THERMAL HISTORY MANAGEMENT OF TCP MANUFACTURING PROCESS

A Key Factor in Designing Industrial Production of Thermoplastic Composite Pipes

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Abstract

This article presents a comparative analysis of one-stage, two-stage and three-stage industrial manufacturing processes for Thermoplastic Composite Pipes (TCP), examining their advantages, limitations and influence on the formation of the composite pipe structure.

The analysis demonstrates that the development of TCP manufacturing technology is driven not simply by increasing the complexity of production lines, but by the need to independently control the physical processes taking place within the material at different stages of manufacturing.

Based on this analysis, the concept of **Thermal History Management of TCP Manufacturing Process** is introduced. It considers the production complex as an integrated system for controlling the sequence of thermal and thermomechanical processes responsible for forming the composite pipe structure.

The article formulates principles for designing next-generation TCP manufacturing complexes based on a transition from designing individual technological operations to designing controlled material-forming processes.

The article is intended for specialists involved in composite pipe manufacturing, developers of production equipment, engineers designing TCP manufacturing facilities, and companies considering the establishment of their own thermoplastic composite pipe production.

1. Why TCP Is Not Simply a Reinforced Plastic Pipe

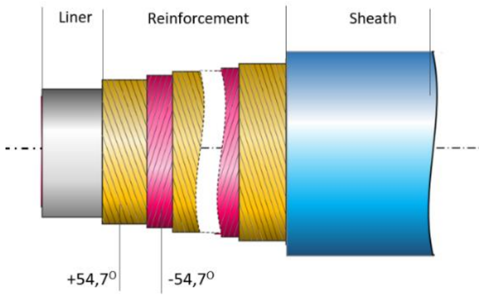
The development of **Thermoplastic Composite Pipes (TCP)** is opening new opportunities for the oil and gas industry, hydrogen energy, chemical processing and infrastructure projects.

High specific strength, corrosion resistance, reduced structural weight and the ability to manufacture flexible pipeline systems make TCP an attractive alternative to traditional metallic pipelines and existing polymer-based solutions.

However, when TCP manufacturing complexes are designed, a fundamental misconception often arises: the technology is treated as a relatively simple operation of wrapping composite tape around a plastic pipe.

This approach is particularly common among companies with experience in manufacturing conventional thermoplastic pipes. Production of utility HDPE or PP-R pipes is primarily based on stable extrusion, dimensional control and cooling management.

TCP is a fundamentally different engineering system.



A TCP is a multilayer, fully bonded composite structure in which:

- the polymer liner provides fluid containment;
- the reinforcement system carries the principal mechanical loads;
- the outer layer protects the structure;
- the individual layers are thermally fused to form a continuous composite wall;
- the interfaces between the layers determine the long-term reliability of the pipe.

Industrial TCP manufacturing is therefore not the production of a plastic pipe with additional reinforcement.

It is a complex process of forming a thermoplastic composite structure in which each layer undergoes its own thermomechanical cycle, while the final properties of the pipe are determined by the combined thermal history, crystallization, shrinkage, relaxation and consolidation processes experienced by the material throughout manufacturing.

This is why **Thermal History Management** becomes one of the key factors determining TCP quality, long-term reliability, compliance with the requirements of oil and gas companies and the economic efficiency of production.

The concept of Thermal History Management naturally leads to a more fundamental principle of TCP manufacturing complex design: the production system must control the sequence of thermal and thermomechanical actions applied to each structural element of the pipe, enabling controlled formation of polymer morphology, interlayer consolidation, crystallization and residual stress state throughout the manufacturing cycle.

A TCP manufacturing complex should therefore be designed around the physical processes occurring in the material, rather than around individual technological operations.

This approach makes it possible to move from simply designing a production line to designing a controlled process for forming a fully bonded composite structure, in which the long-term reliability of TCP is determined not by individual operations but by the reproducibility of the complete thermomechanical history of the material.

2. One-Stage, Two-Stage and Three-Stage TCP Manufacturing Processes

The choice of process architecture is one of the first and most important decisions when designing an industrial TCP manufacturing complex.

Three principal approaches are traditionally considered:

1. **One-stage manufacturing process**
2. **Two-stage manufacturing process**
3. **Three-stage manufacturing process**

Each approach has its own advantages and limitations.

The evolution from one architecture to another should not, however, be viewed simply as a gradual increase in the number of production operations.

