to minimize pressure drop differences and dead zones. Dead zones are particularly undesirable because they can trap material that degrades over time and later breaks free as burnt particles, causing surface contamination or weak spots in the insulation. Modern head designs use streamlined flow paths and polished internal surfaces to promote smooth material movement and reduce the risk of degradation.

Temperature control within the head is another essential factor. The polymer must remain fully molten and homogeneous until it exits the die. If the head is too cool, the melt can begin to solidify prematurely, increasing pressure, causing surface roughness, or creating weld lines. If it is too hot, the polymer may degrade, lose mechanical strength, or develop discoloration. For this reason, extruder heads are typically equipped with multiple heating zones and precise temperature controllers to maintain a stable thermal profile that matches the processing window of the compound.

The relationship between the tip and the die is central to determining the final wall thickness and concentricity. The tip forms the inner boundary of the polymer flow, while the die forms the outer boundary. The gap between them defines the theoretical wall thickness. Any misalignment between the tip and die immediately translates into eccentricity. Even when alignment is correct, variations in material flow, pressure, or core position can still affect concentricity, which is why continuous monitoring and adjustment are often required during production.

In addition to alignment, the surface finish of the tip and die has a strong influence on the appearance of the insulation or jacket. Highly polished surfaces reduce friction and help produce a smooth, glossy finish, while damaged or worn tooling can introduce lines, scratches, or matte areas. Tooling maintenance is therefore not just a dimensional concern but also a cosmetic and functional one, especially for applications where surface quality affects installation or performance.

For more complex cable constructions, dual and triple extruder heads are often used, as shown in **Figure 27**. These heads provide parallel flow paths, allowing multiple polymer layers to be deposited sequentially or simultaneously. For example, in a dual-head setup, the first layer may be extruded onto the conductor as the primary insulation, while a second layer is deposited over it as a protective jacket or semiconductive layer. Triple heads allow for even more complex constructions, such as combining insulation, semiconductive, and outer jacket layers in a single pass.

In a dual-head configuration, the inner head applies the first layer directly to the conductor. This layer is often the most electrically critical, as it provides the primary dielectric barrier. The second head then applies an outer layer before the first layer has fully cooled. This allows the two layers to fuse together, creating excellent interlayer adhesion. The timing between layers is crucial; if the first layer cools too much before the second is applied, bonding may be reduced, while if it is too hot, deformation or thickness instability may occur.

Triple-head configurations extend this principle further by adding an intermediate layer between the insulation and the jacket. In medium- and high-voltage power cables, this intermediate layer is often semiconducting and serves to control the electric field distribution. The inner semiconductive layer smooths the interface between the conductor and insulation, while the outer semiconductive layer provides a uniform electrical interface between the insulation and metallic shielding. Applying these layers in a single pass ensures consistent geometry, excellent adhesion, and precise control of layer thickness.

By carefully controlling the flow in each layer, manufacturers can produce cables with precise layer thicknesses, excellent adhesion between layers, and tailored electrical and mechanical properties. Each extruder feeding a multi-layer head can be operated independently, allowing different materials, colors, and compound formulations to be processed simultaneously. This flexibility makes multi-head extrusion indispensable for modern cable designs that must meet demanding electrical, mechanical, and environmental requirements.

The synchronization of multiple extruders is a critical challenge in multi-layer extrusion. Each extruder must deliver material at a rate that matches the others so that layer thicknesses remain stable. Any fluctuation in one extruder can affect the entire structure, leading to variations in wall thickness, eccentricity, or interface quality. Advanced control systems are often used to coordinate screw speeds, melt pressures, and temperatures across all extruders to maintain consistent output.

Layer adhesion is one of the most important quality aspects in multi-layer cable constructions. Poor adhesion can lead to delamination during bending, pulling, or thermal cycling. Adhesion depends on material compatibility, melt temperature, surface cleanliness, and the time interval between layer applications. Some materials bond naturally, while others require special adhesive layers or tie compounds. The extruder head design must accommodate these material combinations while maintaining stable flow and geometry.

The choice between pressure and tubing application methods also applies to multi-layer heads. In pressure configurations, each layer is applied under positive pressure, promoting strong interlayer contact and excellent concentricity. In tubing configurations, one or more layers may be applied as sleeves that collapse onto the underlying layer. The selection depends on product requirements, layer thicknesses, and material behavior. In many cases, hybrid designs are used to combine the advantages of both methods within a single head assembly.

Flow stability inside the head becomes increasingly important as the number of layers increases. Any disturbance in one layer can propagate outward and affect the outer layers. For example, an unstable inner insulation layer can cause thickness variation in the semiconductive and jacket layers. This interdependence is why multi-layer head design is considered a specialized field requiring extensive computational modeling, prototyping, and practical experience.

Cooling behavior must also be considered in relation to head design. Multi-layer constructions cool at different rates depending on material thermal conductivity and thickness. Uneven cooling can introduce internal stresses between layers, potentially leading to cracking, warping, or long-term performance issues. Proper head design, combined with controlled cooling systems, helps minimize these risks by ensuring uniform heat distribution and gradual solidification.

The extruder head also influences surface quality, which can affect not only appearance but also functional properties such as friction during pulling, resistance to contamination, and compatibility with subsequent processing steps. For example, a rough jacket surface may increase pulling tension during installation, while a smooth surface may reduce friction and improve handling. In specialized applications, surface texture may be intentionally modified through tooling design to achieve specific performance characteristics.

In addition to standard circular profiles, extruder heads can be designed to produce shaped or profiled jackets, such as flat, oval, or multi-lobed constructions. These profiles are used in applications where space constraints, flexibility, or identification requirements are important. Producing such shapes requires precise control of flow distribution and tooling geometry, further highlighting the importance of head design in meeting product specifications.

Another important consideration is the ease of cleaning and material changeover. In manufacturing environments where multiple compounds or colors are processed, the extruder head must allow for efficient purging and cleaning to minimize downtime and material waste. Heads with complex internal geometries can be more difficult to clean, increasing the risk of contamination between production runs. This practical aspect often influences head selection and design choices.

Wear resistance is also a key factor, especially when processing abrasive compounds such as those containing mineral fillers or flame-retardant additives. Over time, these materials can erode internal surfaces, altering flow characteristics and reducing dimensional accuracy. Heads used for such compounds are often made from hardened or coated materials to extend service life and maintain consistent performance.

The extruder head does not operate in isolation but as part of an integrated extrusion system. Its performance is directly influenced by upstream factors such as screw design, melt quality, and temperature stability, as well as downstream factors such as cooling, pulling speed, and tension control. Successful cable extrusion therefore requires a holistic approach in which the head design is matched to the entire process.

In high-speed production environments, the head must also accommodate rapid line speeds without compromising quality. At higher speeds, melt flow becomes more turbulent, pressure levels increase, and the risk of surface defects grows. Advanced head designs use optimized flow channels and balanced distribution systems to maintain laminar flow and stable geometry even at elevated production rates.

