SURF CON INSPECT

WHITE PAPER

From 2D to 3D: why depth matters in pickling-line inspection

SurfConInspect White Paper
Series 1/10

About Us

WHO WE ARE

SurfConInspect (SCI) is a European project funded by the Research Fund for Coal and Steel (RFCS). Our consortium brings together leading steel producers, research institutes, technology developers and innovation experts.

The partners combine industrial expertise, academic knowledge and advanced digital solutions to transform the way steel quality is controlled.

OUR MISSION

The steel industry faces increasing pressure to become more sustainable, efficient and competitive—key goals of the European Green Deal.
Our mission is to enable zero-defect manufacturing in flat steel production by:

- Detecting surface defects earlier and more accurately.
- Reducing waste and improving resource efficiency.
- Supporting operators with advanced visualization tools.
- Providing real-time control actions directly in production lines.

MAIN ACTIVITIES

- Industrial trials in tin-plate and automotive steel production.
- Development of AI-based inspection methods.
- Application of AR for real-time operator support.
- Creation of open datasets to enhance research and industrial collaboration.
- Dissemination of results to industry, research and society through events, publications and digital platforms.

EXPECTED RESULTS

- Zero-defect production through optimized inspection and control.
- Reduced waste and energy consumption, contributing to the
  European Green Deal.
- Higher competitiveness for European steel producers.
- Transferable technologies with potential applications beyond the steel sector.
- Improved working conditions, with operators supported by innovative visualization and decision-making tools.

Executive Summary

Surface inspection plays a critical role in ensuring the quality of flat steel products, particularly in pickling lines where operating conditions are inherently demanding and defects can directly propagate into downstream processes such as cold rolling. In these environments, production speeds, requiring inspection systems that are not only accurate but also robust under the presence of water, acids, and varying surface conditions. Even a single undetected topographic defect at this stage can lead to coil breaks in subsequent processing, generating significant costs through scrap, downtime, and process instability.

For many years, industrial inspection systems have relied primarily on two-dimensional (2D) imaging to detect and classify surface defects. These systems perform well when defects are distinguishable through contrast, texture, or color variations. However, they fundamentally interpret the surface as a flat image. This becomes a critical limitation in pickling-line environments, where many of the most relevant defects—such as dents, abrasions, or shells—are defined not only by how they appear, but by their three-dimensional structure. Industrial observations show that defects which are misclassified or even invisible in 2D inspection can be reliably identified when depth information is available, particularly under wet conditions where optical contrast is reduced.

This white paper provides an accessible introduction to the limitations of 2D inspection in pickling-line environments and explains why adding depth information through 3D inspection represents a step change in surface quality control. By capturing the geometry of the surface through techniques such as laser triangulation, modern inspection systems are able to measure defect depth, elevation, and spatial distribution—parameters that have been shown to be directly linked to defect criticality. In industrial trials, up to 96% of defects associated with coil breaks were identifiable through their topographic characteristics, with a strong concentration near strip edges and clear correlations between defect geometry and failure risk.

This document outlines the basic principles of 3D measurement, illustrates representative defect scenarios, and highlights the practical benefits of depth-aware inspection for operators and quality managers. The objective is to show how moving from a purely visual interpretation of the surface to a geometric understanding enables more reliable classification, more informed operational decisions, and ultimately a more stable and efficient production process.

1. Surface quality challenges in pickling lines
2. Traditional 2D inspection: what it can (and cannot) see
3. Why depth information matters
4. From 2D to 3D: a conceptual shift
5. Topographic defects: a conceptual overview
6. Key advantages of 3D inspection in pickling lines
7. The SurfConInspect perspective
8. Impact on operators and process control
9. Limitations and complementary approaches
10. Conclusions

Surface quality challenges in pickling lines

Pickling lines are designed to remove oxide scale from hot-rolled steel strips through chemical treatment, preparing the material for subsequent processing steps such as cold rolling, coating, or forming. While highly effective from a metallurgical perspective, the process takes place under particularly aggressive conditions: the strip is exposed to acids, water, elevated temperatures, and continuous mechanical stress, often while moving at industrial speeds. These conditions not only challenge the durability of inspection systems, but also directly influence the visibility and detectability of surface defects.

