3DLD Methodology as the Foundation of a Digital Standard for Welding Quality Assessment

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Abstract
Modern standards for evaluating the quality of welded joints (ISO 5817, ISO 17637, AWS D1.1, etc.) are based on defect classification and visual criteria, which limits their applicability in the context of industrial digitalization, robotics, and remote control. This paper demonstrates that the lack of a digital standard for weld geometry assessment acts as a systemic barrier to the further development of welding production. The necessity of creating an international digital standard based on a mathematically rigorous reference profile model and digital quality metrics is substantiated. The 3DLD method is proposed as the foundation of the standard. This method was previously implemented by the authors in the form of a mathematical model and digital assessment algorithms for weld surface shape using a dimensionless criterion—the Weld Quality Index (WQI). It is shown that the digital standard is a key element in the transition of the welding industry to digital twins, robotic systems, and objective welder qualification.
Keywords: visual testing, измерительный контроль, digital standard, Laplacian profile, 3DLD technology, Industry 4.0, fracture mechanics, ABAQUS, Weld Quality Index (WQI), robotic welding, WAAM, digital weld passport, digital welder passport.

Introduction and Urgency of the Modern VT Problem
The current stage of welding production development is characterized by the deep integration of Industry 4.0 concepts, robotic manufacturing processes, and end-to-end digital quality control. The introduction of industrial robotic complexes and intelligent machine vision systems has enabled the automation of the visual and tactile inspection stage—visual testing (VT)—of welded joints. The application of laser 2D/3D scanners (e.g., systems such as *WiKi-SCAN* by Servo-Robot or *RF627Smart-Weld* by RIFTEK) has provided precise digitization of the real weld geometry, practically eliminating the subjective human factor at the primary data collection stage.
However, a deep systemic crisis has emerged in the field of regulatory, legal, and methodological support for non-destructive testing (NDT). Possessing an redundant array of high-precision data in the form of point clouds, the software of modern scanners is forced to artificially simplify these data to primitive templates of Euclidean geometry. This is because current baseline standards (ISO 5817[1], AWS D1.1[2], and ISO 17637[3]) were conceptually and mathematically formulated in the

1970s and 1980s based on the capabilities of the human eye and a mechanical gauge (such as UShS welder gauges).
Consequently, a fundamental scientific and technical contradiction arises between the precision capabilities of digital laser optics and the archaic, tabular-linear apparatus of regulatory documentation that operates solely on local defect extrema.

1. Digital Gap in the Welding Regulatory Framework

Despite significant progress in the development of NDT methods, the regulatory framework of welding production remains oriented toward analog quality assessment methods. The ISO and AWS standards were developed in an era when:

- Inspection was performed visually using simple mechanical measuring tools;
- Quality evaluation depended on the subjective opinion of an expert;
- Laser scanners and digital profilometers were absent;
- Robotic systems with feedback loops did not exist;
- Digital twins of welded joints were not applied.

Today, the situation has fundamentally changed: digital technologies make it possible to measure the weld profile with an accuracy of up to 0.01 mm, build digital replicas, compare them with mathematical references, and automatically evaluate quality. However, not a single international standard contains digital criteria for the weld shape, creating a regulatory vacuum.

2. Limitations of Existing ISO and AWS Standards

2.1. ISO 5817: Defect Evaluation, Not Shape Evaluation

ISO 5817 defines quality levels B, C, and D based on imperfections:

- Deviation of bead geometry from regulatory values;
- Undercuts;
- Pores;
- Lack of fusion/penetration;
- Overlaps;
- Unacceptable weld ripple.

However, the standard does not contain a digital metrology for the weld surface shape, does not define a reference weld profile, and does not permit automated assessment. Even surface shape defects are evaluated only by linear dimensions that can be measured with mechanical tools. Each defect is assigned a digital code (e.g., undercut—5011, weld ripple—515). This standard is a pure table of rejection criteria for three quality levels (B, C, and D).

2.2. ISO 17637: Subjectivity of Visual Testing

Visual testing remains the primary and most widespread method, but it:

- Depends heavily on the qualification of the expert;
- Lacks sufficient accuracy, reliability, and reproducibility;
- Is limited by the size of detectable defects;
- Cannot be automated and possesses low productivity;
- Is unsuitable for digital systems.

This standard is a technological process regulation. It does not contain any weld rejection criteria at all. Its purpose is to force different inspectors to evaluate a weld under identical conditions in order to minimize the human factor.

2.3. AWS D1.1: Combining Methodology and Strict Evaluation Criteria for Each Defect

AWS D1.1 contains strict requirements for defects, but it:

- Does not allow for a numerical evaluation of the shape;

- Does not define a digital profile;
- Cannot be integrated into robotic systems.

For clarity, let us compare the philosophy, structure, and methods for eliminating subjectivity during weld quality evaluation in these documents:

Table 1. Comparative Analysis of Standards

Comparison Criterion	ISO 5817	ISO 17637	AWS D1.1 (Visual Inspection Section)
Concept Definition	Table of defect tolerances (WHAT constitutes a defect)	Inspection technique (HOW should it be viewed?)	Comprehensive structural code (Both HOW to inspect and WHAT constitutes a defect)
Defect Shape Accounting	Mathematical (via ISO 6520-1 codes and defect aspect ratios)	Not accounted for (the standard focuses on the inspection process itself)	Geometric + Graphical (via acceptable weld profile diagrams)
Digital Criteria	Flexible (formulaic). Linked to metal thickness (t). Three quality levels: B, C, D.	Process-based. Digits define lux levels, distance millimeters, and inclination angles.	Rigid (absolute). Fixed numbers in mm/inches. Depend on load type (static/dynamic).
Subjectivity Mitigation	Attempt to digitize defects via formulas, removing "by-eye" estimation.	Alignment of physical inspection conditions for all inspectors.	Use of visual graphical template schemes ("look at the picture and compare").
Application Scope	Universal general industrial standard (steel, nickel, titanium).	Universal methodology for any welds prior to other NDT.	Structural and bridge steel metal structures (US/international projects).

It can be stated that in European and international practice (ISO), functions are separated: ISO 17637 represents the "eyes" of the inspector (methodology), while ISO 5817 is his "rulebook" (criteria). The American AWS D1.1 standard is an "all-in-one" code that replaces complex formulas with rigid fixed numbers and clear graphical profiles.

2.4. Automated Visual Testing Systems

Automated visual testing (auto-VT) is the primary modern approach to completely eliminating human subjectivity. Today, automated VT systems are built on machine vision, laser scanning, neural networks, and AI technologies.

How Auto-VT Resolves the Standards Problem (ISO 5817 and AWS D1.1)

Standard libraries are already embedded into the software of modern systems (e.g., Russian *SmartWeld*, *Tsifra*, or foreign *Meta Vision*, *Servo-Robot*). The system operates according to the following algorithm:

- **Step 1: Shape Recognition (per ISO 6520 / AWS).** The laser digitizes the exact 3D weld profile. Artificial intelligence instantly identifies the geometry. It detects a groove and, based on the aspect ratio, immediately codes it as an "undercut", and a rounded depression as a "pore". Human subjectivity is eliminated: the system evaluates geometry based on predefined mathematical models.
- **Step 2: High-Precision Measurement.** The system measures the defect. The absolute error of laser scanners reaches 0.05–0.1 mm. No inspector with a mechanical gauge can conduct measurements with such accuracy.
- **Step 3: Automated Quality Level Filtering.** Before starting, the operator selects the target criteria in the software interface: "Control per ISO 5817, Quality Level B" or "Control per AWS D1.1". The program automatically

correlates the measured undercut dimensions with the selected standard and outputs a verdict: "Accept" or "Reject".

Thus, the creation of digital visual inspection systems allows for the automated recognition of defects specified in regulatory documents, increases the reliability, reproducibility, and speed of inspection, and eliminates subjective quality assessment. However, high-precision laser scanners are currently utilized merely for the high-tech replacement of manual inspector labor with a mechanical gauge.

3. Methodology Gap Analysis in ISO and AWS Standards: Obsolescence of the Regulatory Base for the Digital Era

3.1. Genesis of ISO 5817 and AWS D1.1 Standards and Their Limitations

Current international standards governing weld quality criteria—such as the universal industrial standard ISO 5817 (and its national equivalent GOST R ISO 5817) [4] and the American structural code AWS D1.1—were created in an era dominated by subjective manual visual testing. The fundamental normalization principles embedded in these documents more than forty years ago were based on the technical capabilities of the human eye, low-magnification optical loupes, and simple mechanical gauges.

This technological limitation formed a discrete-linear evaluation paradigm, which contains three critical methodological gaps when applied to the modern digital era:

1. **Pointwise Discretization (The Extremum Trap):** ISO 5817 and AWS D1.1 require the inspector to find the *maximum linear dimension* of a defect. For instance, the undercut depth (code 5011 per ISO 6520-1) [5] or the weld reinforcement height (code 502) are measured exclusively at their peak extremum point. The standards completely ignore the length, geometric gradient, and total volume of the defect.
2. **Empirical Reductionism of Formulas:** Tolerances in ISO 5817 are calculated using simplified linear dependencies on the base metal thickness (t) (e.g., $0.05 \cdot t$ or $0.1 \cdot t$ for undercuts in quality levels B and C). In AWS D1.1, the approach is even more simplified—rigid fixed digital thresholds are applied (e.g., limiting the undercut depth to $1/32$ inch or 0.8 mm for dynamically loaded structures). These figures are the result of averaged empirical tests from the last century and lack a strict analytical relationship with the real stress-strain state (SSS) of a specific topographic profile.
3. **Disregard for the Spatial Factor:** Regulations impose identical geometric requirements on the weld regardless of the spatial welding position. The standard fails to consider whether the weld was executed in the flat position (PA) or formed under the challenging conditions of the overhead (PE) or vertical (PF) positions, where gravitational forces inevitably alter the profile.