Process monitoring is increasingly integrated with extruder head operation. Pressure sensors, temperature sensors, and flow monitoring systems provide real-time feedback on head performance. This data can be used to detect early signs of blockage, wear, or imbalance, allowing corrective action before product quality is affected. In modern manufacturing, such predictive capabilities are essential for reducing scrap and improving overall equipment effectiveness.

From a product development perspective, the extruder head is also a key enabler of innovation. New cable designs often require new head configurations or modifications to existing designs. By adjusting flow paths, layer arrangements, and tooling geometry, manufacturers can develop cables with improved electrical performance, reduced material usage, enhanced flexibility, or better environmental resistance. In this way, head design directly supports competitiveness and technological advancement in the cable industry.

Training and operator expertise play a major role in realizing the full potential of extruder head technology. Even the best-designed head cannot perform optimally if it is incorrectly assembled, aligned, or operated. Understanding how each component influences flow, temperature, and geometry allows operators to troubleshoot problems more effectively and maintain stable production conditions.

In practical operation, small adjustments to head temperature, tip position, or die alignment can have significant effects on product quality. Experienced operators learn to interpret subtle changes in surface appearance, diameter stability, or spark test behavior as indicators of head performance. This combination of technical design and human expertise is what ultimately ensures consistent, high-quality cable production.
As cable applications continue to expand into areas such as renewable energy, electric vehicles, data transmission, and harsh environments, the demands placed on extruder heads will continue to increase. Thinner walls, tighter tolerances, more complex layer structures, and new material systems all require ongoing development in head design and process control. The extruder head therefore remains not just a component of the extrusion line, but a central element in the advancement of cable manufacturing technology.

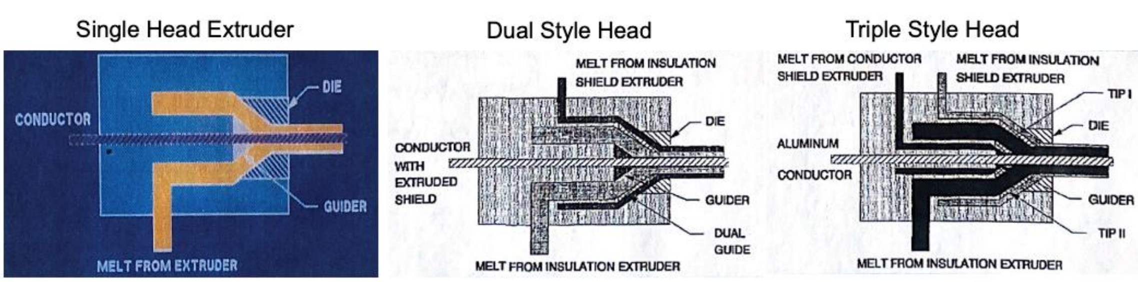
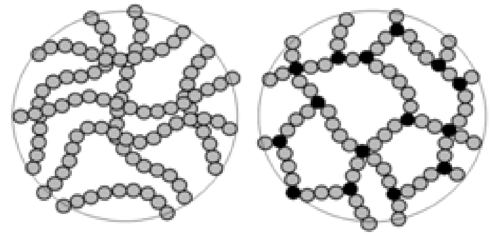


Figure 27 – Single, Dual and Triple Style Extruder Heads

Crosslinking and Vulcanization



One of the key processes that may occur during cable extrusion is **crosslinking**, which, as mentioned in earlier sections, modifies the polymer's molecular structure to enhance its mechanical and thermal properties. As discussed previously, polyethylene is commonly crosslinked for applications that require higher temperature performance, improved dimensional stability, and enhanced resistance to deformation under electrical stress. The most well-known crosslinking method is **vulcanization**.

While other crosslinking techniques exist - such as irradiation and silane-based methods - each has specific equipment requirements and is chosen based on the desired performance characteristics and the capabilities of the manufacturing plant.

Vulcanization remains the most commonly used approach in many cable production lines because it reliably produces thermally stable, durable, and resilient insulation. In the vulcanization process used for cable insulation, a peroxide compound is added to the polymer to initiate chemical reactions that create crosslinks between polymer chains.

Peroxide is highly reactive—similar in behavior to the bleach used to lighten hair—and it works by breaking existing chemical bonds in the polymer. Once these bonds are broken, they reform between adjacent polymer chains while the polymer is "cooked" at a controlled temperature and time, creating a three-dimensional network that significantly strengthens the material.

The crosslinking reaction typically takes place in a catenary vulcanization (CV) line **(Figure 28)**, which is a long, horizontal tube through which the extruded cable passes. The tube is filled with steam or nitrogen to provide a controlled environment.

Figure 28 – Example catenary line

About two-thirds of the line is heated to promote the chemical reaction, while the remaining section is cooled to gradually stabilize the material. Inside the catenary, the cable is exposed to a pressure of approximately 20 bars and a temperature around 100°C, which ensures effective crosslinking and consistent insulation properties along the length of the cable.

The length of a catenary line depends on both the cable size and the desired production speed, but typical lines are around 100 meters long. This extended length allows the cable sufficient time to complete the crosslinking reaction while moving continuously through the process, resulting in a final product that is strong, flexible, thermally stable, and ready for subsequent handling, testing, or spooling.

Vertical Extrusion

When producing high-voltage cables with very thick insulation, gravity can become a challenge. On a horizontal catenary line, the weight of the molten insulation can cause it to sag or deform before crosslinking, resulting in a conductor that is no longer perfectly round. To address this, manufacturers often use a vertical CV line, where the cable moves downward from the extruder. In this orientation, gravity actually helps maintain the cable's shape and ensures uniform insulation thickness.

In a vertical CV line, the length of the heated tube must still be sufficient to allow complete curing of the polymer and partial cooling, so that the insulation solidifies properly before leaving the pressurized environment. Cooling must be carefully controlled—typically slower than in horizontal lines—to avoid introducing internal stresses in the polyethylene, which could compromise mechanical or electrical performance. This cooling is often done under pressure in water heated above its boiling point, ensuring the polymer remains under controlled conditions as it transitions to a solid state.

Figure 29 – Vertical CV

A compact view of a vertical CV installation illustrates the process clearly **(Figure 29).** At the bottom right, the payoff reel and angle pulley feed the conductor into the line, while a cable accumulator allows the payoff to be changed without stopping extrusion. The cable then moves upward to a guiding pulley before entering the extruder. The heated portion of the tube is shown in blue, where crosslinking occurs, while the cooled section is in grey, allowing gradual solidification. The bottom pulley is part of a pressurized enclosure, maintaining the necessary environment for curing. Finally, the fully insulated and crosslinked cable exits the tube and is coiled onto the take-up reel, ready for subsequent testing or shipment.

This configuration is especially useful for large, heavy cables, ensuring uniform insulation, precise geometry, and high-quality crosslinking without deformation.

Basic Setup of an Extrusion Line

The three most common setups for extrusion lines are:

1. Single-layer extrusion for standard plastic insulation
2. Single-layer extrusion for continuous vulcanization (CV)
3. True triple-layer extrusion for CV.