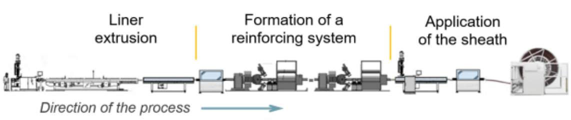
It reflects a deeper evolution in the understanding of the physical processes responsible for forming a reliable fully bonded composite pipe.

2.1. One-Stage Manufacturing Process

Principle

In a one-stage process, the principal manufacturing operations are integrated into a single continuous production line:

Liner extrusion → reinforcement wrapping and consolidation → outer sheath extrusion → cooling



The basic idea is to exploit process continuity in order to reduce the number of intermediate operations and potentially increase production throughput.

Potential Advantages

1. Minimum number of technological operations

The process eliminates:

- intermediate liner winding;
- liner storage;
- subsequent liner unwinding;
- additional liner reheating.

2. Potentially lower capital expenditure

In theory, an integrated line may require:

- less equipment;
- less production floor space;
- fewer auxiliary systems.

3. No separate reheating of the liner

The liner enters the reinforcement section directly from extrusion and therefore does not require a separate reheating operation before reinforcement.

However, this advantage is relative and is accompanied by significant technological limitations.

Main Limitations

1. Reinforcement is applied to a thermally unstable liner

Immediately after extrusion, the thermoplastic liner continues to undergo:

- crystallization;
- volumetric shrinkage;
- relaxation of internal stresses;
- dimensional stabilization.

Applying reinforcement while the liner is still hot and its dimensional stabilization is incomplete means that the substrate on which the reinforcement is applied is still changing.

This may affect:

- liner diameter;
- reinforcement tension;
- actual winding angle;
- residual stresses;

- interfacial conditions between the liner and reinforcement.

Consequently, the reinforcement system is being formed on a substrate whose geometry and thermophysical state have not yet fully stabilized.

2. Limited manufacturing flexibility

Industrial TCP production often requires the ability to change the pipe architecture according to the application.

This may include:

- increasing the number of reinforcement layers;
- changing the type of UD tape;
- using different reinforcement fibres, including glass, carbon or aramid;
- using different thermoplastic matrices such as HDPE, PE-RT, PA, PVDF or PEEK;
- manufacturing pipes for different pressure classes;
- manufacturing pipes for different transported media.

These applications may include:

Group 3 — water and chemical service: produced water, technical water, inhibitor and chemical solutions;

Group 2 — oil and multiphase service: crude oil, produced water, oil and gas mixtures;

Group 1 — hydrocarbon gases: natural gas and associated petroleum gas.

Higher operating pressures frequently require a greater number of reinforcement layers and therefore repeated reinforcement cycles.

In a one-stage production line, repeated reinforcement of an already manufactured liner is technically difficult because the liner extrusion section and its cooling system are positioned on the same axis as the reinforcement zone.

To perform another reinforcement cycle, the extrusion section and cooling system must effectively be moved away from the pipe axis and subsequently returned to the production position.

This significantly reduces the flexibility of the production system.

3. Limited ability to independently control thermal history

In a one-stage process, the thermal processes associated with:

- liner extrusion;
- reinforcement application and consolidation;
- outer sheath application;
- cooling

are strongly coupled.

The thermal regime selected for one part of the line inevitably affects the conditions in the adjacent process zones.

As a result, it is difficult to independently optimize:

- liner dimensional stabilization;
- reinforcement consolidation;
- crystallization;
- residual stress relaxation;
- reinforcement-to-sheath bonding.

The process architecture therefore inherently imposes compromises between different thermal requirements.

This is not simply a question of equipment performance.

It is a consequence of the process architecture itself.

2.2. Two-Stage Manufacturing Process

The two-stage process separates liner manufacturing from reinforcement and outer-sheath production.

The first stage produces a dimensionally stable liner.

The second stage applies and consolidates the reinforcement system and subsequently forms the outer sheath.

This separation eliminates one of the principal limitations of the one-stage process: reinforcement is no longer applied to a freshly extruded liner that is still undergoing significant shrinkage and relaxation.