3.2. Conflict of ISO/AWS Standards with Modern Laser 3D Scanner Capabilities

Modern laser scanners and machine vision systems are capable of measuring the weld surface shape with an extremely high data density—thousands of points per micron. The output is a continuous digital surface reflecting the real geometry and physical formation of the weld.

However, attempting to apply these data within the framework of ISO 5817 or AWS D1.1 causes a methodological conflict. The scanner software is forced to "downgrade" the digital profile in 3D weld sections to a level compatible with the logic of the standard:

- Smooth out the real weld profile curve into a simple broken line;

- Search for a single local deviation peak;
- Compare this peak with a tabular norm;
- Output a "reject" verdict even in the absence of any real operational danger.

As a result, high-precision laser scanners are used not for analyzing the weld shape, but for simulating manual measurements according to obsolete regulations.

3.3. Geometric Tolerances and Stress Concentration: The Key Discrepancy

The main issue with ISO/AWS standards is that they evaluate defects by linear dimensions—depth and width. However, these parameters are weakly correlated with the actual operational danger.

From the perspective of fracture mechanics during computer 2D modeling using the SIMULIA/Abaqus package, the critical factor is not just the undercut depth itself, but also:

- The shape of the undercut;
- The profile radius of curvature in the weld transition zone;
- The metal blend/toe angle;
- Local stress concentration.

A deep but smooth transition with a large radius of curvature practically creates no dangerous stress concentrators (Fig. 1). A shallow but sharp lack of fusion at the weld root causes a sharp stress peak and can become a source of failure (Fig. 2).

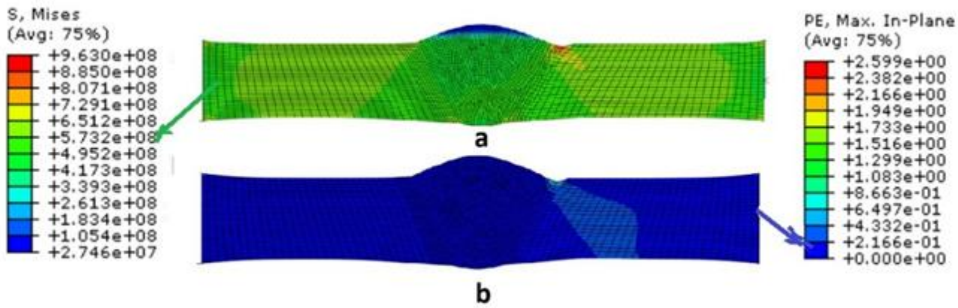


Figure 1. Localization of maximum stresses (a) and strains (b) in a simulated welded joint with a one-sided smooth undercut of 0.6 mm depth.

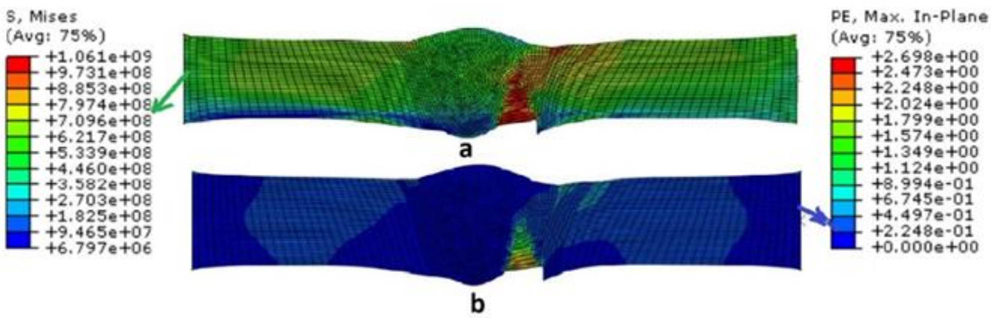


Figure 2. Localization of maximum stresses in a simulated welded joint with a one-sided lack of root fusion.

ISO 5817 and AWS D1.1 do not account for the profile radius of curvature or defect sharpness, leading to erroneous decisions: safe welds are rejected, and enterprises incur redundant costs for repairing non-hazardous sections. Moreover, re-welding can degrade the metal structure and reduce structural reliability.

Section Conclusion

Modern digital technologies have revealed a fundamental limitation of current ISO and AWS standards: they are not designed to analyze continuous digital profiles and do not account for physically meaningful parameters such as the radius of curvature and stress distribution. This necessitates the development of a new digital standard based on continuous shape invariants, such as the Laplacian reference profile[6].

4. Industrial Consequences of the Lack of a Digital Standard: Systemic Retardation of the Welding Industry Development

The lack of a digital standard for weld geometry assessment is not a local NDT laboratory issue. It is a fundamental barrier restricting the development of the entire welding industry. A regulatory base grounded in the visual-measuring methods of the last century impedes the digitalization of key segments: personnel qualification, material development, equipment marketing, and robotic production.

4.1. Impossibility of Objective Welder Qualification

Welder certification systems like AWS [7], ISO [8], and NAKS [9] rely on subjective visual testing and a binary "pass/fail" assessment. This approach:

- Does not measure skill stability;
- Does not distinguish between an "ideal" weld and one "on the brink of tolerance";
- Prevents the use of digital quality metrics.

Without a digital standard, it is impossible to introduce objective craftsmanship indicators based on the digital evaluation of the weld surface shape. Consequently, the qualification process remains non-transparent and dependent on the human factor.

4.2. Impossibility of Digital Marketing for Welding Equipment

Manufacturers of modern inverters and semi-automatic machines claim "synergic modes" and "intelligent drop transfer algorithms". But proving the effectiveness of these modes within the ISO/AWS framework is impossible: the standards contain no digital criteria for the weld shape. Therefore, marketing is forced to rely on subjective descriptions ("softer arc", "less spatter") rather than measurable parameters.

A digital standard would allow manufacturers to specify objective indicators, for example: *"Mode X ensures a profile stability of 95% and a deviation from the reference of less than Y%."* This would establish a transparent market and allow equipment to be compared using real digital metrics.

4.3. Impossibility of Digital Certification of Welding Materials

Welding materials affect surface tension, viscosity, wettability, and weld meniscus formation. But standards evaluate materials only by the mechanical properties of the deposited metal and chemical composition. Technological properties—the ability to form a correct profile—are completely ignored.

A digital standard would allow materials to be certified by their ability to form a physically correct Laplacian profile. This would open the path to creating new materials with controlled capillary characteristics.

4.4. Challenges of Control and Management Automation: The "Blind Spot" of Robotic Systems

Modern welding robots and WAAM systems are equipped with feedback sensors that measure the weld profile in real time. But they lack a mathematical criterion for the reference weld profile.

The robot:

- Sees the weld shape;
- But does not know whether it is acceptable;

- Cannot evaluate the danger of a local deviation;
- Cannot correct the technological welding (deposition) process when the weld shape changes.

In additive manufacturing, this leads to error accumulation: if the first layer deviates from the ideal profile, each subsequent layer amplifies the defect. Without a digital standard, robots remain "blind executors", incapable of managing metal formation quality.

Section Conclusion

The lack of a digital standard for the weld surface shape blocks the development of end-to-end digital technologies. Its creation is not a local update of visual inspection instructions, but a key condition for the transition of the welding industry to autonomous, self-learning Industry 4.0 systems.

5. 3DLD Methodology as the Foundation of the Future Digital Standard

The transition from traditional empirical VT methods to an infrastructure digital standard requires an informed choice of a measurement platform capable of playing the role of its technological and mathematical core. Analysis of existing NDT methods shows that techniques such as ultrasonic testing, radiography, and capillary testing are critically important for finding internal defects, but are fundamentally incapable of providing precision digitization of the complex outer weld surface topology.

The only technology that fully satisfies the requirements of end-to-end digital production is the 3D Laser Diagnostics (3DLD) methodology. It was originally designed as a fundamental analytical system, rather than a local "point-stress" measurement tool, and possesses a set of unique invariant properties necessary for international standardization.

Physical and Mathematical Basis of Reference Formation

The 3DLD methodology is based on a fundamental physical and mathematical model that allows calculating, with a specified accuracy, the equilibrium shape of the molten metal surface of the weld pool located in a uniform field of mass forces. The mathematical description of this process is the classical Laplace capillary equation, which in an arbitrary coordinate system has the form:

$$\kappa = -\frac{P_0 - h}{a_k^2} \qquad (1)$$

where:

- k — curvature of the meniscus surface;
- P_0 — excess capillary pressure at the reference point (expressed in units of liquid column height);
- h — vertical coordinate (height) above the selected reference point;
- a_k — capillary constant of the weld interfacial surface.