At this stage of the process, a wide range of defects may either originate or become clearly observable once the scale has been removed. Typical examples include abrasions caused by mechanical contact, dents generated by entrapped particles or handling issues, and shell defects linked to upstream material conditions. What makes these defects particularly critical is not only their presence, but their geometry. Industrial evidence shows that parameters such as depth, elevation, size, and position—especially proximity to strip edges—are decisive in determining whether a defect is merely cosmetic or capable of triggering failures in downstream processes. In practice, a significant proportion of coil breaks observed in tandem mills can be traced back to topographic defects already present at the pickling stage, with around 90% of these defects located close to the strip edge and the vast majority exhibiting measurable three-dimensional characteristics.

Reliable surface inspection in pickling lines is therefore not simply a quality control function, but a critical element of process stability. The inspection system must operate continuously under harsh environmental conditions, maintain accuracy at high line speeds, and deliver information that can be acted upon immediately—whether to trigger inline cutting, adjust process parameters, or allow the strip to proceed without interruption. Traditionally, this task has been addressed using 2D imaging systems, which provide valuable visual information but are inherently limited in their ability to fully characterise the most critical defect types encountered in this environment.

Traditional 2D inspection: what it can (and cannot) see

2D inspection systems analyze images captured by industrial cameras, typically supported by controlled illumination designed to enhance contrast and highlight surface features. In pickling-line environments, these systems operate with high-resolution line-scan cameras—often exceeding 4000 pixels with sampling rates in the order of tens of kHz—to ensure full coverage of the strip at production speed. This configuration makes them well suited to detecting variations in brightness, contrast, texture, and color, allowing reliable identification of stains, residual scale, scratches, and other visually distinct surface anomalies.

However, 2D systems fundamentally interpret the steel surface as a flat projection. All information is reduced to intensity variations in an image, meaning that the system captures how a defect appears, but not how it is shaped in three dimensions. This distinction becomes particularly relevant in pickling lines, where surface conditions—such as water films, reflections, and chemical residues—can significantly alter the visual appearance of defects without changing their physical geometry.

This limitation becomes critical when dealing with topographic defects. Industrial observations show that defects which are clearly critical from a mechanical perspective can appear ambiguous or even misleading in 2D images. For example, defects influenced by wet conditions may be incorrectly classified as “underpickled” or “wet” areas, while others may not be detected at all in the 2D channel despite having a pronounced geometric impact. In contrast, when the same areas are observed through a topographic representation, their depth profile becomes immediately evident, revealing their true severity.

Two defects may therefore appear very similar in a 2D image—sharing shape, size, and contrast—while having completely different depths. One may be a shallow surface irregularity with negligible impact, while the other may be a deep indentation capable of triggering defects in subsequent rolling processes. From the perspective of a 2D system, these cases are difficult to distinguish in a consistent and reliable way.

As a consequence, 2D inspection often struggles with ambiguous classification, where visually similar defects are assigned to the same category despite having different implications. It may also lead to systematic overestimation or underestimation of defect severity, depending on lighting conditions and surface state. This uncertainty translates into higher rates of false positives and false negatives, which directly affect production efficiency. In practice, this means either rejecting material that could be safely processed, or allowing critical defects to pass through undetected—both scenarios generating avoidable costs and operational risk in downstream processes.

Why depth information matters

Depth is a key parameter for understanding the true nature of a surface defect. While visual appearance provides useful clues, it is the geometric profile—depth, elevation, and spatial extension—that determines how a defect will behave under mechanical stress, during thickness reduction, or in subsequent coating and forming operations. In industrial practice, these parameters are directly linked to defect criticality: defects that appear similar in 2D images can lead to completely different outcomes once the material enters downstream processes.

This is particularly evident in pickling-line environments, where topographic defects are one of the main root causes of instability in later stages. Analyses performed on real production data show that the vast majority of defects associated with coil breaks exhibit measurable three-dimensional characteristics, with depth and height variations being consistently present. In fact, around 96% of defects that led to coil break events were clearly identifiable through their topographic signature, confirming that depth is not a secondary attribute but a primary discriminator of risk.