Other configurations, such as 1+1+1 or 1+2 extrusion, exist but are less common and are not discussed here.

In **single-layer extrusion (Figure 30)**, a conductor enters the extruder and receives a single layer of insulation. This setup can also be used to add a protective jacket or a second layer in a subsequent pass, depending on the cable design. This type of line is straightforward, efficient, and widely used for lower-voltage or simpler cable constructions.

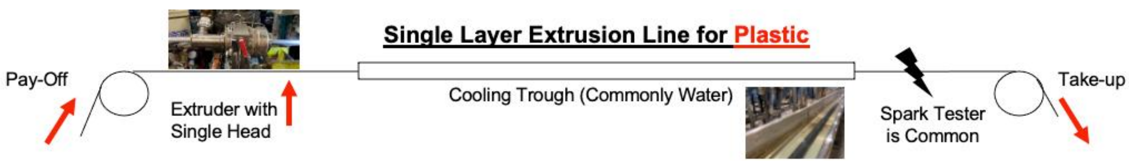


Figure 30 – Single Layer Extrusion Line for Plastics (typically low voltage)

A **single-layer extrusion line for continuous vulcanization (Figure 31)** incorporates an additional curing zone after the extrusion die. This curing section allows the polymer—typically crosslink-able polyethylene—to undergo the crosslinking reaction, most commonly using steam. Alternative curing methods include radiant heat, molten salt, or electron beam irradiation, depending on the material and plant capabilities. The CV zone ensures the insulation achieves the desired mechanical, thermal, and electrical properties.

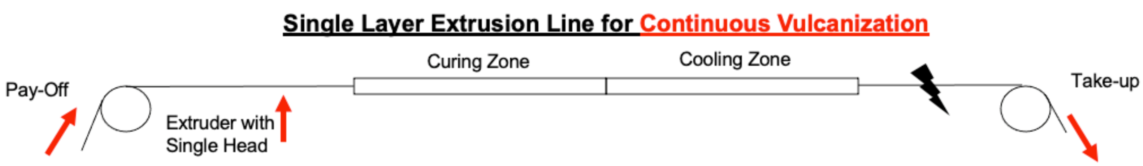


Figure 31 – Single Layer Extrusion Line for CV (typically low voltage)

In a **true triple-extrusion setup (Figure 32)**, three polymer layers are applied in a single pass, often medium voltage cables requiring a 3-layer insulation system with semiconducting layers. For XLPE insulation, curing is commonly performed using radiant heat, which provides uniform energy transfer to crosslink the inner layers without damaging the outer layers. True triple extrusion is particularly advantageous for medium/high-voltage and complex cable designs, as it reduces processing time while ensuring precise layer thickness, adhesion, and consistent material properties.

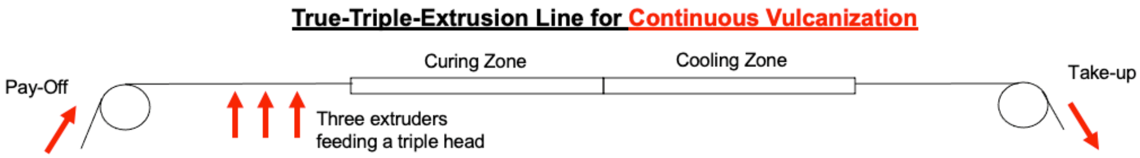


Figure 32 – True-Triple Extrusion Line for CV (typically medium voltage)

4.2.5 Cabling

Once the basic components of the cable such as the conductor, insulation, semiconductive layers, fillers, and any additional reinforcements are prepared, the next stage is the cabling step. Cabling involves assembling all these elements into the final cable structure, ensuring that each layer and component is positioned correctly, with proper tension and alignment. This step is critical because it defines the cable's mechanical integrity and overall geometry, setting the foundation for any additional layers such as shielding, armoring, or outer jacketing. See **Figure 33**.

During cabling, conductors may be twisted together, insulated cores may be bundled, and filler materials added to occupy voids and maintain shape. The process requires careful control of tension, lay length, and alignment, as uneven assembly can lead to defects, weak points, or reduced flexibility in the finished cable. Essentially, the cabling step transforms individual components into a cohesive, structurally sound cable ready for subsequent processing and finishing operations.

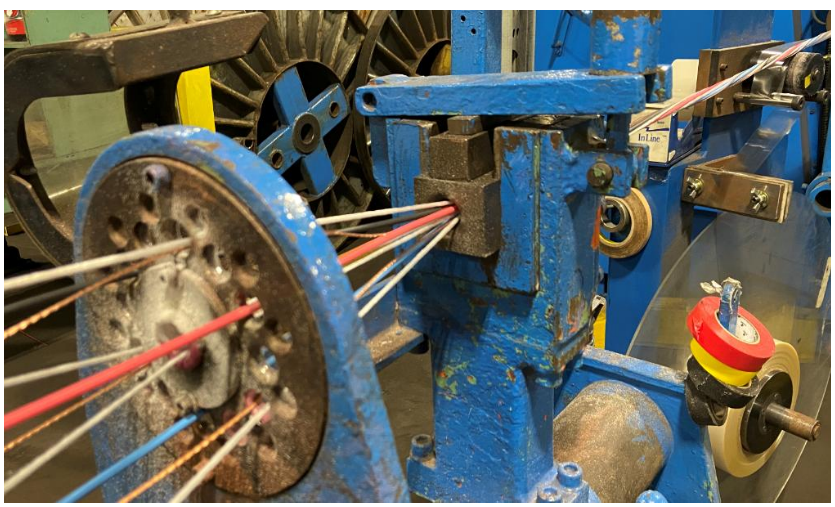


Figure 33 – Cabling operation

Cables can be assembled in two different ways depending on whether the individual wires or bundles are twisted during the cabling process:

1. Assembly with torsion
2. Assembly without torsion

In **assembly with torsion**, each wire or bundle is twisted along its own axis, usually one turn for each turn of the overall assembly, which can improve mechanical stability and balance in certain cable designs.

On the other hand, **assembly without torsion** involves laying the individual elements or conductors onto the cable core without twisting them on their own axis**,** which may be preferred for flexible cables or when minimizing internal stresses is important.

There are also **two main mechanical methods for performing cabling**:

1. **Rotating pay-off with fixed take-up**; and
2. **Fixed pay-off with rotating take-up**.

Figure 34 – Rotating pay-off

In the **rotating pay-off, fixed take-up** setup **(Figure 34)**, the pay offs rotate to feed material while the finished cable is wound onto a stationary take-up.

This configuration is simple and allows multiple layers to be assembled in a single step. Additional cages can be added to incorporate more conductors, and the cages can rotate in the same or opposite directions to achieve the desired lay. However, the need to rotate large masses of material limits the achievable production speed.