The detailed mathematical apparatus and numerical solution algorithms for equation (1) in polar and curvilinear coordinate systems as applied to various spatial welding positions are detailed by the authors in [10]. The numerical solution of this equation allows calculating the reference shapes of the surface of fillet and butt welds for any spatial positions (Fig. 3).

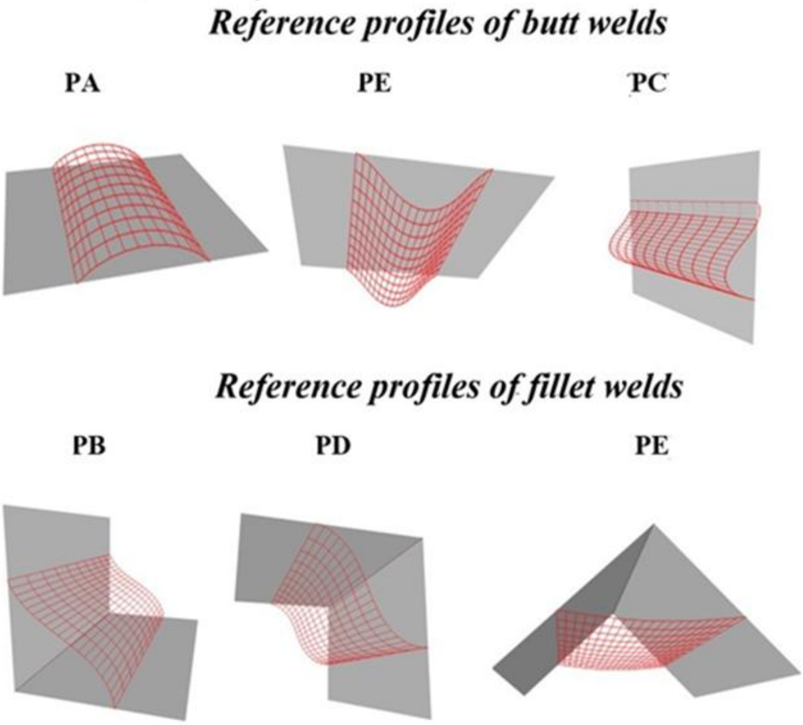


Figure 3. Reference shapes of the weld surface in various spatial positions.

Based on the mathematical model, the authors created a computational module in the *Microsoft Excel* environment, allowing rapid generation of reference weld shapes (Fig. 4). The program mathematically models the behavior of liquid metal under gravity when changing the spatial angles of weld inclination.

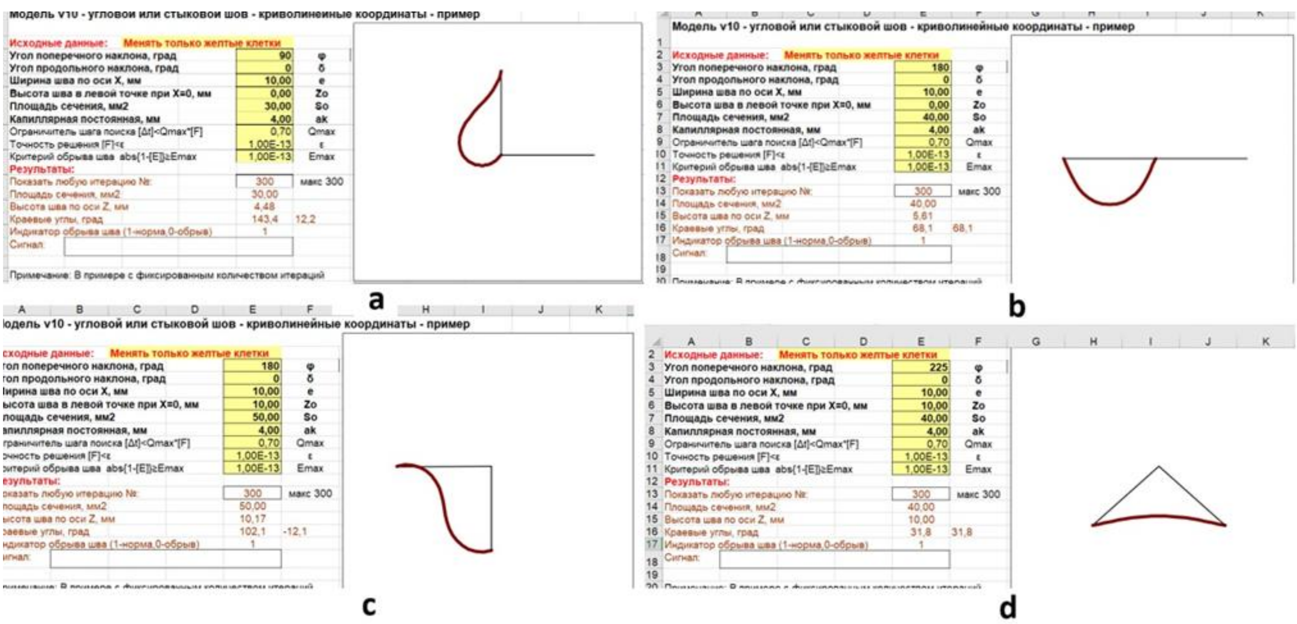
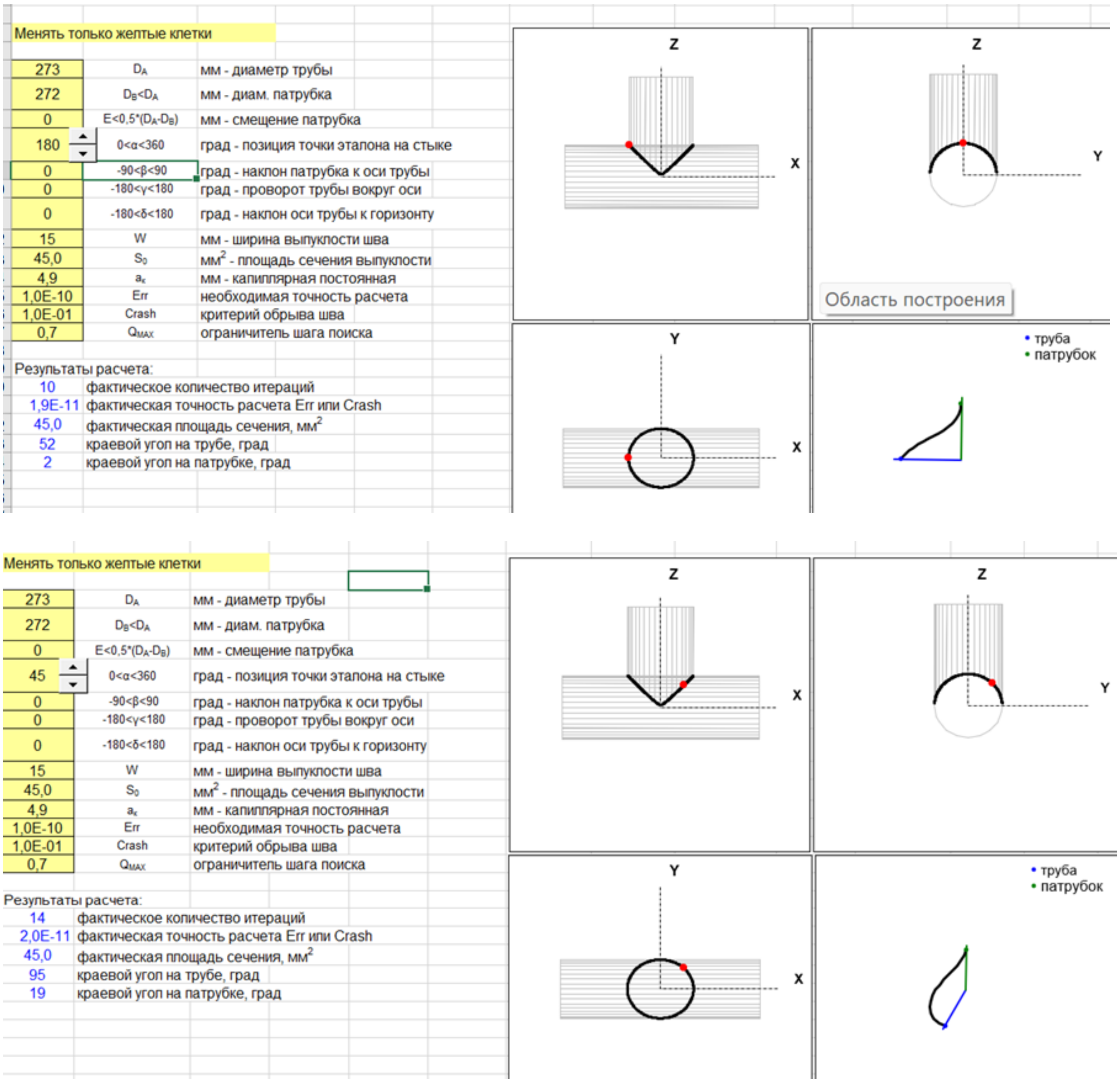


Figure 4. Calculated reference profiles: butt weld in vertical (a) and overhead (b) positions; fillet weld in vertical (c) and overhead (d) (flat-V/gravity) positions.