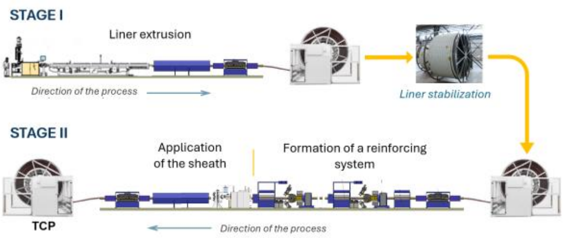
Principle

The simplified process architecture is:

Stage 1: Liner extrusion → cooling → dimensional stabilization → winding/storage

followed by:

Stage 2: Liner unwinding → reinforcement wrapping and consolidation → outer sheath extrusion → final cooling



The separation of liner extrusion from reinforcement provides significantly greater technological flexibility.

Main Advantages

1. Stable liner geometry

The liner can complete the principal processes of:

- cooling;
- crystallization;
- volumetric shrinkage;
- relaxation;
- dimensional stabilization

before entering the reinforcement process.

The reinforcement system is therefore formed on a geometrically stable substrate.

This improves control of:

- winding angle;
- tape tension;
- layer geometry;
- dimensional accuracy;
- residual stresses.

2. Greater flexibility in pipe architecture

Because the liner is produced separately, the reinforcement process can be configured according to the required pipe architecture.

The number of reinforcement layers can be changed without redesigning the extrusion section.

This makes it easier to manufacture different:

- diameters;
- pressure classes;
- reinforcement architectures;
- material combinations;
- product families.

3. Greater flexibility in production planning

The liner and reinforcement processes can be organized as separate production operations.

This creates opportunities for:

- intermediate liner storage;
- batch production;
- different reinforcement cycles;
- production of several pipe architectures from a common liner range.

However, the two-stage architecture introduces a new and more complex problem.

The main technological challenge moves from liner stability to the thermal history of the reinforcement system.

2.2.1. Thermal History of the Reinforcement System

During reinforcement application, each UD tape layer is heated and consolidated against the liner or the preceding reinforcement layer.

As the number of wrapping machines increases, the reinforcement system is exposed to a sequence of repeated thermal cycles.

A typical industrial reinforcement line may contain from **4 to 16 wrapping machines**, with configurations of up to 8 machines being particularly common.

As each successive machine adds another layer, heat accumulates within the composite wall.

The thermal state of the reinforcement system therefore changes continuously along the line.

Without appropriate thermal management, excessive heat accumulation may lead to:

- local softening of previously consolidated layers;
- partial loss of consolidation;
- redistribution of residual stresses;
- changes in crystallization behaviour;
- dimensional instability;
- local degradation of the previously formed composite structure.

The risk may become particularly significant after several wrapping stages.

However, this does not mean that multi-machine reinforcement lines are inherently incapable of producing high-quality TCP.

With **automated control of heating, consolidation and cooling cycles at each wrapping machine and along the reinforcement line as a whole**, uncontrolled re-softening of previously consolidated layers can be substantially reduced or eliminated.

The critical issue therefore becomes not simply the number of wrapping machines, but the ability of the production system to manage the thermal history of the reinforcement system throughout the entire reinforcement process.

2.2.2. The Thermal Conflict at the Outer Sheath

The next challenge appears when the consolidated reinforcement system enters the outer-sheath extrusion stage.

The outer sheath is normally applied as a hot polymer melt.

This creates an additional thermal input into a reinforcement system that may already contain a significant amount of accumulated heat.

The additional heat from the outer sheath can alter the established temperature field within the reinforcement system and, under unfavourable combinations of process parameters, may locally reduce the consolidation state of previously formed layers.

At the same time, the reinforcement system immediately before sheath application is not necessarily in a thermally optimal condition for autohesive bonding.

This is because the temperature after the reinforcement-line IR heating, layer consolidation and partial cooling is selected primarily to achieve optimum consolidation and crystallization of the **last reinforcement layer**.

The temperature of the outer sheath melt, meanwhile, is selected according to the optimum processing window of the sheath polymer in the extrusion process.

These two independently optimized temperature conditions do not necessarily create the optimum thermal combination for forming a strong and durable autohesive interface between the reinforcement system and the outer sheath.

This creates a fundamental limitation of the two-stage process:

The thermal condition required for optimum reinforcement consolidation is not necessarily the thermal condition required for optimum bonding of the outer sheath.

The problem is therefore not simply the temperature of the outer sheath.

It is the absence of an independently controlled thermal transition between the reinforcement process and the sheath-bonding process.

This is precisely where the logic of the three-stage process begins.