Figure 35 – Fixed pay-off

In the **fixed pay-off, rotating take-up** setup **(Figure 35)**, the pay-off reels remain stationary while the take-up rotates to pull the cable through the cabling process. Because the moving mass is much lower, this configuration is more compact and capable of higher production speeds**.** The trade-off is that only one layer can be assembled at a time**,** so additional layers require multiple passes. From a cable performance perspective, both methods are equivalent; the choice depends primarily on the production requirements, machine design, and speed considerations**.**

4.2.6 Shielding

Metallic shielding is used in a cable to improve electrical performance, provide grounding paths, and protect the insulation from external electrical interference. Metallic shields serve multiple purposes, including carrying fault currents, reducing electromagnetic interference (EMI), controlling voltage stress. Two of the most common forms of metallic shielding are concentric neutral wires and copper tapes**.** Metallic braid shields are also possible **(Figure 36).**

Concentric neutral shields **(Figure 37)** are individual copper wires or flat straps that are stranded around the insulated conductor in a concentric pattern. They form a continuous metallic path that can carry fault currents safely to ground, making them particularly important in medium- and high-voltage power cables**.** The application of concentric neutral wires involves precision stranding equipment that ensures uniform spacing and tension, preventing gaps or overlaps that could compromise the cable's electrical performance. These wires are typically laid over the insulation layer after extrusion, using controlled rotation and tension to maintain a consistent concentric geometry.

Figure 36 – Copper braid shield

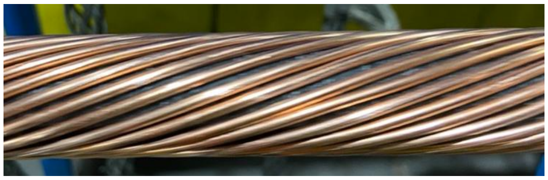


Figure 37 – Concentric neutral wires

Tapes**,** on the other hand, are flat strips, typically copper, that are helically wrapped around the insulated conductor or cable core **(Figure 38).** They may also be longitudinally applied and corrugated (LACT) **(Figure 39)**. Copper tape shields can be applied with or without overlap, depending on the required level of coverage and electrical performance. The wrapping process is carefully controlled to maintain uniform tension and alignment**,** preventing wrinkles, gaps, or tearing, which could reduce the effectiveness of the shield and damage the other components of the cable assembly.

Figure 38 – Helically wrapped tape

Figure 39 – LACT

4.2.7 Armouring

Cable armour is a protective layer incorporated into a cable designed to enhance both mechanical strength and overall durability. Its primary role is to protect the cable's inner conductors and insulation from external physical damage, which may occur through crushing, impact, or abrasion during installation or throughout its service life. In many environments, cables are buried underground, laid in ducts, installed on trays, or routed through industrial facilities where they may be exposed to heavy machinery, sharp objects, vibration, moisture, and even rodent activity. The addition of armour ensures that the integrity of the cable is preserved in these demanding conditions while also contributing to overall safety and reliability.

Armour can also provide additional functions. In certain designs, it contributes to electromagnetic shielding, serves as a grounding path, or improves fire and impact resistance. In subsea or mining applications, armour becomes an essential structural element that allows the cable to withstand extreme tension, pressure, and environmental stress. Because of these diverse requirements, the armouring process is not simply an added manufacturing step, but a carefully engineered operation that must integrate material selection, machine configuration, and precise process control.

Armouring requires a careful balance between machine speed, tape or wire positioning, armour tightness, and operator expertise. The armouring machines used to produce power cable products are complex systems designed to apply metal layers with consistent overlap, tension, and alignment. Armour is typically constructed using aluminum or steel tape, or layers of steel or aluminum wires, with the choice of material depending on the required balance between strength, flexibility, corrosion resistance, and weight. Steel wire armour provides very high mechanical protection and is often used in submarine, mining, and heavy-duty industrial cables. Aluminum or steel tape armour is more common in industrial, commercial, and building applications where moderate protection and lighter weight are preferred. In flexible cables, helical wire armour allows durability to be maintained without severely compromising bending performance.

The two most common armors in power cables are aluminum interlocked armour (AIA) and continuously welded and corrugated armour (CWC). Both designs aim to protect the cable while allowing a practical balance between strength, flexibility, and ease of installation, yet they differ significantly in construction method, mechanical behavior, and manufacturing complexity.

Before examining these armour types in detail, it is important to understand the general preparation required before armouring begins. The cable core entering the armouring line typically consists of insulated conductors, often with fillers, binders, and an inner sheath or bedding layer. This inner sheath provides a smooth and stable surface for the armour and prevents the metal from damaging the insulation layers beneath. The bedding material is usually PVC, PE, paper, or another suitable polymer that provides cushioning and electrical separation. Without a proper bedding layer, the armour could introduce stress concentrations or abrasion points that would compromise long-term reliability.

Once the core is prepared, it is fed into the armouring machine through a series of guides and tension control devices. Maintaining stable and consistent core tension is essential. Excessive tension can stretch or deform the inner layers, while insufficient tension can lead to irregular armour application, poor overlap, or waviness. Modern armouring lines often use dancer systems or electronic tension control to maintain consistent conditions throughout the process.

In tape armouring processes, flat metal tape is formed around the cable in a helical or interlocked pattern. The tape may be aluminum or steel, and its thickness is selected based on mechanical protection requirements. In interlocked armour, the edges of the tape are mechanically formed so that they lock together as the tape wraps around the cable. This interlocking action creates a continuous metallic sheath that provides excellent mechanical protection while retaining a degree of flexibility. The interlock also allows the armour to expand and contract slightly during bending, reducing the risk of cracking.

The interlocking process itself is highly sensitive to machine setup. The forming rolls must shape the tape precisely so that the interlock is secure without being overly tight. If the interlock is too loose, the armour may open under mechanical stress. If it is too tight, flexibility is reduced and installation becomes more difficult. The overlap angle, tape width, and forming geometry must all be matched to the cable diameter and armour thickness requirements.

Aluminum interlocked armour is widely used in building wire and industrial power cables because it offers good corrosion resistance, relatively low weight, and adequate mechanical protection. Aluminum also provides an inherent grounding path when properly bonded. Steel interlocked armour offers higher mechanical strength but requires additional corrosion protection, often in the form of galvanizing or coatings, and is heavier than aluminum.

Continuously welded and corrugated armour represents a more advanced and robust armouring method. In this process, a flat metal tape is formed around the cable, and the longitudinal seam is continuously welded, typically using high-frequency welding. After welding, the tube is corrugated to introduce flexibility. The corrugation allows the otherwise rigid metal tube to bend without cracking, making it suitable for applications that require both high protection and reasonable flexibility.

The welding stage is critical. The weld must be continuous, uniform, and free from porosity or inclusions. Any defect in the weld can become a point of mechanical weakness or a pathway for moisture ingress. Quality control systems such as ultrasonic or eddy current inspection are often used to monitor weld integrity in real time. After welding, the corrugation process must be carefully controlled to ensure consistent pitch and depth. Irregular corrugation can lead to stiffness variations, stress concentrations, or difficulty during installation.