The reference shape of the weld surface within the framework of the proposed standard acts as an objective physical measure. It uniquely determines the reference (defect-free) profile of the deposited metal under given technological parameters: weld width, area under the integral weld curve, spatial inclination angles, and the capillary constant of the melt interface. Using the Laplacian reference as a measure of the weld surface shape provides the digital standard with a number of unique properties:

5.1. Mathematical Rigor of Inspection

The introduction of the reference shifts inspection from qualitative expert descriptions to objective criteria-based evaluation. The advantages of referencing are most clearly manifested during the inspection of complex joints, such as the intersection of a pipe and a nozzle (Fig. 5), when the joint type continuously transforms from fillet to butt. Traditional linear standards are fundamentally incapable of normalizing such a complex dynamic weld geometry, whereas the Laplacian reference maintains continuity and mathematical rigor at any point along the intersection circumference.



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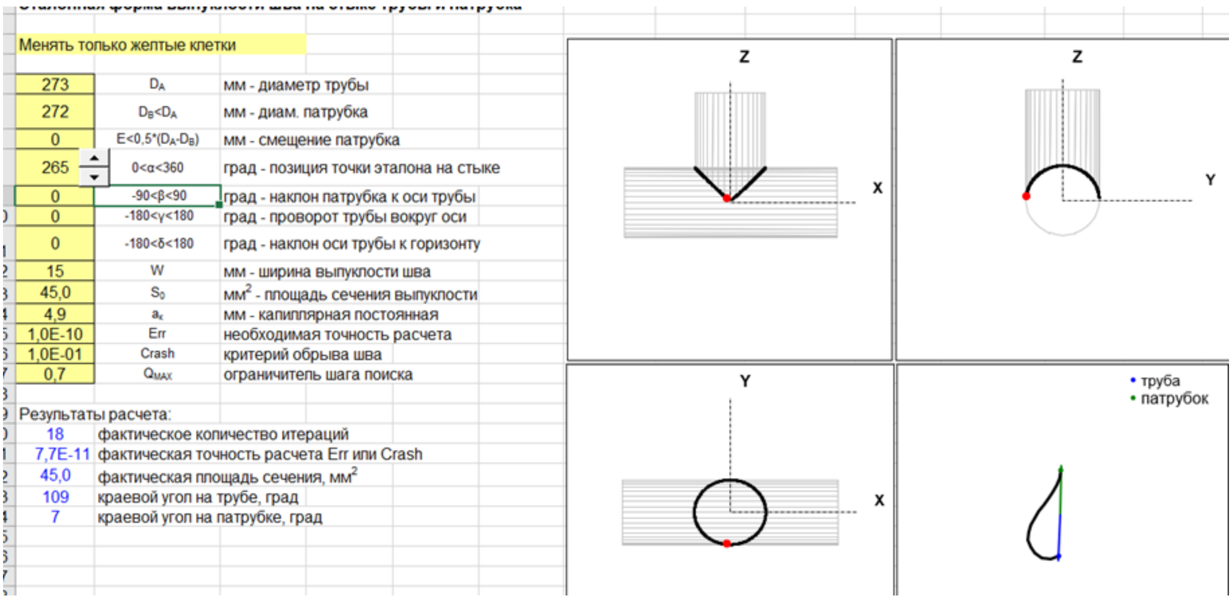

Figure 5 (continued). Transformation of the weld reference from fillet to butt during pipe intersection (The red dot indicates the spatial position of the weld reference).

The application of a digital reference allows abandoning the empirical tolerances of the last century, replacing them with a strict calculation of a digital criterion. The scheme for comparing a digital replica of the weld cross-sectional shape with the reference is shown in Figure 6

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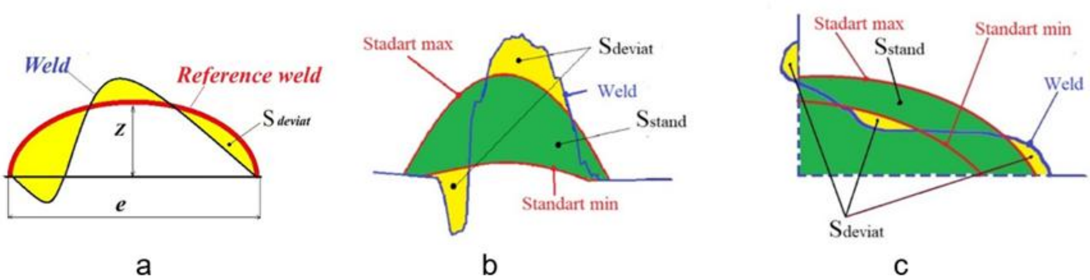


Figure 6. Scheme for comparing a digital weld shape replica with the reference by nominal values (a) and by tolerance range for butt (b) and fillet (c) welds.

The weld quality is determined by a numerical index characterizing the deviation of the digital weld copy area from the reference area, specified by nominal dimensions (Fig. 6a) or allowable dimensional deviations (Fig. 6b, c) in accordance with regulatory documents:

$$WQI = \frac{100}{N}\sum_{j=1}^{N}\left(1 - \frac{S_j^{DEVIAT}}{S^{STAND}}\right) \qquad (2)$$

where:

- WQI — weld quality index;

- N — number of measured weld sections;
- j— current index of the measured weld cross-section;
- S^{STAND}— reference area;
- S_j^{DEVIAT} — absolute deviation of the area of the j-th weld surface section from the reference area.

5.2. Reproducibility of Results

The subjectivity inherent in manual measuring inspection due to the human factor is completely eliminated. The laser scanner operates according to the immutable trigonometric laws of optics (Fig. 7), and the algorithm for calculating the complex dimensionless index—the Integral Weld Quality Criterion (WQI)—is rigidly fixed in the software code. Repeated scanning sessions of the same joint area, performed under any shop conditions by different operators, yield an identical data array with a known measurement error and uncertainty, which guarantees the reproducibility of the weld quality assessment by surface shape.

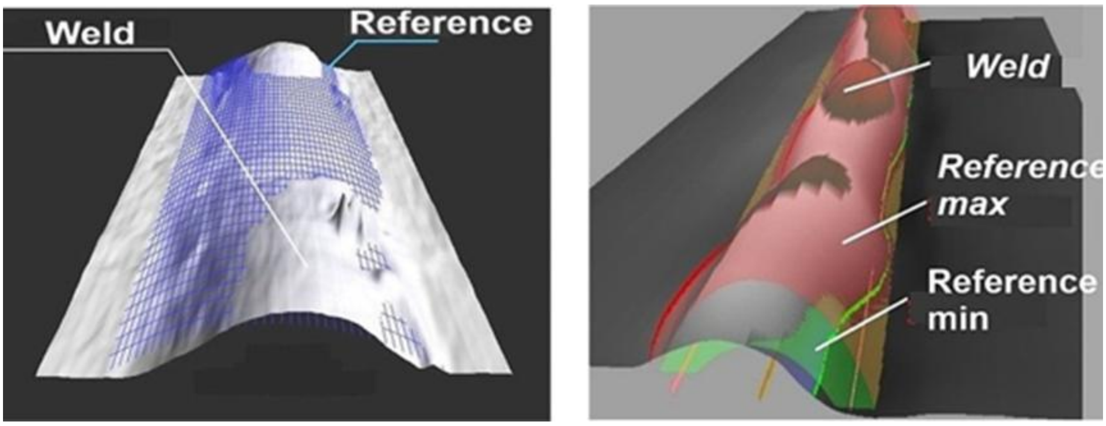


Figure 7. Visualization of the metallurgical alignment process of the real 3D point cloud of a digital weld replica with the theoretical reference Laplacian mesh (a) and the formation of a virtual "allowable geometric corridor" (b）.

5.3. Hardware Independence (Equipment Invariance)

The 3DLD methodology is not tied to specific brands or closed technologies of scanning hardware manufacturers. As a data source, the system uses a standard spatial point cloud (coordinates X, Y, Z). Thanks to this, manual portable scanners, robotic laser scanners, or stationary optical systems can be equally successfully applied for visual inspection. If the measuring device satisfies the minimum standard requirements for point density (sampling), absolute error, and measurement uncertainty, the 3DLD mathematical core guarantees reproducibility and objectivity of the IWQC calculation regardless of the hardware brand.

5.4. Independence from Expert Evaluation and Digital Arbitration

The system completely excludes human judgment from the acceptance process, recording exclusively the dry physical fact of the degree of agreement between the real weld geometry and the Laplacian reference. The final verdict is issued by an automated algorithm based on the calculation of the residual area S_j^{DEVIAT} (Fig. 8), which eliminates corruption risks, inspector errors, and prolonged arbitration disputes between the customer and the executor.