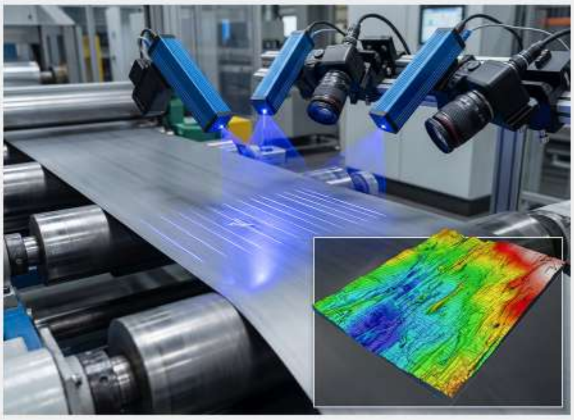
A practical example helps clarify this point. A shallow abrasion, even if visually pronounced, may only affect surface roughness and remain within acceptable limits for further processing. By contrast, a dent with a depth in the order of fractions of a millimetre—such as typical indentations around 0.8 mm observed in industrial conditions—can act as a stress concentrator, leading to crack initiation or even perforation during rolling. Although these two defects may appear comparable in a 2D image, their geometric profiles—and therefore their impact—are fundamentally different.

Depth information allows inspection systems to move from a purely visual assessment to a geometric one. This shift enables a more objective and physically grounded interpretation of surface conditions, where defect evaluation is no longer based solely on appearance but on measurable parameters that correlate with process outcomes. As a result, defect discrimination becomes more reliable, and classification can better reflect the actual severity of the defect rather than its visual representation.

In practical terms, knowing the depth of a defect provides direct support to operational decision-making. It allows operators and automated systems to determine whether a defect is critical or tolerable, whether it requires immediate intervention such as inline cutting, or whether the strip can safely continue at full production speed. It also opens the possibility of adapting process parameters dynamically—balancing productivity and quality—based on quantitative information rather than conservative assumptions.

From 2D to 3D: a conceptual shift

3D inspection introduces an additional dimension to surface evaluation: the ability to measure height variations across the steel strip in real time. Instead of treating the surface as a flat image defined by intensity and contrast, the inspection system reconstructs its actual topography, capturing how the material is physically shaped at a microscopic level. This transition is particularly relevant in pickling lines, where the most critical defects are not defined by their visual signature alone, but by their geometric characteristics.



In industrial implementations, one of the most widely adopted approaches to 3D measurement is laser triangulation. In this configuration, line lasers—typically in the blue wavelength range—project a defined light profile onto the moving strip, while multiple cameras observe the deformation of this profile from different angles. In the SurfConInspect context, the system is configured with three cameras and corresponding laser sources per side, enabling full-width inspection of both the top and bottom surfaces at production speed. With sensor resolutions in the order of 2500 × 800 pixels and synchronized acquisition, the system generates a dense height matrix that describes the surface geometry continuously along the strip.

The key point is not the specific hardware configuration, but the nature of the information produced. Unlike 2D systems, which provide intensity-based images, 3D inspection delivers quantitative measurements of depth, elevation, and spatial distribution of defects. This allows the system to directly access the physical parameters that determine defect severity, rather than inferring them indirectly from visual cues.

This represents a fundamental shift in how surface defects are detected and assessed. The inspection process moves from an image interpretation problem to a measurement problem. Instead of relying on pattern recognition alone, the system can evaluate whether a defect exceeds defined geometric thresholds or whether its profile matches known failure-inducing patterns observed in production.

Rather than asking "What does this defect look like?", the system can now ask "How deep is this defect, and how does it compare to acceptable process limits?". This shift enables a more consistent and physically grounded evaluation of surface quality, forming the basis for more reliable classification and more effective integration with process control systems.

Topographic defects: a conceptual overview

Topographic defects are defined by their three-dimensional geometry rather than by visual appearance alone. In pickling lines, these defects are particularly relevant because their impact on downstream processes is governed by measurable physical parameters such as depth, elevation, size, and position along the strip. Industrial analyses confirm that these geometric attributes are the primary factors determining whether a defect will remain benign or evolve into a critical issue during subsequent rolling stages.

Among the most representative examples encountered in production environments are abrasions, dents, and shells. Abrasions typically appear as elongated surface wear marks caused by mechanical contact. When observed through a 3D inspection system, these defects reveal pronounced height variations, even when their visual signature in 2D appears relatively uniform. In certain cases, such defects have been associated with the formation of holes or perforation sequences during downstream processing, highlighting the importance of capturing their geometric profile rather than relying solely on appearance.

