

3D Laser Diagnostics Technology as a Digital Welding Quality Management Tool

Authors:

Vladimir M. Bukin, PhD, Independent Expert (*Corresponding Author*)
Viktor V. Pankov, PhD, Independent Expert
Sergey V. Pankov, PhD, Independent Researcher
Igor G. Bogorodsky, PhD, Independent Researcher
Leonid M. Gurevich †, DSc, Independent Researcher

Contact Information:

Corresponding Author: Vladimir M. Bukin, PhD, Independent Expert, Weston, Connecticut, USA | Email: vmbukin54@gmail.com
Co-author Contact: Viktor V. Pankov, PhD, Independent Expert | Email: erzoff@rambler.ru

. ABSTRACT

The article presents a new industrial technology for the objective quantitative evaluation of weld quality and welder proficiency, based on the method of three-dimensional laser diagnostics (3DLD). The method utilizes high-resolution laser scanning to create a digital twin of the weld surface and compares it with a calculated reference profile derived from the Laplace equation of capillary equilibrium. The system computes the Welder Qualification Index (WQI) and the Weld Profile Quality Index (WPQI) on a scale from 0 to 100, providing full visualization of deviations and eliminating the subjectivity inherent in manual visual testing. This technology enables the evaluation of welder performance, the quality of welding consumables, and equipment stability. Furthermore, it facilitates the resolution of inspection disputes through geometric analysis of transition zones and serves as the baseline for establishing a digital passport of welder qualifications. The 3DLD method has been successfully validated under industrial conditions and at international competitions; it can function as a platform for digital welding quality management in compliance with the principles of Industry 4.0.

Keywords: 3D laser diagnostics (3DLD); Welding quality management; Welder Qualification Index (WQI); Digital twin; Laser scanning; Industry 4.0; Patent.

INTRODUCTION

In industrial manufacturing, welding is classified as a "special process" because the reliability of the finished joint cannot be completely verified on the real product without destroying the

weld. Traditional welding quality management relies on continuous controlled quality checks of all welding process components. These components typically include welder qualification, the quality of welding consumables, welding equipment, and welding technology. Their audit relies on manual visual and testing inspection (VT) of the weld quality using mechanical tools [1]. This approach suffers from subjectivity, low productivity, and poor reproducibility of results.

To address these challenges, an innovative 3D Laser Diagnostics (3DLD) technology is proposed. The technology is based on comparing a digital replica, obtained via laser scanning of the weld surface (Fig. 1), with a reference shape. In regulatory and technical documentation (RTD), weld dimensions are defined by a range of deviations from nominal values. Therefore, the weld quality assessment can be performed both by the nominal value (Fig. 1a) and by a range of values (Fig. 1b and 1c)

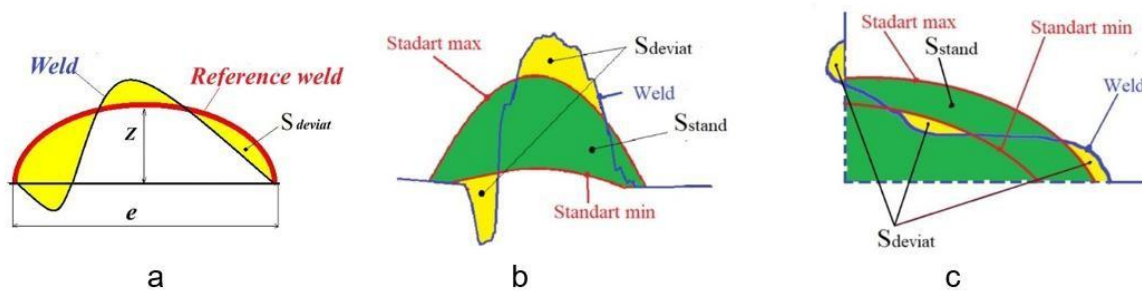


Figure 1. Scheme for comparing the digital replica of a weld shape with a reference by nominal values (a) and by range for a butt weld (b) and a fillet weld (c).

The reference shape is calculated using a physical-mathematical model by solving the fundamental equations of capillary equilibrium (the Laplace equation) [2]. The weld quality is determined by a numerical index characterizing the area deviation of the digital weld replica from the reference area [3].

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

Where:

- WQI — Welder Qualification Index; or Weld Quality Index.
- $N = Lw/dLw + 1$ — number of measured weld cross-sections with a measurement step of $dLw \geq 1$ mm;

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

The laser scanning software suite (Fig. 2a, b, c) automatically calculates the integrated Welder Qualification Index (WQI) and the Weld Profile Quality Index (WPQI) ranging from 0 to 100 points. It visualizes deviations (Fig. 2d), enabling an independent and unbiased evaluation of the welder's practical skills, as well as the quality of the equipment and consumables.