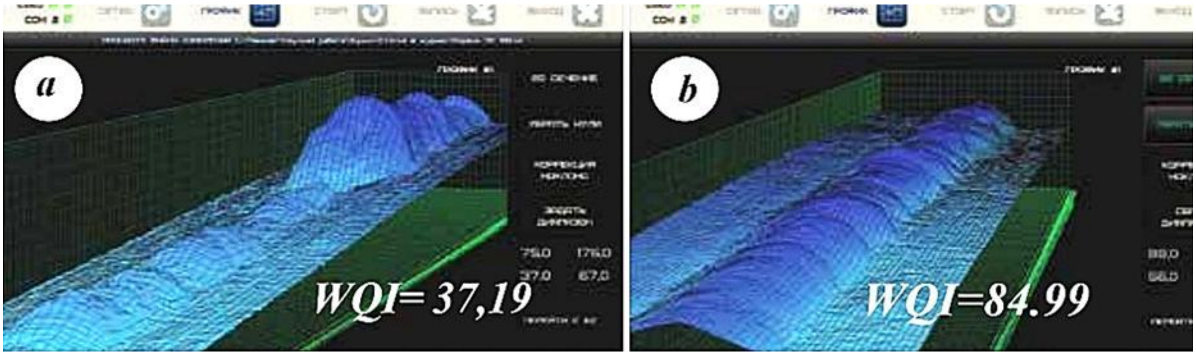


Figure 8. Comparative analysis of laser diagnostics results for two welded joints: "unsatisfactory formation" (a) and "satisfactory formation" (b).

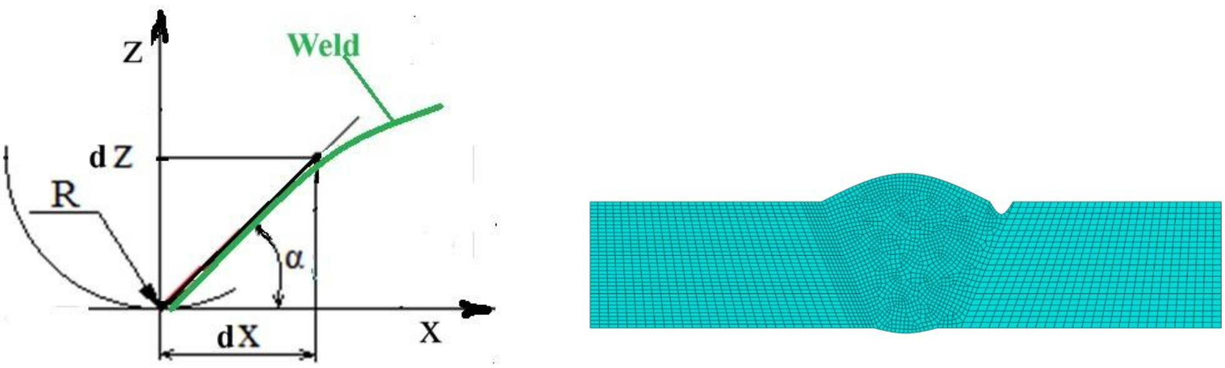
5.5. Manufacturing Cycle Automation Potential

Full digitalization of the algorithm—from the moment of the laser beam sweep to the generation of a digital quality passport—opens broad opportunities for organizing continuous round-the-clock inspection in production lines. The method integrates into the control loop of welding robots and wire arc additive manufacturing (WAAM) systems, completely eliminating the geometric "blind spot" problem through adaptive feedback algorithms.

5.6. Backward Compatibility and Integration into ISO/AWS Codes

The developed standard does not require the cancellation of the existing international regulatory base, possessing the property of "dual compatibility". The algorithm based on the Laplacian core is capable of operating in a dual-interface mode (Fig. 9):

- Calculate promising parameters (radii of curvature, toe angles of the weld with the base metal (Fig. 9a), toe angles of beads in a multi-pass weld, integral deviation areas $S_{j\{}^{DEVIAT}$ for transfer into specialized CAE computer engineering and finite-element analysis packages (specifically, ABAQUS) with the aim of precision calculation of the local stress-strain state of the real joint geometry (Fig. 9b);
- Automatically recalculate these data into the linear metrics familiar to current editions of ISO 5817 and AWS D1.1 standards (record the maximum depth of undercuts or the weld bead reinforcement height) (Fig. 9c).



a b

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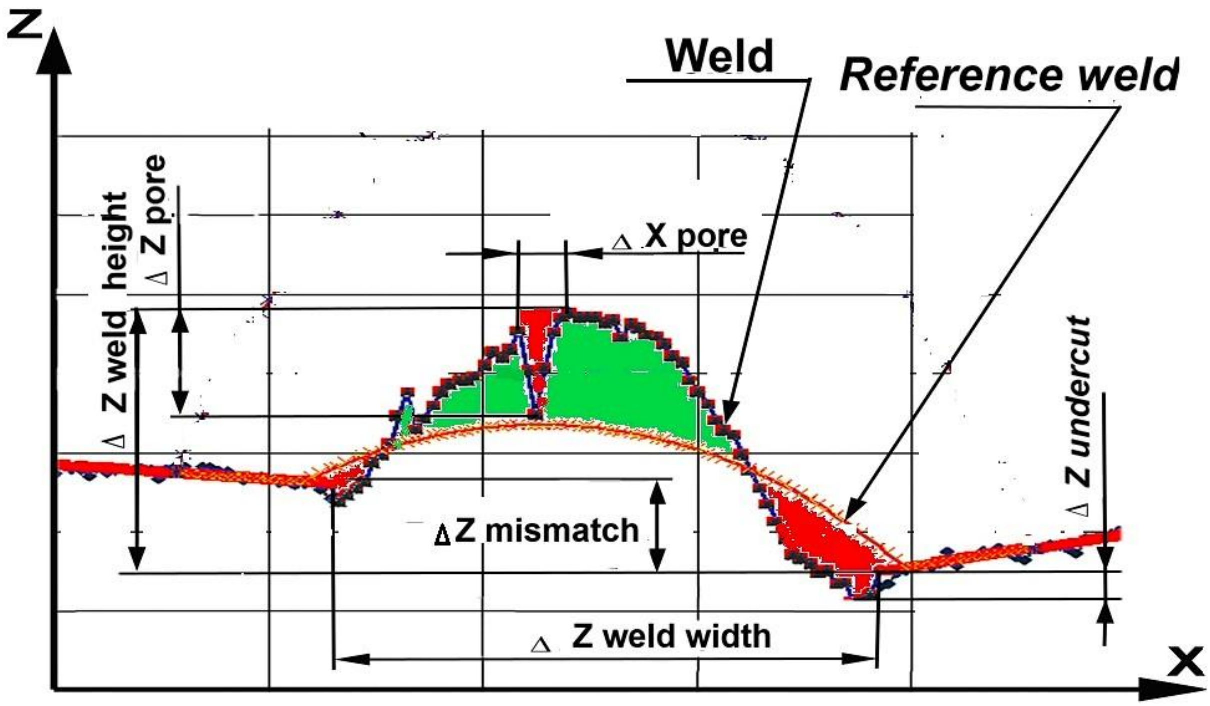

c

Figure 9 (continued). Mathematical decomposition of real weld parameters in the 3DLD software: a- calculation of promising differential metrics (local radii of curvature at the toes, transition angles); b- finite-element mesh of a specimen with a one-sided undercut for ABAQUS; c- transformation of data into classical linear defect parameters per ISO/AWS.

Section Conclusion

The 3D-laser diagnostics (3DLD) methodology possesses a full complex of fundamental metrological and physical properties necessary to fulfill the role of the technological core of a new international digital standard. The combination of the mathematical rigor of the Laplace equation, hardware invariance, reproducibility (traceability) of results, and flexible backward compatibility with ISO/AWS codes makes the proposed approach the sole alternative candidate for building the digital infrastructure of the future welding industry.

6. Paradigm Shift: The Digital Standard as the Infrastructure of the Welding Industry

The transition from traditional inspection methods to 3D methodologies requires not just a tool update, but a complete revision of the welding quality assessment concept. The main error of today's approach is perceiving the laser scanner as an "improved mechanical gauge".

This work proposes a new paradigm: a digital standard based on the Laplacian reference is not a technological option, but a fundamental infrastructure of the digital welding industry [11]. Without a unified mathematical language for describing the weld shape, it is impossible to build closed automated systems, integrate robots, train neural networks, and ensure international technology compatibility. The main elements of this infrastructure are presented below.

6.1. Digital Weld Passport as Part of the Product's Digital Twin

In the Industry 4.0 concept, every product has a digital twin. However, the "Welding" section in modern digital passports is limited to scans of paper inspection acts marked "Accept". A digital standard based on the 3DLD methodology allows creating a mathematically homogeneous digital weld passport containing:

- A digital twin of the weld (Fig. 10);
- A continuous function of profile deviation from the reference (Fig. 10);
- An integral quality index criterion (IWQC/WQI) (Fig. 10);
- Data for calculating the residual life of the weld (Fig. 11).

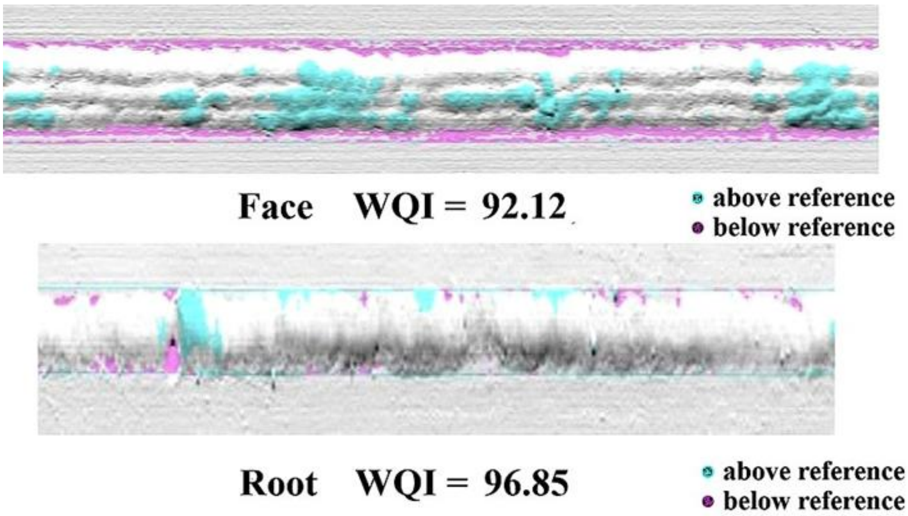

Figure 10. Digital twin of a weld with profile deviations from the reference and a quality index for the face and root surfaces.