The three-stage architecture introduces an additional thermal-management stage that makes it possible to independently establish the thermal conditions required for formation of the reinforcement-to-sheath interface.

In this way, the evolution toward a three-stage process represents a transition from treating the production line as a sequence of equipment units to treating it as an integrated system for controlling the thermomechanical history of the composite structure.

2.3. Three-Stage Manufacturing Process

The three-stage process is not simply a more complicated version of the two-stage process.

It represents a different technological philosophy.

The three-stage process emerged because it became increasingly difficult to optimize several physically independent material-forming processes within a single thermal cycle.

As TCP technology developed, it became clear that:

- liner stabilization;
- reinforcement consolidation;
- reinforcement stabilization;
- formation of the reinforcement-to-sheath interface;
- final stabilization of the composite structure

require different temperature regimes, heating rates, cooling conditions and degrees of thermal exposure.

The three-stage architecture provides the technological separation necessary to independently control these processes.

2.3.1. Why the Three-Stage Process Became a Natural Stage in TCP Technology Development

At the early stages of TCP technology development, the principal criteria for improving production lines were:

- increasing production speed;
- reducing the number of technological operations;
- reducing capital expenditure.

As operating pressures and pipe diameters increased and the range of transported media expanded, however, it became clear that further development could no longer be determined simply by the speed of UD tape wrapping.

The main engineering challenge became the **reproducible formation of the composite pipe structure**.

This means that each major process stage must solve its own physical problem:

- manufacture of a dimensionally stable liner;
- formation of a fully consolidated reinforcement system;
- formation of a durable autohesive bond between the reinforcement system and the outer sheath.

Attempting to solve all of these problems within a single thermal cycle inevitably creates compromises between different process requirements.

Further development of TCP manufacturing complexes therefore requires not the maximum integration of operations, but the creation of conditions in which these processes can be optimized independently.

This logic forms the basis of the three-stage TCP manufacturing architecture.

2.3.2. Principle of the Three-Stage Process

The three-stage architecture can be represented as:

Stage 1 — Stable liner production

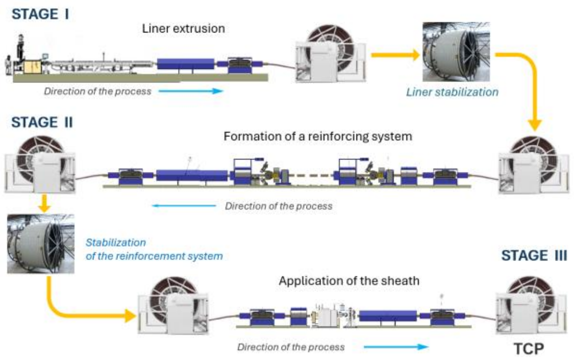
Liner extrusion → controlled cooling → crystallization and shrinkage → dimensional stabilization

Stage 2 — Reinforcement formation

Liner reheating → UD tape wrapping → IR heating → consolidation → controlled cooling

Stage 3 — Outer-sheath formation

Controlled surface preheating → outer sheath extrusion → autohesive bonding → final cooling and stabilization



The key feature is that the thermal history of each major structural component is controlled independently.

2.3.3. Reinforcement Consolidation as an In-Situ Process

The three-stage process can essentially be considered an **in-situ consolidation process** in which the individual reinforcement layers are fused together during their application, forming a strong, rigid and continuous composite wall.

The process begins with controlled IR preheating of the finished liner.

At this point, the liner has already completed the principal stages of shrinkage and dimensional stabilization.

The liner is therefore brought to the required temperature before entering the wrapping machine and subsequent full-fusion IR heating, consolidation and partial cooling zones.

The contact area between the UD tape and the liner surface — or between the tape and the previously applied layer — can be heated above the melting point using the full-fusion IR heating system.

The process can be further improved by applying additional controlled heating directly to the incoming UD tape.

Preheating the UD tape facilitates the initial fusion stage and helps reduce the thermal load required from the main heating system.

It can also improve process stability by reducing the risk of defects associated with the incoming tape, including fibre deformation, insufficient tape tension and other disturbances during tape application.

The consolidation roller — which may also be implemented as a consolidation belt — acts as the mechanical consolidation device.

The consolidation rate is ultimately limited by the time required to achieve:

- sufficient autohesion;
- intimate contact between surfaces;
- molecular interdiffusion;
- polymer-chain entanglement.