CWC armour provides excellent mechanical strength, high impact resistance, and superior moisture protection. For this reason, it is often used in underground, submarine, and harsh industrial environments. However, it is more expensive and complex to manufacture than interlocked armour, and it requires highly specialized equipment and skilled operators.

Wire armouring is another widely used method, particularly in heavy-duty applications. In this process, individual steel or aluminum wires are helically applied around the cable core. The wires are laid with a specific lay length and tension to achieve the desired balance between strength and flexibility. Single-layer wire armour is common in many power cables, while double-layer wire armour may be used for very demanding applications such as submarine cables.

The wire armouring process involves multiple payoff spools feeding wires into a rotating cage or planetary system. Each wire must be maintained at equal tension to ensure uniform coverage. Variations in wire tension can result in gaps, overlaps, or uneven pressure on the core. Modern machines use electronic tension control to synchronize all wires and maintain consistent application.

Wire diameter, material, and lay angle all influence the mechanical performance of the armour. A shorter lay length increases mechanical strength but reduces flexibility, while a longer lay length improves flexibility but reduces resistance to crushing and impact. Engineers must therefore select parameters based on installation method, operating environment, and expected mechanical loads.

In submarine cables, wire armour serves not only as protection but also as a structural element that supports the cable's own weight over long spans. In these applications, multiple layers of

galvanized steel wires are often used, and the design must account for tension during laying, water pressure, and long-term fatigue. Corrosion protection becomes especially important, and additional coatings or bituminous compounds may be applied over the armour.
Regardless of the armour type, maintaining concentricity and uniform coverage is essential. If the armour is applied eccentrically, it can create uneven stress distribution when the cable is bent or loaded. This can eventually lead to deformation of the inner layers or premature failure. Precision guiding systems and continuous monitoring are therefore integral parts of modern armouring lines.

After armouring, an outer sheath is usually applied. This sheath protects the armour itself from corrosion, abrasion, and environmental exposure. It also improves handling and appearance. The compatibility between the armour and outer sheath materials must be carefully considered. For example, certain polymers may interact chemically with bare steel, requiring additional protective coatings or bedding layers.

The interaction between armour and grounding is another important consideration. In many power cable designs, the armour is intended to act as a grounding conductor. To perform this function effectively, electrical continuity must be maintained along the entire length of the cable. In interlocked or welded armors, continuity is relatively straightforward, while in wire armors, bonding methods may be required to ensure low-resistance paths. Testing of armour continuity is therefore a standard part of quality control.

Armouring also influences cable weight, bending radius, and pulling tension during installation. Heavily armoured cables require more robust handling equipment and careful planning to avoid excessive stress. Engineers must therefore consider installation methods when selecting armour type and thickness. A design that provides excellent protection but is too stiff or heavy may create practical installation challenges.

The armouring process is highly dependent on operator skill and experience. While modern machines provide advanced control systems, the ability to recognize subtle changes in armour appearance, tension behavior, or machine sound can help operators detect issues before they result in defective product. Training and experience remain essential components of high-quality armoured cable production.

Quality control during armouring includes dimensional checks, visual inspection, tension monitoring, and in some cases destructive testing to verify adhesion and mechanical performance. For welded armors, weld inspection is particularly critical. For wire armors, lay consistency and wire integrity must be verified. These inspections ensure that the armour performs as intended throughout the cable's service life.

The selection of armour type is always a compromise between protection, flexibility, cost, and weight. Aluminum interlocked armour offers a practical balance for many building and industrial applications. Steel interlocked armour provides higher strength where needed. Continuously welded and corrugated armour delivers superior protection for harsh environments. Wire armour excels in heavy-duty and subsea applications. Understanding these trade-offs allows manufacturers and engineers to match cable construction to real-world requirements.

The armouring process also interacts closely with standards and regulations. National and international standards define minimum armour thickness, material properties, overlap requirements, and test methods. Compliance with these standards ensures that cables meet safety and performance expectations in different markets. Manufacturers must therefore design their armouring processes not only for efficiency but also for regulatory compliance.

As cable applications expand into renewable energy, offshore wind, electric vehicle infrastructure, and underground urban networks, the demands on armoured cables continue to grow. Higher currents, higher voltages, tighter installation spaces, and more aggressive environments all place greater stress on armour systems. This has driven ongoing innovation in armour materials, coatings, and manufacturing methods.

Lightweight aluminum alloys, improved corrosion-resistant steels, and hybrid armour designs are increasingly being explored. Some designs combine tape and wire armouring to achieve both surface protection and tensile strength. Others integrate polymer-metal composites to reduce weight while maintaining mechanical performance. These innovations further highlight the importance of precise and adaptable armouring processes.

In manufacturing terms, the armouring stage often represents one of the highest capital investments in a cable plant. Armouring machines are large, complex, and energy-intensive. Their performance directly affects production speed, product quality, and operating cost. Maximizing machine utilization while maintaining quality is therefore a key objective for cable manufacturers.

Maintenance of armouring equipment is equally critical. Worn forming rolls, misaligned guides, or damaged tension systems can quickly degrade armour quality. Preventive maintenance programs, combined with regular calibration and inspection, help ensure long-term stability of the process.

The armouring process is often one of the most challenging stages for new operators to master. It combines mechanical engineering, materials science, and practical machine operation. A deep understanding of how armour interacts with the underlying cable structure allows operators and engineers to make informed decisions when troubleshooting or optimizing production.

In practical operation, even small adjustments can have significant effects. Slight changes in tape tension, wire lay angle, or forming geometry can alter flexibility, appearance, and mechanical performance. This sensitivity is what makes armouring both a technical challenge and a craft developed through experience.

Figure 40 – AIA (left) and CWC (right)

Interlocked Aluminum Armor

Interlocked Aluminum Armour (AIA) is formed by wrapping a shaped tape around the cable to provide mechanical protection. It is typically made from aluminum, although galvanized steel may also be used in some designs. While this type of armour is effective for physical protection, it cannot serve as a bonding conductor. One of its key advantages is flexibility. However, this flexibility comes with certain limitations. If the armour is bent too sharply, it can break open, compromising the cable's protection. In addition, AIA does not provide a complete moisture barrier, which means that water can penetrate to the core of the cable.

The AIA process begins with large rolls of aluminum strip, which are carefully fed into the machine. The coil holding the strip is positioned perpendicular to the conductors, allowing the conductors to pass directly through the center of the coil. The aluminum strip is then helically wrapped around the conductors in a continuous motion, forming a protective layer that interlocks onto itself to ensure structural integrity and resistance to deformation. During this wrapping and forming process, friction between the aluminum strip and the conductors generates heat. To prevent overheating and maintain the quality of the armor, a light application of oil is used to reduce friction and facilitate smooth formation.

This process ensures that the conductors are both well-protected and flexible enough for practical handling and installation. See **Figure 41**.