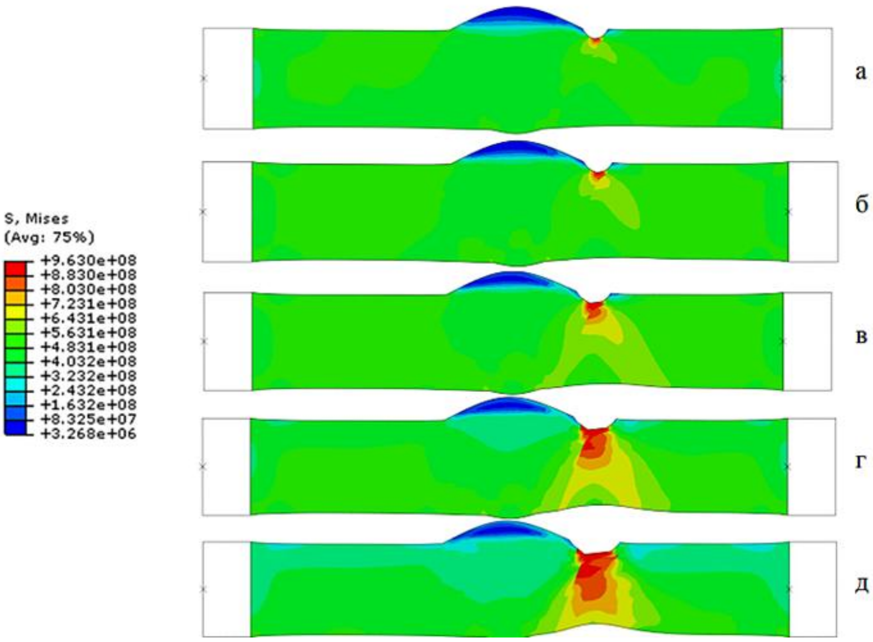

Figure 11. Kinetics of stress development in a weld under accumulated residual deformation: a) 4 mm; b) 5 mm; c) 6 mm; d) 7 mm; e) 8 mm.

Such a passport becomes part of CAD/CAE models and ERP systems, transforming the weld from a "black box" into a fully digitized object.

6.2. Digital Metrics as a Unified Foundation for Robotics

Today, each robot and scanner manufacturer uses proprietary algorithms to search for and analyze surface defects and analyze the weld profile. This creates equipment incompatibility and requires complex integration.
The Laplacian standard forms a universal mathematical protocol, including:

- Integral parameters of the weld shape;
- Differential parameters of the weld shape;
- Deviation areas from the reference— S^{DEVIAT}

Robots from different manufacturers receive a unified objective function: to minimize the deviation of the real weld shape from the reference. As a result, welding machines and robots of different brands begin to work in a single network using a common "language of physics", automatically managing weld quality without human intervention. This transforms disparate systems into a unified flexible manufacturing environment.

6.3. Support for Wire Arc Additive Manufacturing (WAAM) Technologies [12].
The production of large-scale metal items by wire arc additive manufacturing (WAAM) is critically dependent on the geometric accuracy of each deposited layer. In the absence of a digital geometry standard, layer-by-layer metal 3D printing faces the problem of error accumulation: unacceptable waviness or a local defect in the first layer leads to a geometric collapse of the entire grown part by the hundredth layer.
A digital standard based on the 3DLD methodology forms a regulatory base for layer-by-layer verification in additive manufacturing. The scanner digitizes each deposited bead, and the software compares it with the reference. The WAAM system gains the ability to adjust the height of the subsequent pass layer by layer, ensuring the defect-free nature of the grown metal matrix (Fig. 12).

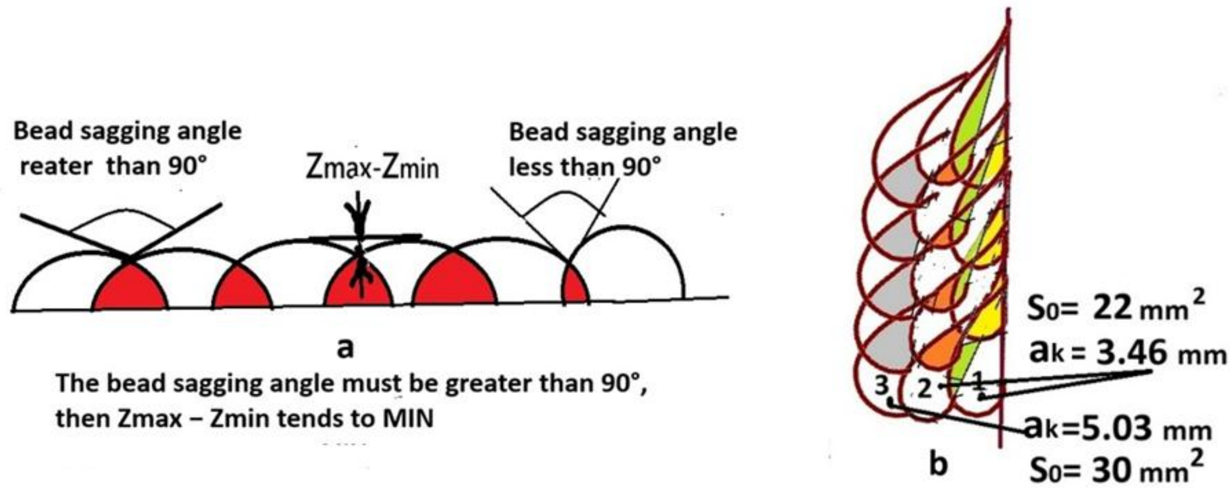

Figure 12. Bead layout on a horizontal (a) and vertical wall (b) during additive manufacturing.

6.4. Physically Substantiated Reference as a Basis for Neural Network Training

Modern neural networks in NDT suffer from a shortage of labeled data. Training requires thousands of defect photographs, which is expensive and subjective. The Laplacian reference resolves this issue:

- The neural network receives a precise analytical image of the reference weld;
- Training proceeds on the principle of anomaly detection;

- Any deviations from the reference are recorded automatically.

This reduces training time by tens of times and ensures the reproducibility of solutions by artificial intelligence.

6.5. Integration with Digital Twins Technologies

A product's digital twin cannot be accurate if the welded joints are described by idealized CAD lines. A real weld always has deviations that affect the strength of the welded structure, such as a pressure vessel (Fig. 13)

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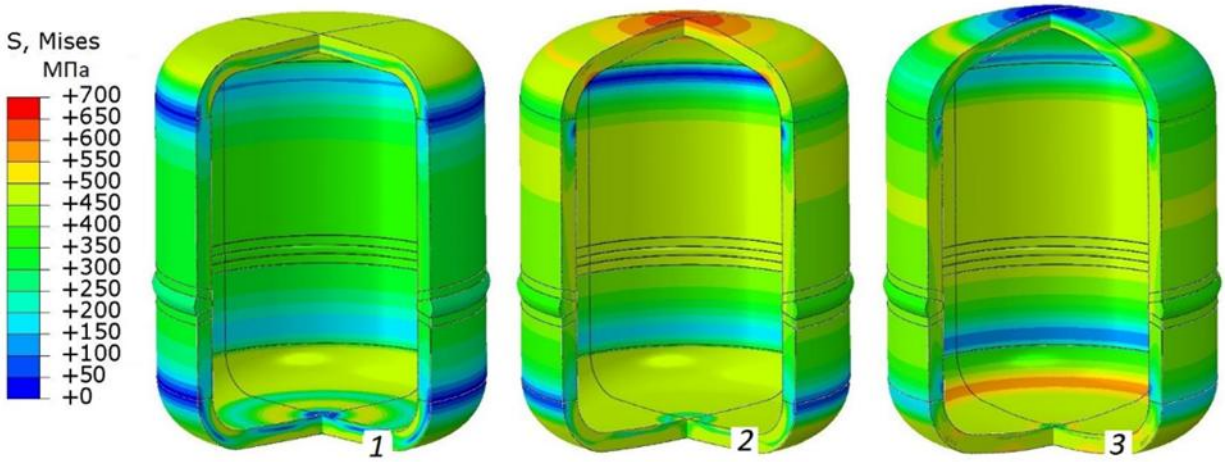


Figure 13. Visualization of von Mises stress distributions in vessel walls at applied pressures of 9.0 (1), 15.0 (2), and 21 MPa (3).

The digital standard allows:

- Transforming the weld profile into a finite-element mesh;
- Exporting data to ABAQUS/ANSYS (Fig. 14a);
- Accounting for real stress concentrators (Fig. 14b);
- Calculating the actual residual life of the structure.