From a process-engineering perspective, three parameters fundamentally define the consolidation window:

- **consolidation pressure;**
- **heating intensity;**
- **consolidation speed.**

The consolidation process can further be considered as a sequence of:

1. localized melting;
2. non-isothermal consolidation;
3. controlled cooling and crystallization.

Crystallization is another important stage because the characteristics and rate of crystallization influence the final mechanical properties of the thermoplastic matrix, including the balance between stiffness and flexibility.

2.3.4. Independent Thermal Control of the Outer-Sheath Interface

One of the principal advantages of the three-stage architecture is the ability to establish a dedicated thermal regime immediately before outer-sheath application.

At the beginning of the outer-sheath line, a controlled IR preheating system can be installed.

Its function is fundamentally different from the heating systems used during reinforcement consolidation.

The objective is not to reheat the entire composite wall.

The objective is to establish an appropriate temperature at the **surface of the reinforcement system** immediately before the application of the outer-sheath melt.

This creates an independent thermal window for formation of the reinforcement-to-sheath interface.

The outer-sheath extrusion process can therefore be optimized for the processing requirements of the sheath polymer, while the surface of the reinforcement system is independently brought to the temperature required for reliable autohesive bonding.

This substantially reduces the need to compromise between:

- reinforcement consolidation;
- reinforcement crystallization;
- reinforcement cooling;
- sheath polymer processing;
- reinforcement-to-sheath bonding.

The three-stage process therefore provides a degree of thermal independence that cannot be achieved as effectively in a conventional two-stage architecture.

3. From Process Operations to Physical Processes

The evolution from one-stage to two-stage and then three-stage TCP manufacturing can be viewed as a change in the fundamental object of production-line design.

The traditional approach can be represented as:

Extruder → Wrapping Machine → Sheath Extruder

The engineering approach underlying the three-stage architecture is different:

Liner Stabilization → Reinforcement Consolidation → Reinforcement Stabilization → Interface Formation → Final Structural Stabilization

The difference is fundamental.

In the first model, the production line is designed as a sequence of technological operations.

In the second, it is designed around the physical processes taking place in the material.

This transition changes the way equipment is selected and integrated.

The question is no longer simply:

How fast can the wrapping machine operate?

The more important question becomes:

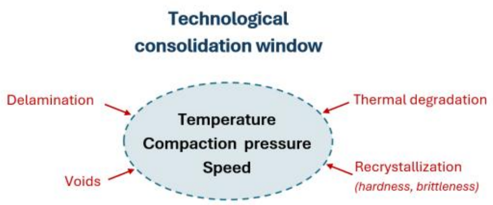
What consolidation conditions can be maintained reproducibly at the required production speed?

3.1. Process Speed and Consolidation Speed

The linear speed of the pipe through the reinforcement line is an important production parameter, but it does not by itself define the true productivity of the process.

The fundamental physical process is the **consolidation of the UD tape in the contact zone with the liner or the previously applied layer**.

The linear production speed is therefore, in effect, a result of the consolidation process and its available technological window.



If the material requires a certain combination of:

- heating intensity;
- contact temperature;
- pressure;
- intimate contact;
- residence time;
- cooling rate;

then the achievable line speed is determined by the ability of the equipment and control system to maintain these conditions.

For this reason, quoted line speeds should not be considered independently of the reinforcement material, matrix polymer, tape architecture, number of layers, winding angle and required consolidation quality.

In practical terms, the production speed of the line is a consequence of the **available consolidation window**.

3.2. Automated Process Control and Production Speed

This is where automated process control becomes a critical element of TCP manufacturing technology.

A high-performance reinforcement line should not simply operate at a fixed speed.

It should continuously control the principal variables determining the thermal and mechanical state of the composite structure.

These may include:

- surface temperature;
- heating power;
- tape temperature;
- consolidation pressure;
- tape tension;
- contact conditions;
- cooling intensity;
- interlayer temperature;
- process speed.

Automated control makes it possible to maintain the process within the optimum technological window rather than operating with unnecessarily conservative settings.

As a result, automation can contribute not only to quality and reproducibility, but also to **increased production speed**.

In other words, higher productivity is not necessarily achieved by simply increasing the nominal speed of the wrapping machine.

It can be achieved by **optimizing the thermal and thermomechanical process window and maintaining it automatically during production**.

This is an important distinction when comparing different TCP production lines.