Dents represent localized depressions, often caused by particles being pressed into the strip surface during handling or processing. Industrial measurements show that these defects can reach depths in the order of tenths of a millimetre, with lengths ranging from a few centimetres up to 15 cm. Despite their sometimes subtle visual contrast, these geometric features can act as stress concentrators and are frequently linked to failure mechanisms such as crack initiation or material rupture during rolling.

Shell defects, on the other hand, are often associated with upstream material conditions and may not always present a pronounced three-dimensional signature at the pickling stage. However, their geometric evolution becomes critical during thickness reduction processes, where even minor irregularities can propagate into break-outs or surface failures. This makes their early identification and characterization particularly important, even when their initial appearance is not clearly distinguishable.

In 2D images, all these defect types may appear as shadows, lines, or texture variations, often with overlapping visual characteristics. However, their depth profiles can differ significantly, and it is precisely this variation that determines their relevance for quality control. A shallow abrasion may only influence surface roughness within acceptable limits, while a deeper defect of similar visual appearance may exceed process tolerances and require immediate intervention.

3D inspection enables a more precise and physically grounded characterization of such defects by directly measuring their geometry. By capturing the height matrix of the surface, the system provides a consistent basis for distinguishing between defect types, assessing their severity, and supporting decisions that are aligned with the actual behaviour of the material in subsequent production stages.

Key advantages of 3D inspection in pickling lines

Introducing 3D inspection in pickling lines offers a set of practical advantages that directly address the limitations observed in traditional 2D systems and respond to the operational needs of high-speed production environments. The most immediate benefit lies in improved defect discrimination. By incorporating depth as a measurable parameter, the system is able to distinguish between defects that appear similar in 2D images but differ significantly in their geometric profile. Industrial evidence shows that critical defects associated with downstream failures often exhibit measurable height or depth characteristics, making geometry a far more reliable discriminator than visual appearance alone.

This improved discrimination capability translates into a reduction of both false positives and false negatives. In conventional 2D inspection, environmental factors such as water, reflections, or surface contamination can lead to misclassifications—for example, critical defects being interpreted as harmless "wet" areas, or non-critical features being flagged unnecessarily. The introduction of 3D measurement reduces this ambiguity by relying on physical surface data. In practice, defects that were previously undetected or incorrectly classified in 2D can be consistently identified in the 3D channel, contributing to a more reliable detection process.

Another key advantage is the move towards a more objective quality assessment. Instead of basing decisions on visual interpretation, which can vary depending on conditions and parameter settings, 3D systems provide quantitative measurements of depth, elevation, and size. These parameters can be directly linked to acceptance criteria and process thresholds, enabling more consistent and repeatable quality decisions across operators, shifts, and production campaigns. This is particularly important in environments where even small variations in defect geometry can have a significant impact on downstream performance.

3D inspection enables a more effective integration with online decision-making systems. The availability of structured, depth-aware data allows quality processors and supervisory control systems to act in real time, supporting applications such as automated cutting of critical defects or adaptive process control. For instance, knowing not only that a defect exists but also its precise geometry and position—often concentrated near strip edges—enables targeted interventions that minimize scrap while preventing failures such as coil breaks in subsequent rolling stages.

Taken together, these advantages contribute to a more efficient and robust quality control process. By reducing uncertainty, improving detection reliability, and enabling data-driven decisions, 3D inspection supports a transition from reactive quality management to a more predictive and process-integrated approach.

The SurfConInspect perspective

Within the SurfConInspect project, 3D inspection is explored not as an isolated technological upgrade, but as a key enabler for a new generation of surface quality control systems operating under real industrial conditions. The project investigates how depth information can be effectively integrated into online inspection architectures on pickling lines, where production constraints such as high strip speeds, full-width coverage, and harsh environmental conditions impose strict requirements on system performance and robustness.

A central aspect of this work is the validation of 3D inspection in a fully operational environment. In the industrial setup considered, the system is deployed directly on the pickling line and configured to inspect both sides of the strip across its entire width, using laser triangulation with multiple synchronized sensors. This configuration allows continuous acquisition of topographic data at production speed, demonstrating that depth measurement is not limited to controlled laboratory conditions but can be reliably achieved in real manufacturing scenarios.