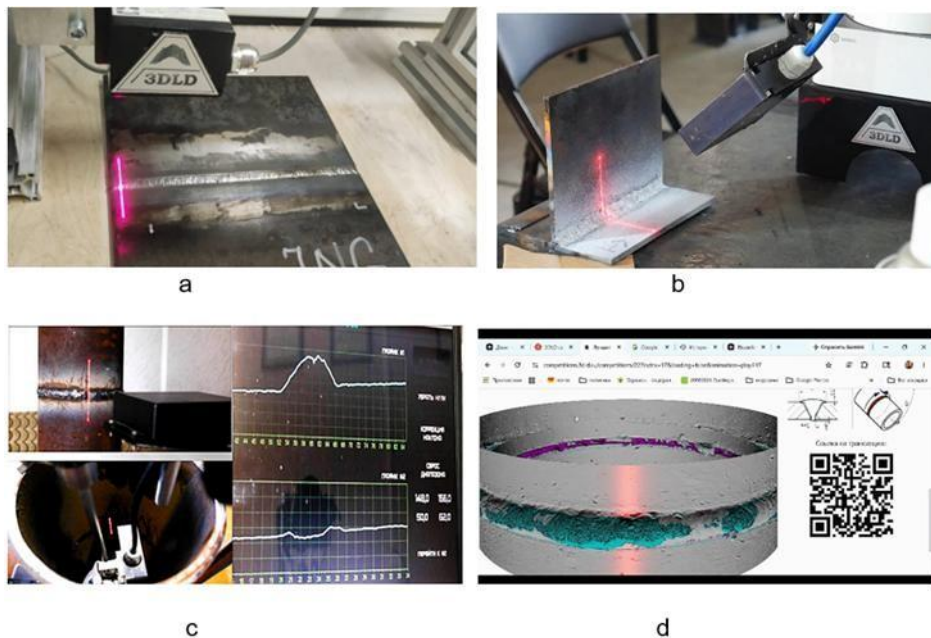


Figure 2. Laser scanning of a butt weld (a), a fillet weld (b), a coupon plate, and a coupon pipe with deviation visualization from the reference (d). ● above reference; ● below

1. THE HUMAN FACTOR: ELIMINATING THE SUBJECTIVITY OF MANUAL VT

The subjective factor remains the most volatile variable in welding production. Traditional welder certification has a binary nature ("pass/fail") and heavily depends on the human factor of the expert commission. To demonstrate the limitations of this method, the 3DLD technology was used to evaluate the practical skills of a group of 20 certified gas metal arc welding (GMAW) operators. Each of them performed weld overlay on coupon plates with a thickness of 16 mm made of 09G2S steel over a length of 220 mm in the flat position. The results were revealing: continuous 3D laser scanning proved that 100% of the welders failed to maintain the strict RTD requirements for bead width and height along the entire length of

the weld. The calculated WQI values fluctuated within a huge range — from 37.19 to 98.85 points (Fig. 3). This mathematically confirmed the massive variance in the welders' practical skills.



Figure 3. Indices for evaluating the practical skills of welders.: $WQI = 37.19$ (a), $WQI = 84.99$ (b).

The 3DLD technology allows calculating references for any spatial welding position (Fig. 4), making the method universal for all types of weld coupons.

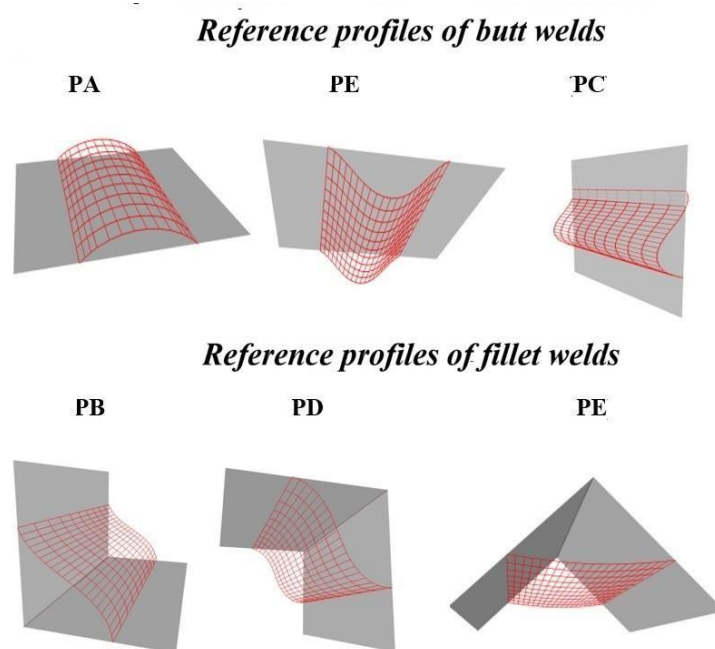


Figure 4. Calculated surface references for butt and fillet welds in various spatial positions (ISO/AWS standards: PA/1G, PE/4G, PC/2G, PB/2F, PD/4F)