4. Manufacturing Complex Productivity: More Than Linear Speed

Another common misunderstanding concerns the meaning of the overall productivity of a TCP manufacturing complex.

Potential equipment manufacturers are often asked:

How many metres of pipe can the plant produce per year?

Equipment suppliers may quote values such as:

- 300,000–400,000 m/year;
- 400,000–1,400,000 m/year.

However, these figures have little meaning without specifying the **production programme** on which they are based.

The actual productivity of a TCP manufacturing complex depends on the architecture of the pipe being produced.

Two principal factors are particularly important:

1. the number of reinforcement layers required for a given pipe diameter, pressure rating and safety factor;
2. the number of wrapping machines installed in the reinforcement line.

For example, producing a DN50 pipe designed for an operating pressure of 8 MPa may require a relatively small number of reinforcement layers, depending on the mechanical properties and architecture of the UD tape.

A DN200 pipe designed for a significantly higher pressure may require several times more reinforcement.

The same line speed therefore produces fundamentally different annual output depending on the pipe architecture.

4.1. Number of Wrapping Machines

The number of wrapping machines directly affects the number of reinforcement cycles required to manufacture a pipe.

For example, if a particular TCP architecture requires **24 reinforcement layers**:

Wrapping Machines	Reinforcement Cycles
4	6
8	3
12	2
16	1.5*

** The actual process architecture and production capacity depend on the process speed, the required number of reinforcement layers, the number of wrapping machines, the number of reinforcement cycles, and the selected winding configuration.*

Thus, the same nominal line speed does not necessarily mean the same plant productivity.

A line equipped with eight wrapping machines can manufacture a given reinforcement architecture in substantially fewer cycles than a line equipped with four machines.

4.2. Productivity Must Be Defined for a Production Programme

The productivity of a TCP manufacturing complex should therefore be evaluated against a realistic forecast production programme rather than a single nominal annual figure.

Such a programme should normally include several representative pipe types, for example:

Product group	Nominal diameter	Operating pressure	Share of annual production
Product A	DN50	16 MPa	30%
Product B	DN100	21 MPa	30%
Product C	DN150	12 MPa	20%
Product D	DN200	8 MPa	20%

The actual values should, of course, be determined by the target market and the investment programme of the specific project.

Only after defining such a programme can the required number of wrapping machines, process speed, equipment configuration and realistic annual production volume be determined.

This explains why two equipment suppliers can quote very different annual production capacities while both figures may technically be correct.

One production complex may be optimized for relatively low-pressure pipes requiring fewer reinforcement layers, while another may be designed for higher-pressure TCP requiring a substantially greater reinforcement volume.

Therefore:

> **The productivity of a TCP manufacturing complex is not a fixed characteristic of the equipment. It is a characteristic of the equipment–process–product combination.**

5. Evolution of TCP Manufacturing Architecture

The development of TCP manufacturing technology can therefore be summarized as a transition from increasingly integrated operations toward increasingly independent control of the physical processes responsible for forming the composite structure.

The three-stage process should therefore not be interpreted simply as an additional production stage.

It represents a transition toward a fundamentally different method of designing TCP manufacturing systems.

Manufacturing architecture	Primary objective	Main limitation	Engineering focus
One-stage	Maximum process integration	Unstable liner + limited thermal independence	Process continuity
Two-stage	Stable liner + greater manufacturing flexibility	Thermal history of reinforcement and sheath interface	Reinforcement thermal management
Three-stage	Independent optimization of major physical processes	Greater system complexity	Integrated thermal history management

6. Thermal History Management of TCP Manufacturing Process

The three-stage architecture makes it possible to consider the TCP manufacturing complex as an integrated system for managing the thermal and thermomechanical history of the composite structure.

The object of control is no longer simply the temperature of individual pieces of equipment.

It is the **thermal history of each structural element of the pipe throughout the manufacturing cycle**.

This includes:

- the thermal history of the liner during extrusion, cooling and stabilization;
- the thermal history of each reinforcement layer during heating and consolidation;
- heat accumulation within the reinforcement system;
- cooling and crystallization of the composite wall;
- the thermal state of the reinforcement surface before sheath application;
- formation of the reinforcement-to-sheath interface;
- final cooling and stabilization of the complete pipe.

This concept provides a framework for integrating:

- process design;
- equipment design;
- thermal management;
- mechanical consolidation;
- automated process control;
- product architecture.