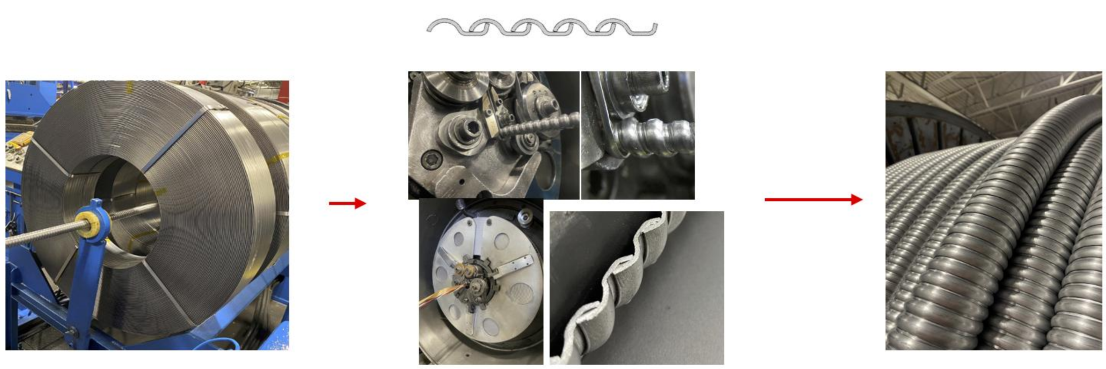


Figure 41 - AIA process

Continuously Welded and Corrugated Armour

Continuously Welded and Corrugated Armour (CWC), on the other hand, is constructed using a welded tube, most often corrugated, that is placed over the cable. This design, typically made of aluminum, provides strong and consistent protection while also maintaining some flexibility thanks to the corrugation. It also offers a key advantage in terms of environmental resistance, as it prevents moisture from reaching the cable core. However, while durable, CWC can still be damaged if bent excessively, which may reduce its effectiveness. Like AIA, it is usually supplied with an additional outer covering for enhanced protection against mechanical and environmental stress.

The CWC process begins with large rolls of aluminum strip, which are carefully fed into the machine in a controlled manner. Unlike interlocked armouring, the strip is fed parallel to the conductors, and as it is wrapped around them, it forms a smooth, uniform tube. This tube is then continuously TIG welded along its length, creating a seamless and strong armor that provides consistent protection against mechanical stresses and environmental factors. Once the welding is complete, the smooth aluminum tube passes through a corrugator, a machine that imparts a series of ridges or corrugations along its surface. This corrugation significantly improves the flexibility of the armored conductor, allowing it to bend and flex without compromising the integrity of the aluminum armor. Additionally, the corrugation enhances the mechanical strength of the conductor, helping it resist crushing, impact, and other forms of physical stress. The result is a conductor that combines robust protection with practical flexibility, making it suitable for a wide range of electrical installations where both durability and adaptability are critical. See **Figure 42**.

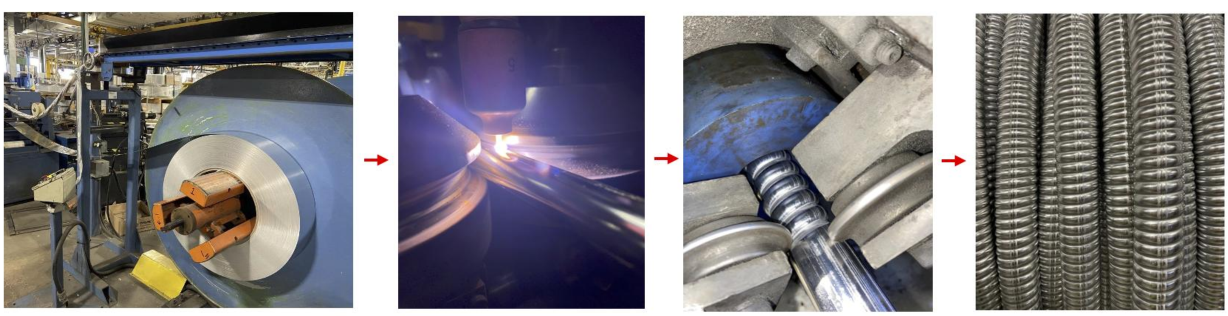


Figure 42 - CWC process

4.2.8 Jacketing

The jacketing process is an extrusion process and so it follows the same concept as explained in Section 4.2.3.

Cable jackets can be applied either overlaid or encapsulated as shown in **Figure 43**.

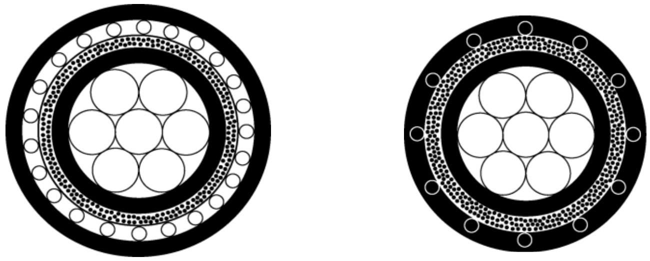


Figure 43 – Overlay jacket (left) and encapsulating jacket (right)

Overlay jackets typically have a separator tape placed over the inner core to prevent fall-in between wires. This set up offers greater flexibility for terminating. On the other hand, encapsulating jackets are extruded to fill void spaces in the inner core. This set up provide less flexibility for terminating.

Cable jacketing is a critical stage in wire and cable manufacturing because it provides the final layer of protection for the cable against mechanical damage, moisture, chemicals, ultraviolet radiation, and environmental exposure. While the insulation layer ensures electrical performance, the jacket preserves the integrity of the entire cable system during handling, installation, and long-term service. This is why the jacketing process must be carefully controlled to ensure uniform thickness, good concentricity, smooth surface finish, and consistent material properties.

The jacketing process begins when the insulated or assembled cable core is fed from a payoff into the extrusion line. Depending on the material and plant conditions, the core may pass through a preheater or drying unit to remove surface moisture and stabilize temperature. The extruder then melts and pressurizes the polymer compound that will form the jacket. Temperature control along the barrel is essential, as excessive heat can degrade the material and insufficient heat can lead to poor flow, rough surfaces, or incomplete fusion. Screw design and speed also influence how well the polymer is mixed and homogenized before entering the crosshead.

Once the molten material reaches the extruder head, it is directed around the cable core to form the jacket. The design of this head has a major influence on product quality, and two main configurations are used in cable manufacturing: **pressure type** and **tubing type**.

In a **pressure setup**, the polymer is forced directly onto the surface of the cable core under positive pressure. This results in very good control of wall thickness and concentricity, and it promotes strong contact between the jacket and the underlying layer. Pressure extrusion is therefore preferred when thin jackets, tight tolerances, or strong layer contact are required. However, it is more sensitive to variations in core diameter and surface quality, and poor alignment can lead to surface marks or uneven walls.

In a **tubing setup**, the polymer exits the die as a hollow tube, and the cable core enters this tube slightly downstream. The jacket then collapses onto the core as it passes through the cooling and vacuum sizing system. This method is less sensitive to surface imperfections on the core and is well suited for thick jackets and large cable constructions. The trade-off is that concentricity control is slightly less precise, and adhesion between layers is generally weaker than with pressure extrusion. For applications where bonding is not required and where robustness and surface protection are more important than tight tolerances, the tubing method is often preferred.