At the same time, the project explicitly addresses the limitations of relying on a single inspection paradigm. Depth information is treated as a fundamental, but not exclusive, component of a broader inspection ecosystem. For instance, while 3D data provides a robust basis for identifying and characterising topographic defects, complementary 2D channels are still relevant for detecting area-based phenomena such as scale distribution, where aggregation of surface features is more important than individual defect geometry. This combined approach reflects a pragmatic understanding of industrial requirements, where different sensing modalities contribute to a more complete and reliable assessment of surface quality.

Another key focus of SurfConInspect is the translation of raw measurement data into actionable insights. Depth information alone is not sufficient unless it can be interpreted in a way that supports operational decisions. For this reason, the project investigates classification strategies that go beyond simple rule-based approaches, combining geometric features derived from the height matrix with image-based information to improve the reliability of defect categorisation. This is particularly important in reducing misclassifications and ensuring that critical defects are consistently identified and treated accordingly.

Ultimately, the perspective adopted in SurfConInspect is strongly application-oriented. The goal is to provide operators and quality managers with reliable, real-time information that can be directly used within existing workflows—whether for triggering inline interventions, supporting process optimisation, or improving traceability. In this sense, 3D inspection is positioned as a practical tool for enhancing decision-making, rather than as a standalone analytical capability.

Impact on operators and process control

For operators, the introduction of 3D inspection fundamentally changes how surface quality is perceived and managed on the line. Instead of relying solely on visual cues—often influenced by lighting conditions, surface wetness, or subjective interpretation—operators gain access to quantitative indicators that directly reflect defect severity. Height and depth measurements provide an immediate and physically meaningful representation of the defect, allowing operators to distinguish more clearly between tolerable irregularities and defects that require intervention.

This enhanced situational awareness is particularly valuable in high-speed pickling lines, where decisions must be taken in real time and under continuous production flow. In the industrial setup considered, operators are supported not only by visual inspection through mirrors and monitors, but also by direct feedback from the inspection system, including automatic signals when critical defects are detected. The availability of depth information adds a further layer of confidence to this process, enabling more consistent interpretation of defect relevance and reducing dependence on subjective judgement.

From a process control perspective, depth-aware inspection supports faster and more confident decision-making. Operators can react based on measurable thresholds rather than conservative assumptions, deciding whether a defect requires immediate action—such as edge cutting or removal of a section—or whether the strip can continue without interruption. This is particularly important given that different intervention strategies apply depending on defect location, with near-edge defects often treated differently from those in the centre of the strip.

The availability of precise geometric information also enables more targeted interventions. Instead of applying blanket slowdowns or overly cautious rejection criteria, operators and control systems can act selectively, focusing only on defects that exceed defined critical thresholds. This contributes to minimizing unnecessary scrap while still preventing downstream issues such as coil breaks.

In addition, depth-aware inspection improves the traceability of quality-related events. Each detected defect can be associated with measurable parameters and precise positional data along the strip, creating a structured record that supports root cause analysis and continuous process improvement. Over time, this data-driven approach allows production teams to better understand defect patterns, correlate them with process conditions, and refine operational strategies accordingly.

These improvements contribute to more stable process control, better product consistency, and a more efficient use of production resources. By reducing uncertainty and enabling informed decisions at the operator level, 3D inspection supports a transition towards a more proactive and controlled approach to surface quality management.

Limitations and complementary approaches

While 3D inspection offers clear advantages for the detection and evaluation of topographic defects, it does not represent a universal solution for all surface quality challenges encountered in pickling lines. Its strength lies in capturing geometric information—depth, elevation, and spatial distribution—but not all defect types are primarily defined by these attributes. In industrial environments, a significant number of surface anomalies are related to chemical interactions, residual scale, or variations in surface condition, particularly under wet processing stages, where visual and material properties may change without a corresponding geometric signature.