The production complex is therefore designed around the sequence of physical processes occurring in the material rather than around a fixed sequence of equipment operations.

7. From Thermal History Management to a More Fundamental Design

Principle

Thermal History Management represents an important step beyond conventional process control.

The deeper principle is:

> **A TCP manufacturing complex should be designed around the physical processes occurring in the material, rather than around technological operations.**

The traditional approach can be expressed as:

Extruder → Wrapping Machine → Sheath Extruder

The process-oriented approach is:

Liner Stabilization → Reinforcement Consolidation → Reinforcement Stabilization → Interface Formation → Final Structural Stabilization

This represents a transition from designing equipment sequences to designing controlled material-forming processes.

The equipment becomes a means of creating and maintaining the required physical conditions.

Heating systems are designed according to the thermal requirements of the material.

Consolidation systems are designed according to the requirements of autohesion and intimate contact.

Cooling systems are designed according to crystallization and stabilization requirements.

Automated control systems are designed to maintain these conditions within the optimum process window.

This approach also provides a basis for increasing production speed without compromising product quality.

Instead of defining speed as an independent equipment characteristic, the process is optimized around the maximum stable consolidation rate and the thermal window required to maintain it.

8. Conclusion

The analysis of one-stage, two-stage and three-stage TCP manufacturing processes demonstrates that the development of TCP technology is not simply a matter of progressively increasing the complexity of production lines.

It reflects a transition toward a deeper understanding of the physical processes that determine the formation of the composite pipe structure.

As requirements for operating pressure, durability, reliability and application range increase, traditional criteria for evaluating production complexes — such as nominal line speed, number of technological operations or equipment capacity — become insufficient as standalone indicators.

The decisive factor is the ability of the production complex to reproducibly form a fully bonded composite structure with controlled properties throughout the entire manufacturing cycle.

The three-stage architecture provides the technological basis for independently managing the principal physical processes involved in TCP formation:

- liner stabilization;
- reinforcement consolidation;
- reinforcement thermal stabilization;
- reinforcement-to-sheath interface formation;
- final stabilization of the composite structure.

This creates the foundation for **Thermal History Management of TCP Manufacturing Process** — an approach in which the production complex is designed as an integrated system for controlling the sequence of thermal and thermomechanical processes occurring in the material.

The concept is not limited to thermal management alone. It establishes a broader engineering principle in which the production complex is designed around the physical processes responsible for forming the final composite structure.

Principles for Designing Next-Generation TCP Manufacturing Complexes

1. **Design the plant around the product.** The architecture of the pipe and its required operating characteristics determine the architecture of the manufacturing complex.
2. **Stabilize the liner before forming the reinforcement system.**
3. **Treat reinforcement consolidation as a controlled thermomechanical process, not simply as tape wrapping.**
4. **Manage the thermal history of the reinforcement system throughout the entire wrapping process.**
5. **Independently control the thermal conditions required for reinforcement consolidation and reinforcement-to-sheath bonding.**
6. **Design the production complex around physical processes occurring in the material rather than around individual equipment operations.**
7. **Use automated process control to maintain the optimum technological window and increase production speed without compromising consolidation quality.**
8. **Define plant productivity through a representative production programme rather than a nominal annual metre figure.**
9. **Design the production complex for product flexibility and future expansion of the product range.**
10. **Treat the complete thermomechanical history of the material as a fundamental parameter of TCP manufacturing quality and long-term reliability.**

The Next Stage of TCP Manufacturing Development

The development of TCP technology is already moving beyond the traditional concept of a production line as a sequence of extrusion and wrapping operations.

Modern TCP manufacturing complexes increasingly represent integrated systems in which equipment, process parameters, automation and product architecture are designed as parts of a single engineering system.

The next stage of development is therefore associated not simply with higher equipment speeds or greater automation, but with increasingly precise control of the physical processes that form the composite structure.

> **The further development of TCP technology can thus be viewed as a transition from designing technological lines to designing controlled material-forming processes throughout the entire production cycle — which constitutes the essence of Thermal History Management of TCP Manufacturing Process.**

About the Concept Developers

This article is the result of a joint effort combining expertise in TCP manufacturing technology, production-complex engineering and analysis of the physical processes involved in forming thermoplastic composite structures.

The **Thermal History Management of TCP Manufacturing Process** concept reflects the authors' engineering approach to the further development of industrial manufacturing technologies for fully bonded thermoplastic composite pipes.

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