Both setups rely on correct tooling selection and alignment. The relationship between the tip and die determines how evenly the polymer flows around the core. Poor alignment can cause eccentric walls, ovality, or surface defects. Even small deviations can translate into measurable quality issues over long production runs, which is why tooling inspection and setup discipline are essential in jacketing operations.

After extrusion, the jacket must be cooled in a controlled manner. Cooling is usually performed in water troughs using spray or immersion methods, and in tubing setups vacuum is often applied to help shape and stabilize the jacket. Cooling that is too rapid can induce internal stresses and surface defects, while cooling that is too slow can allow deformation or ovality. Uniform cooling ensures that the jacket maintains its designed dimensions and mechanical properties.

Once cooled, the jacketed cable passes through online inspection systems. One of the most important of these systems is the sparker box, which is used to detect defects in non-conducting jackets. The sparker applies a high voltage between an electrode and the conductor. If the jacket contains a pinhole, crack, or thin section, the electrical field breaks down at that point and produces a visible or audible spark, triggering an alarm. This allows immediate identification of defects and helps prevent defective product from being wound onto reels.

Sparker boxes are highly effective for jackets made from insulating materials such as PVC, polyethylene, LSZH compounds, TPU, and other non-conductive polymers. In these materials, the jacket itself blocks current flow, so any discontinuity is easy to detect. The effectiveness of spark testing depends on proper grounding of the conductor, stable voltage control, and correct electrode contact. Poor grounding or contamination can lead to missed defects or false alarms.

Sparker boxes cannot be used for semiconducting jackets because these materials are intentionally formulated to allow controlled electrical conductivity. In such jackets, current can pass through the material itself, making it impossible for the sparker to distinguish between normal conductivity and a true defect. Continuous arcing or constant alarms would occur, rendering the test meaningless. For semiconducting jackets, quality control relies instead on visual inspection, dimensional measurements, surface resistivity testing, and offline electrical and mechanical evaluations.

Dimensional control is another key aspect of the jacketing process. Laser or capacitance gauges are commonly used to monitor outer diameter, ovality, and sometimes concentricity. Many modern lines use closed-loop control systems that automatically adjust extruder or capstan speed to maintain target dimensions. This reduces scrap, improves consistency, and allows tighter tolerances to be maintained over long production runs.
Defects in cable jackets can originate from many sources, including material contamination, moisture, incorrect temperature settings, misaligned tooling, unstable melt flow, or improper cooling. Typical defects include pinholes, rough surfaces, die lines, bubbles, thin spots, and poor adhesion. Because the jacket is the final layer, any defect at this stage usually results in product rejection or rework, making preventive process control far more efficient than corrective action.

Consistent jacketing quality depends heavily on disciplined process documentation and operator training. Standardized setup sheets for both pressure and tubing configurations help ensure that proven parameters are reused. Tooling history, material batch records, and inspection data provide traceability and support continuous improvement. When operators understand how each parameter influences jacket quality, they are better able to respond quickly to deviations and prevent defects from propagating.

Safety is also a major consideration in jacketing operations. The combination of high temperatures, rotating equipment, cooling water, and high-voltage spark testers creates a working environment that requires strict adherence to safety procedures. Proper guarding, grounding, lock-out practices, and routine inspections are essential to protect personnel and equipment.

5 Factory Testing and Quality Assurance

Factory testing and quality assurance are fundamental pillars of modern wire and cable manufacturing. Because cables are safety-critical products used in power transmission, industrial systems, transportation, telecommunications, and infrastructure, even minor defects can lead to severe consequences such as electrical failure, service interruption, fire hazards, or costly downtime. For this reason, cable manufacturers implement rigorous, systematic, and multi-layered testing programs that span the entire production lifecycle—from initial design development to final shipment of finished products.

Quality assurance in cable manufacturing is not limited to a single inspection point. Instead, it is a continuous process embedded into every stage of production. This philosophy recognizes that quality cannot be "inspected into" a product at the end; it must be built into the product from the beginning through controlled design, qualified materials, disciplined manufacturing processes, and comprehensive testing.

The factory testing program is designed to ensure that each cable:

- Meets all applicable industry standards and regulatory requirements.
- Performs safely and reliably under its intended electrical, thermal, mechanical, and environmental conditions.
- Demonstrates consistent quality from batch to batch.
- Satisfies customer specifications and contractual obligations.
- Maintains long-term durability throughout its service life.

Testing requirements vary depending on the type of cable (power, control, instrumentation, communication, flexible, armored, fire-resistant, etc.), voltage rating, installation environment, and applicable standards such as IEC, IEEE, UL, CSA, AEIC, or national codes. However, despite these differences, factory testing can be broadly divided into four fundamental categories:

1. Design qualification tests
2. Incoming material tests
3. In-process tests
4. Finished product tests

Together, these four categories form a closed-loop quality assurance system that verifies performance at every stage and minimizes the risk of defects reaching the customer

5.1 Qualification Testing

Qualification testing, often referred to as design qualification or type testing, is performed at the earliest stage of product development. Its primary purpose is to confirm that a proposed cable design is technically sound, manufacturable, and capable of meeting all performance requirements over its intended service life.

Before a cable design is released for routine production, it must demonstrate compliance with:

- Applicable industry standards.
- Electrical and mechanical performance targets.
- Environmental and durability expectations.
- Installation and handling requirements.

Qualification testing is typically performed on prototype or pre-production samples manufactured under controlled conditions. These tests are not intended to verify daily production quality; instead, they validate the fundamental design concept.
Without proper qualification testing, manufacturers risk introducing designs that may perform adequately in the short term but fail prematurely in service.

Electrical Performance Tests

Electrical qualification tests verify that the insulation system, conductor design, and overall cable construction can withstand the intended voltage stresses and current loads.

Typical electrical tests include:

- **Voltage withstand tests:** Applying AC or DC voltage above the rated level to confirm insulation integrity.
- **Partial discharge tests:** Detecting localized insulation defects that could lead to long-term degradation.
- **Insulation resistance measurements:** Evaluating the dielectric quality of insulation materials.
- **Capacitance and dielectric loss tests:** Particularly important for medium- and high-voltage cables.

These tests ensure that the cable can operate safely without breakdown, tracking, or excessive leakage current.

Thermal and Load Cycling Tests

Load cycling tests simulate real operating conditions by repeatedly heating and cooling the cable through electrical loading. During these cycles, the cable is subjected to:

- Thermal expansion and contraction of conductors.
- Mechanical stress on insulation and shielding.
- Changes in electrical resistance.

The objective is to verify that the cable maintains stable electrical and mechanical performance after many cycles, representing years of service operation. Any cracking, deformation, or insulation breakdown observed during these tests indicates that the design is not suitable for long-term use.