When evaluating pipe coupons in the 6G (H45) position, the weld reference changes in every scanned cross-section. The 3DLD technology evaluates the welder qualification index for

each 2D cross-section and provides an integrated index across the entire surface of the face and root welds. For each 2D weld replica (crosssection), all surface shape defects can be viewed in detail. In every section, the software evaluates the WQI and displays measured weld height and width values. Thus, the consistency of a welder's skills in forming the face and root surfaces can be evaluated with mathematical rigor in all spatial positions (Fig. 5). Utilizing artificial intelligence capabilities transforms subjective inspection into a detailed skills analysis, allowing employers to select welders with the exact required qualifications

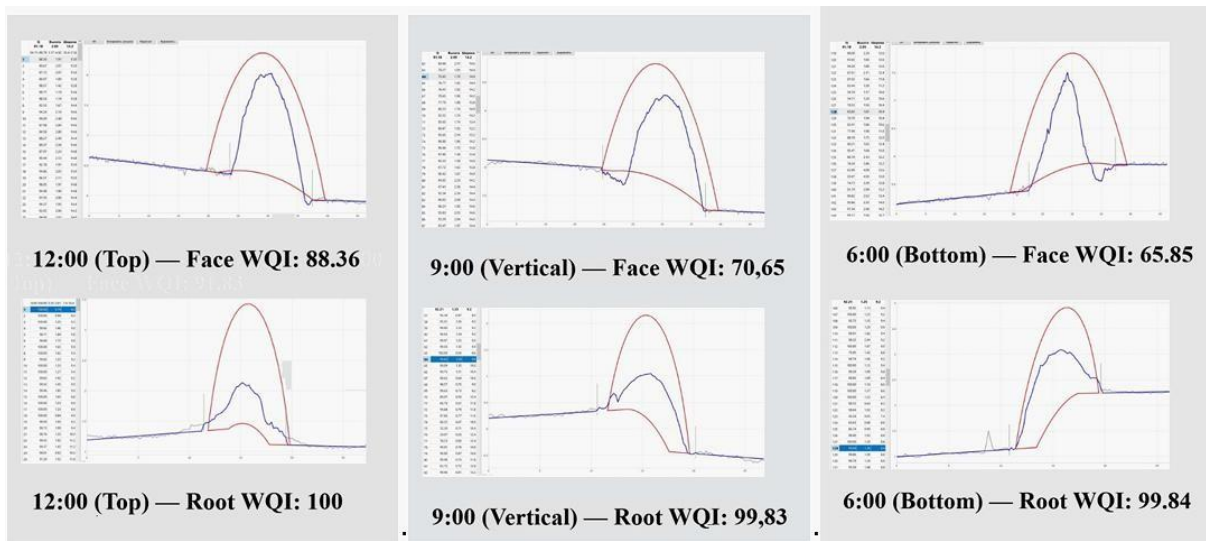


Figure 5. Example of Welder Qualification Index evaluation by 2D crosssections of a pipe coupon (159×6 mm) in the 5G (VI) position. (Profiles show: 12:00 (Top position) — Face WQI: 88.36 / Root WQI: 100; 09:00 (Vertical position) — Face WQI: 70.65 / Root WQI: 99.83; 06:00 (Overhead position) — Face WQI: 65.85 / Root WQI: 99.84).

For instance, after analyzing 256 2D cross-sections, the AI classified this welder as a highly skilled root welding specialist, recommending them for critical joints subject to radiographic testing, which confirms the practical applicability of the method for personnel certification [4].

2. RESOLVING INSPECTION DISPUTES: MATHEMATICAL GEOMETRY OF THE BLEND ZONE

In critical sectors such as the construction of main oil and gas pipelines, the transition zone from the face bead to the base metal (the weld toe / heat-affected zone boundary) is the primary source of disputes between contractors and quality inspectors. Regulatory

documentation requires a "smooth transition" but does not provide an accurate instrumental method for evaluating this smoothness.

The digital 3DLD technology completely eliminates this subjectivity by geometrically calculating the exact transition angle (α) and radius of curvature (R) in each scanned cross-section of the weld based on point coordinates (Fig. 6).