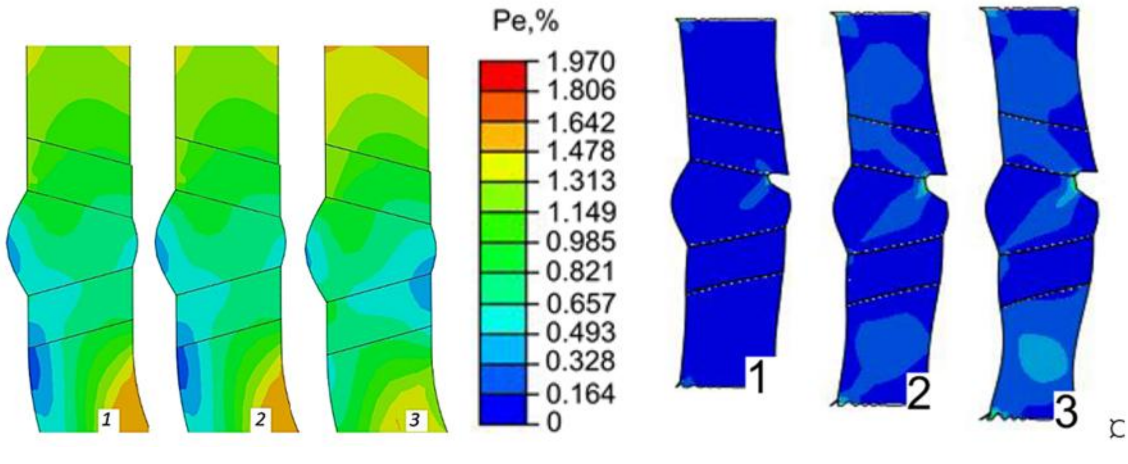


Figure 14. Visualization of von Mises stress distributions (a) in a vessel welded joint at applied pressures of 9.0 (1), 15.0 (2), and 21 MPa (3), and visualization of plastic strain distribution in a welded joint lack of root fusion at plastic strains of 3.75 (1), 6.75 (2), and 9 mm (3).

Thus, the digital twin allows preserving information about the weld quality and its operating conditions, making it physically correct.

6.6. Digital Criteria as the Basis of International Certification in Evaluating Qualifications, Welding Equipment, and Material Quality

Today, international certification is complicated by differences in AWS, ISO, EN, and GOST standards. A digital standard based on the 3DLD methodology translates quality assessment into the universal language of physics, identical for all countries. The dimensionless WQI index, calculated by formula 2, becomes a transnational invariant.

Welder Qualification Assessment [13]

Evaluating the manual (motor) skills of a welder lies in their ability to form the face and root surfaces of a weld within the boundaries specified by regulatory documents, using designated materials, and in a specified spatial position, and is characterized by the digital Welder Qualification Index (WQI) calculated by formula 2. All standards specify deviations for weld dimensions; therefore, welder motor skills must be evaluated within the range of specified tolerances (Fig. 4b, c). In international practice, welding a pipe coupon in positions PF or PH-L045 is adopted for qualification evaluation. 3DLD technology calculates the WQI value for each 2D section (Fig. 15), forms a color map of deviations from the reference, and outputs an integral index for the entire surface of the face and root welds (Fig. 16)

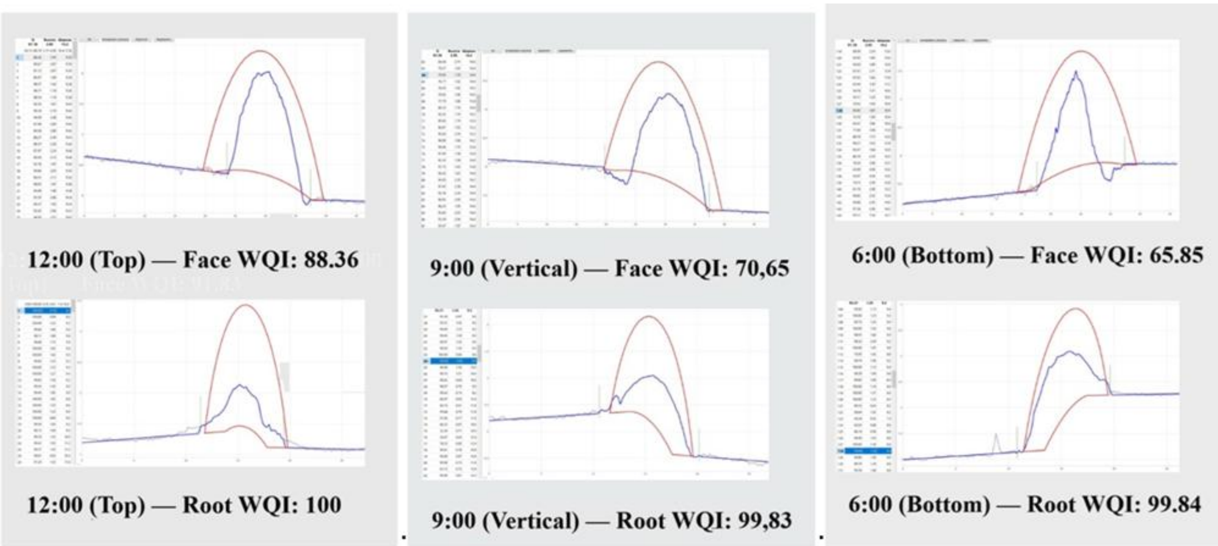


Figure 15. Example of Welder Qualification Index evaluation across 2D sections of a pipe coupon (159x6) in position PF

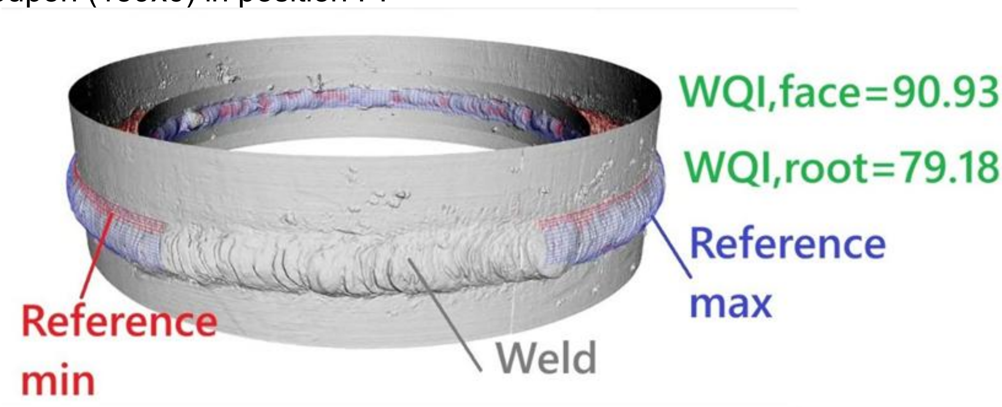


Figure 16. Deviation map from the reference and qualification index of a pipe coupon face and root surface.

The transition to a digital standard based on the 3DLD methodology enables the creation of a Global Transnational Register for unified assessment and verification of welder practical skills. Instead of a binary "pass/fail" grade, the welder receives a unique international digital ID (QR code) containing their digital metric—the Personal Welder Qualification Index (WQI). This index characterizes not just the final outcome, but the mathematical stability of their capacity to maintain the weld pool in all spatial positions. The results of periodic qualification for each welder, in the form of digital replicas of completed welds, deviation color maps from reference values, and WQI values, are recorded in a personal digital welder passport (Fig. 17) and automatically transmitted to the Unified International Digital Register.

Digital Passport of welding skills of «MOSGAZ» welder Konstantinov K.A.

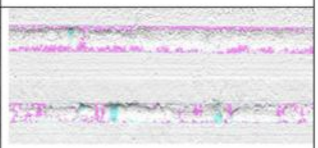
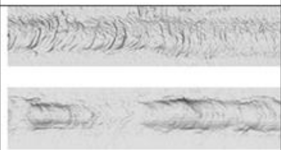
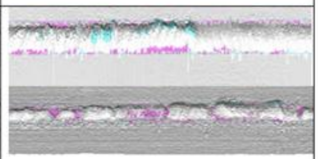
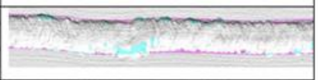
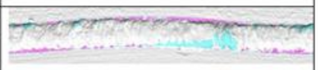
Certificate	Welding process	Test peaces	WQI face	WQI root	WQI average	Qqualification level	3D replicas of the face and root surfaces of the weld	Visualization of deviations from the standard of the face and root surfaces of the weld
24.04 2017	SMAW (111)	T159x6	91,83	92,15	91,99	6		
25.04 2017	SMAW (111)	T159x6	97,40	91,49	94,45	6		
21.08 2019	OFW (311)	T60x4	97,79		97,79	6		
08.09 2019	OFW (311)	T60x4	95,06		95,06	6		

Figure 17. Digital welder passport.

Thus, stable (motor) welder skills can be evaluated with mathematical rigor. Complementing the passport with non-destructive testing results (RT, UT, and dye penetrant inspection) and mechanical testing[14], it becomes possible to evaluate not only the welder's motor skills but also their ability to execute welding in accordance with the welding procedure specification (WPS). This includes joint edge cleaning, slag removal, adherence to the thermal cycle during preheating and interpass temperature control, bead deposition sequence, hot bead peening, etc. In this case, one can judge the welder's overall qualification.