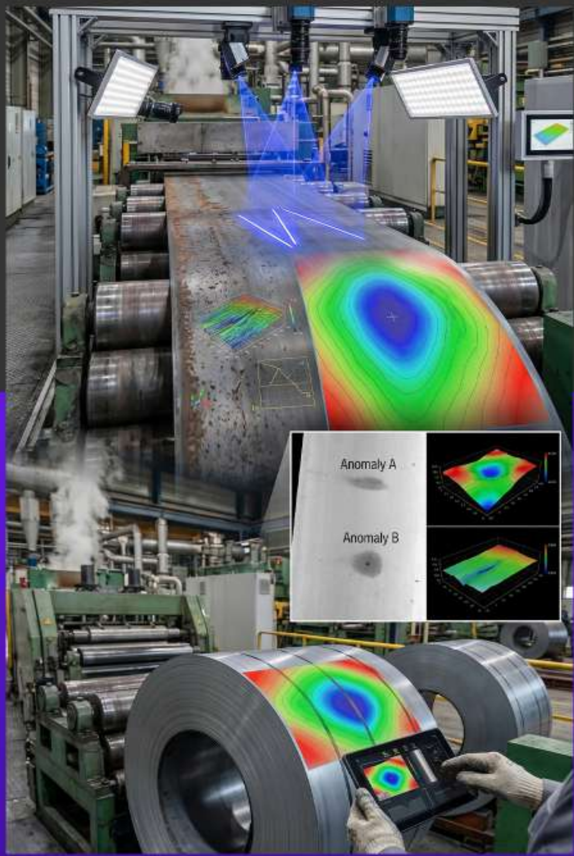
For this reason, certain defect categories—such as stains, underpickling effects, or material heterogeneities—may not be adequately characterised through topographic measurement alone. Even within the SurfConInspect industrial setup, it has been observed that while 3D inspection provides robust detection of defects with measurable depth, complementary 2D channels remain relevant for capturing area-based phenomena, where the aggregation of features across the surface is more informative than individual geometric variations.

This leads to a key conceptual point: 3D inspection should be understood as part of a complementary inspection strategy rather than a replacement for existing technologies. The integration of multiple sensing modalities—combining geometric information with visual, spectral, or other surface-sensitive data—enables a more complete and balanced assessment of surface quality. In this context, 3D inspection provides the physical foundation for evaluating defect severity, while other approaches contribute to identifying defect origin, composition, or surface condition.

Within the broader SurfConInspect framework, this multi-dimensional approach is essential for building inspection systems that are both robust and adaptable to different production scenarios. The exploration of complementary methods, including techniques capable of addressing non-topographic defects, is therefore a natural extension of the work presented in this paper and is further developed in subsequent contributions of the series.

Conclusions

Moving from 2D to 3D inspection represents a significant step forward in surface quality control for pickling lines. By introducing depth as a measurable parameter, inspection systems gain access to the physical characteristics that most directly determine defect criticality. Industrial evidence confirms that the majority of defects leading to downstream failures exhibit clear topographic features, making depth-aware inspection a key enabler for more reliable quality assessment.



For steel producers, this shift translates into more informed and consistent decision-making. The ability to distinguish between critical and non-critical defects based on quantitative geometry reduces both unnecessary rejections and the risk of undetected failures, contributing to lower scrap rates and improved process stability. At the same time, the integration of 3D data into online inspection systems supports more precise and targeted interventions, aligning quality control with the actual behaviour of the material during production.

Within this context, SurfConInspect plays a crucial role in bridging the gap between conceptual advances and industrial application. The project demonstrates that 3D inspection can be reliably deployed on high-speed pickling lines, operating under harsh environmental conditions and providing continuous, full-width coverage of the strip. It also addresses the practical challenges of integrating depth information into existing workflows, including classification strategies, operator interaction, and real-time decision support.
By combining depth-aware inspection with complementary sensing and data processing approaches, SurfConInspect shows how surface quality assessment can evolve beyond purely visual criteria towards a more comprehensive and physically grounded methodology. This white paper represents the starting point of a structured knowledge-sharing effort, aimed at making these advances accessible to industrial stakeholders while laying the foundation for further developments in non-topographic defect detection, data fusion, and operator-oriented quality visualisation.

FURTHER READING

- SurfConInspect Project Website
- Introductory resources on 3D surface inspection
- Related white papers in the SurfConInspect series

The Consortium

SurfConInspect unites a diverse group of partners:

- **Steel producers:** thyssenkrupp Rasselstein (RAS), Salzgitter Flachstahl (SZFG)
- **Research & Academia:** VDEh-Betriebsforschungsinstitut (BFI), Scuola Superiore Sant'Anna (SSSA), CETIC
- **Technology developers:** Clecim France (CLECIM)
- **Communication & dissemination experts:** yourscienceEDU (YSE)

STAY CONNECTED

Follow our updates, publications and events on:
🌐 Project Website: **surfconinspect.eu**
💼 LinkedIn: **SurfConInspect**

Together, we are shaping the future of **sustainable steel production**.