Mechanical Integrity Tests

Mechanical qualification tests evaluate the cable's ability to withstand installation and service stresses. These include:

- **Tensile tests:** Measuring the strength of conductors, insulation, and jackets.
- **Elongation tests:** Assessing flexibility and ductility.
- **Deformation tests:** Checking resistance to compression and flattening.
- **Abrasion resistance tests:** Evaluating jacket durability against mechanical wear.

These tests are essential because cables are frequently pulled through ducts, trays, or conduits, where they are exposed to friction, bending, and tension.

Strippability and Installation Tests

Strippability tests ensure that insulation and jacket layers can be removed cleanly without damaging underlying components. Poor strippability can lead to:

- Damaged conductors.
- Improper terminations.
- Increased installation time.
- Higher risk of field failures.

Installation simulation tests may also include bending, pulling, and routing trials to confirm that the cable can be handled easily under realistic conditions.

Environmental Durability Tests

Cables are often exposed to extreme environments. Qualification testing therefore includes:

- **Cold bend and cold impact tests:** Verifying flexibility and impact resistance at low temperatures.
- **Heat shock tests:** Evaluating insulation stability under sudden temperature changes.
- **Cracking tests:** Ensuring materials do not become brittle over time.
- **Oil, chemical, and moisture resistance tests:** For industrial and outdoor applications.
- **UV resistance tests:** For sunlight-exposed installations.

These tests confirm that the cable design can withstand harsh environmental conditions without degradation.

Once all qualification tests are successfully completed, the cable design is formally approved for production. The results are documented and become part of the product's technical file. Any future design changes, such as material substitutions or dimensional modifications, typically require partial or full re-qualification to ensure continued compliance.

5.2 Incoming Material Testing

Incoming material testing ensures that all raw materials entering the manufacturing process meet required specifications. Since cable performance is directly dependent on the quality of its materials, this stage is critical in preventing defects before production even begins.

Materials commonly tested include:

- Conductors (copper, aluminum, alloys).
- Insulation compounds.
- Jacket materials.
- Shielding tapes and wires.
- Armoring components.
- Fillers, binders, and separators.

Even small variations in material properties can significantly affect cable performance, particularly in high-voltage or high-temperature applications.

In-House Compound Testing

When compounds are produced in-house, manufacturers perform extensive testing that may include:

- Melt flow index
- Density
- Tensile strength and elongation
- Thermal stability
- Aging performance
- Electrical resistivity

These tests confirm consistency between batches and ensure that compounds will process correctly during extrusion.

Purchased Material Verification

For externally sourced materials, manufacturers rely on:

- Supplier certificates of analysis.
- Supplier qualification audits.
- Periodic sample testing.
- Incoming inspection protocols.

While supplier certificates provide initial assurance, spot testing is essential to verify ongoing compliance and detect any deviations.

Dimensional and Visual Inspections

Incoming conductors and tapes are checked for:

- Diameter accuracy.
- Surface cleanliness.
- Absence of oxidation or contamination.
- Proper packaging and handling.

Visual inspection often detects issues that laboratory testing might miss, such as mechanical damage during transport.

Traceability and Documentation

Each batch of incoming material is typically assigned a lot number and recorded in the manufacturer's quality system. This traceability allows any future product issue to be traced back to specific material batches, enabling rapid root-cause analysis and corrective action.

Impact on Manufacturing Efficiency

Effective incoming material testing reduces:

- Scrap rates.
- Machine downtime.
- Rework costs.
- Customer complaints.

By ensuring only compliant materials enter production, manufacturers protect both product quality and operational efficiency.

5.3 In-Process Testing

In-process testing is performed continuously during cable manufacturing. Its goal is to detect deviations as early as possible, when corrective action is still feasible and material waste is minimal.

Because cable production involves multiple sequential processes, such as conductor stranding, insulation extrusion, shielding, armoring, and jacketing, errors at any stage can compromise the entire product.

5.3.1 Dimensional Control

Key dimensions such as conductor diameter, insulation thickness, eccentricity (centering) and overall cable diameter, are measured frequently using laser gauges, micrometers, or automated inspection systems. Proper centering is especially important to ensure uniform electrical stress distribution in insulated cables.

5.3.2 Surface Cleanliness and Defect Detection

During extrusion, surfaces are monitored for:
- Voids.
- Contaminants.
- Bubbles.
- Scratches or inclusions.

Any surface imperfection can act as a stress concentration point and reduce insulation life.

5.3.3 Spark Testing

Spark testing is a critical real-time electrical test performed on insulated conductors or completed cores. A high voltage is applied between the conductor and an external electrode to detect pinholes or insulation defects.
Spark testing ensures that insulation integrity is maintained continuously during production.

5.3.4 Curing and Crosslinking Control

For cross-linked insulation systems, proper curing is essential. In-process tests verify:
- Degree of crosslinking
- Gel content
- Thermal performance

Improper curing can result in poor mechanical strength and reduced thermal endurance.

5.3.5 Process Parameter Monitoring

Manufacturers continuously monitor parameters such as:
- Extrusion temperature
- Line speed
- Cooling rate
- Tension control

Automated control systems and statistical process control techniques help maintain consistency and detect trends before defects occur.

5.3.6 Benefits of In-Process Testing

In-process testing:

- Reduces scrap and rework.
- Improves yield.
- Enhances product consistency.
- Enables rapid corrective action.
- Builds confidence in finished product quality.

It represents the most cost-effective stage of quality control, as problems are corrected before significant value is added to the product.

5.4 Finished Product Testing

Finished product testing is the final verification step before cables are released for shipment. These tests confirm that the completed cable meets all design, standard, and customer requirements.

While previous testing stages reduce the likelihood of defects, finished product testing provides formal confirmation that each production batch is compliant.

Electrical Tests

Typical electrical tests include:

- **AC or DC spark tests:** Final insulation integrity check.
- **Insulation resistance tests:** Verifying dielectric quality.
- **Conductor resistance measurements:** Ensuring compliance with electrical conductivity requirements.
- **High-voltage withstand tests:** For medium- and high-voltage cables.

These tests ensure that the cable will perform safely in service.

Mechanical Tests

Finished cables may be subjected to:

- Tensile tests.
- Elongation tests.
- Bending tests.
- Impact tests.

These verify that the cable can withstand handling and installation stresses.

Dimensional Verification

Final measurements confirm compliance with:

- Overall diameter.
- Layer thicknesses.
- Ovality limits.

Dimensional accuracy is important for compatibility with connectors, glands, conduits, and accessories.

Marking and Identification Checks

Cable markings are inspected to ensure:

- Correct product identification.
- Voltage rating.
- Standard references.
- Manufacturer identification.
- Production date or batch code.

Proper marking is essential for traceability and regulatory compliance.

Special and Customer-Specific Tests

Depending on application, additional tests may include:

- Fire resistance or flame propagation tests.
- Smoke density and toxicity tests.
- Oil and chemical resistance tests.
- Water penetration tests.
- Rodent resistance tests.

These are often required for specialized environments such as tunnels, offshore platforms, nuclear facilities, or transportation systems.

6 References

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