Large international holdings (e.g., in the construction of nuclear power plants or LNG terminals) gain the opportunity to hire personnel worldwide remotely. Companies no longer need to trust paper certificates from different countries—it is sufficient to open the global register, view the candidate's mastery characterized by the WQI value, the digital replica of the formed weld shape, and NDT results to select welders of the required qualification. Utilizing AI capabilities allows evaluating errors most frequently made by young welders, providing a base for the modernization of welding simulators and educational programs worldwide.

Evaluation of Welding Materials and Welding Equipment

When evaluating the quality of welding materials and welding equipment (including welding robots), the IWQC index defines the bead surface topology not by rigid tolerance boundaries, but by the nominal deviation magnitude from the average width and height values of a specific deposited weld (Fig. 4a), allowing objective comparison of materials and equipment with each other (Fig. 18). This characterizes the stability of welding materials and power sources in maintaining arc stability in any predefined spatial position of the weld.

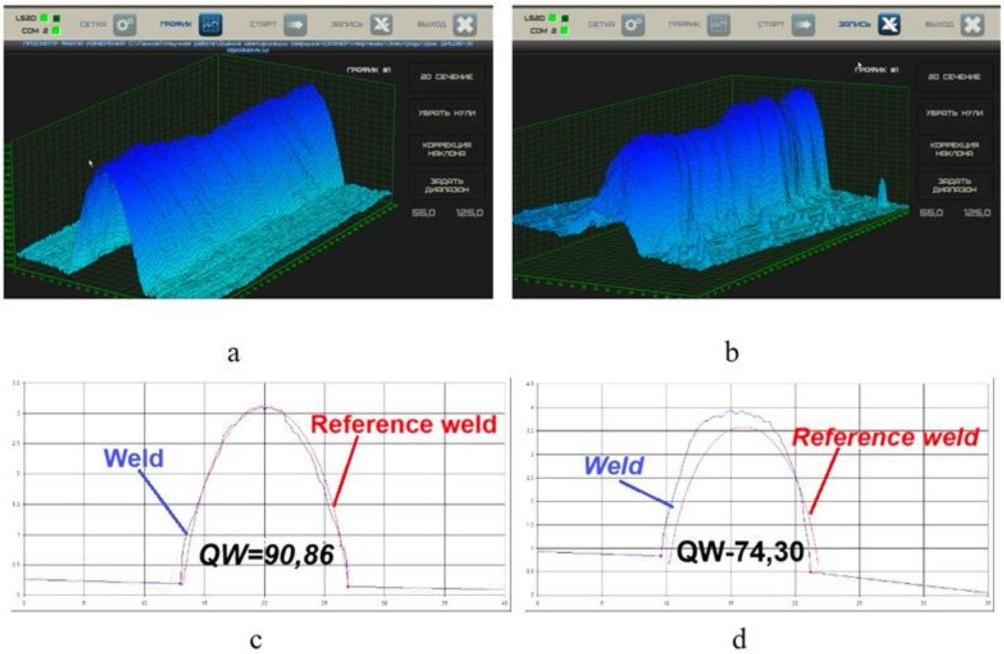


Figure 18. Evaluation of welding-technological properties of electrodes by nominal values: quality (a, c) and budget (b, d) electrodes.

By varying the value of the capillary constant (a_k}, which influences the weld surface shape and is derived from the inverse solution of the Laplace [15] equation, one can purposefully design the compositions of electrode coatings, fluxes, and shielding gases to manage the profile shape of the weld bead in various spatial positions (Fig. 19).

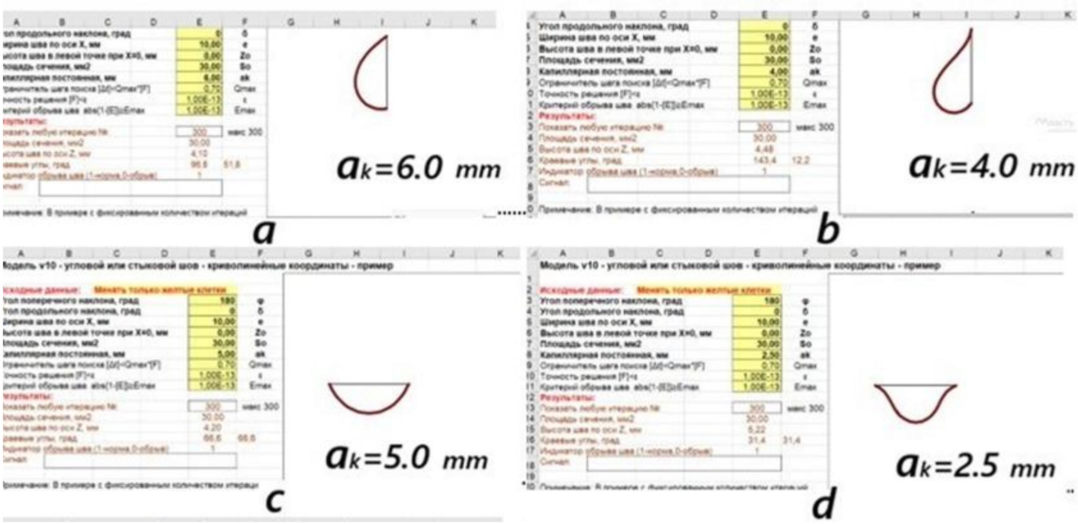


Figure 19. Influence of the capillary constant a_k on the weld profile in various spatial positions.

Instead of qualitative evaluation criteria for welding-technological properties, the digital standard will allow mathematically precise quantitative evaluation of this criterion, excluding mutual claims between suppliers and consumers of welding equipment and materials.

Thus, the dimensionless IWQ index becomes a transnational invariant. Welder qualifications, welding equipment, and materials capable of ensuring weld formation matching the shape of the Laplacian reference are recognized as high-quality regardless of the country, since their reliability is confirmed by physical laws, rather than local tolerance tables.

Section Conclusion
A digital standard based on the 3DLD methodology is not a narrow NDT document, but a systemic integrator linking welding with digital twins, robots, additive technologies, and cloud systems. It transforms welding processes into a transparent, manageable, and reproducible element of the future digital industry.

Final Conclusions

As a result of the conducted theoretical-methodological analysis of existing regulatory documents, mathematical modeling via 3DLD technology, and verification of the stress-strain state using the SIMULIA/Abaqus package, the following key results were obtained:

1. **Methodological Deadlock of VT:** It is proven that traditional linear-tabular metrics of ISO 5817 and AWS D1.1 standards, oriented toward recording the peak depth or height of a defect, are hopelessly obsolete for the digital era. They completely ignore the profile radius of curvature and geometric gradient, which leads to redundant rejection of serviceable structures and forms a conceptual "blind spot" for adaptive control systems of welding robots and metal 3D printers (WAAM).
2. **Digital Standard as an Infrastructural Basis:** A paradigm is formulated according to which the new digital standard is not a local update of non-destructive testing instructions, but a fundamental infrastructure of the entire modern cyber-physical industry. The standard acts as a universal mathematical interface (API) linking molten metal physics, structural strength calculations of digital twins, AI machine learning algorithms, and Big Data predictive analytics cloud systems.
3. **No-Alternative Nature of 3DLD Methodology:** It is substantiated that 3D Laser Diagnostics (3DLD) technology is the sole method capable of becoming the foundation of the new digital standard. Due to its properties of mathematical rigor, reproducibility, hardware invariance, and independence from expert opinion, 3DLD provides objective quality arbitration at all manufacturing cycle stages.
4. **Transformation of Human Capital Evaluation:** The developed concept allows shifting international personnel certification from a subjective scale to the universal language of physical laws. The introduction of the dimensionless WQI index opens the possibility of creating a Global Transnational Register of welder practical skills with secure data verification, which will radically increase the cross-border mobility of qualified personnel and the transparency of the global labor market.

Conclusion

The welding world has reached a point where further development is impossible without a digital standard. The approach presented in this work, based on comparing a digital weld shape replica with a reference shape and utilizing 3DLD tools, establishes a solid scientific and methodological foundation for overcoming the current technological crisis and implementing a full-scale transition of the welding industry to next-generation autonomous manufacturing based on the development of a modern Digital Standard.

Postscript (P.S.): Call for Global Collaboration

The authors believe that overcoming the current methodological deadlock in welding quality assessment requires a unified efforts from international industry leaders, regulatory bodies, and technology developers. Standardizing a continuous, physically substantiated reference profile is a foundational step toward truly autonomous Industry 4.0 manufacturing.

We invite all interested parties—including welding research institutes, NDT equipment manufacturers, industrial robotics developers, and international standardization committees (such as IIW, AWS, ISO, and ASME)—to join forces in establishing an international digital standard. The 3DLD technology, with its proven mathematical rigor, hardware invariance, and real-time processing capabilities, is fully operational and open to serve as the technological and collaborative platform for this global initiative.

For inquiries, collaboration proposals, or technology demonstrations, please contact the corresponding author at Vladimir M. Bukin, vmbukin54@gmail.com or co-author at Viktor V. Pankov, erzoff@rambler.ru.

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