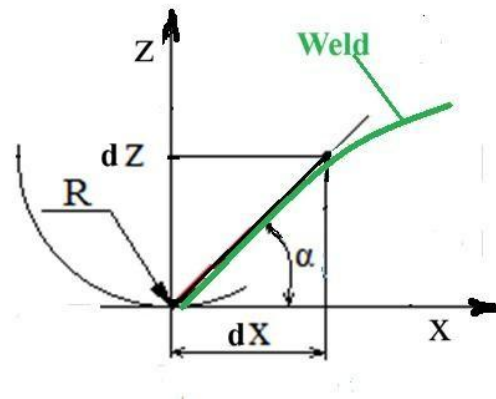


Figure 6. Scheme for determining the transition angle (α) and radius of curvature (R) in a 2D cross-section of the weld surface.

When comparing the real profile with the mathematical model of the ideal nominal reference line, any shape defects are instantly visualized and color-coded on the 3D replica (Fig. 7):

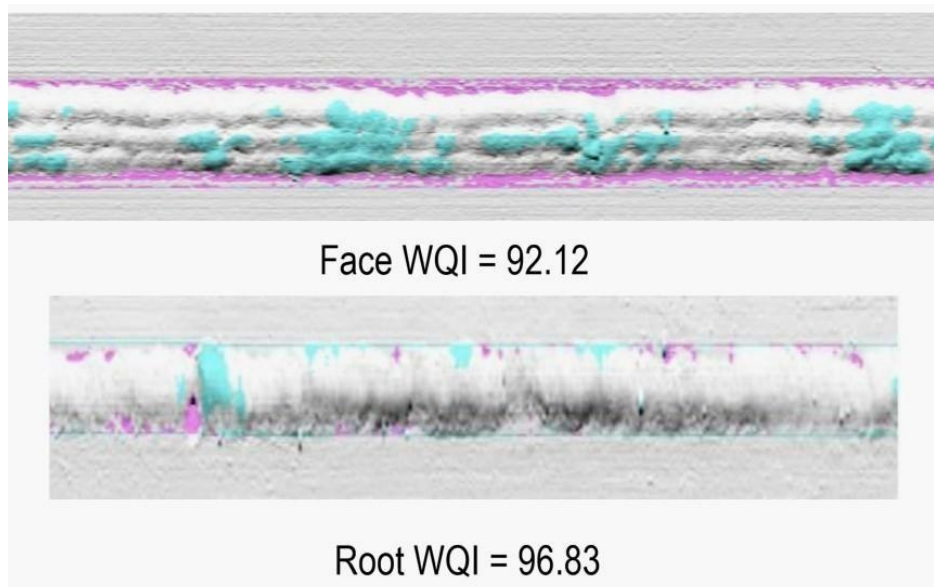


Figure 7. Deviation from the reference for the face and root surfaces of the weld. (Face WQI = 92.12; Root WQI = 96.83).

- Surface pores, pinholes, and craters produce sharp local dips (red color) below the reference line.
- Base metal undercuts are clearly captured as an area deficit in the blend zone, calculating the exact defect depth.
- Ripple marks and overlaps are displayed as an excess area (blue color) above the reference.

3. EVALUATION OF MATERIALS AND EQUIPMENT

To evaluate the stability of welding equipment and the quality of materials, the subjective factor must be minimized or completely eliminated. This is achieved by involving a top-tier welder (WQI > 95) or using a welding robot in the experiment. In this mode, the 3DLD algorithm switches to calculating the Weld Profile Quality Index (WPQI). This index evaluates the bead surface topology not by rigid tolerance limits, but by the magnitude of deviations from the average width and height values of the specific deposited weld, enabling an objective benchmarking of materials and equipment.

3.1. Benchmarking of Welding Consumables (Electrodes)

Under controlled conditions, the same certified welder used covered electrodes from different manufacturers with identical current settings (100 A) to deposit weld beads. The 3DLD method established an accurate, independent rating of the welding and technological properties of the materials based on the stability of the electrode metal transfer:

- **Premium imported brands (Askaynak/Lincoln Electric, Turkey/USA):** provided high arc stability and an ideal fine-ripple profile with a WPQI of 90.86 points (the 2D replica practically matched the virtual reference).
- **Global industry standards (Conarc 52 by Lincoln, LB-52U by Kobe Steel, OK 48.00 by ESAB):** formed stable beads in the range of 84.94–87.16 points.
- **Low-budget electrodes:** demonstrated unstable arc burning, spatter, and irregular bead height, recorded by the system as a sharp drop in WPQI to 74.30 points.

3.2. Benchmarking of Welding Equipment (Power Sources)

Similarly, a quantitative assessment of the influence of welding power source technological properties on the weld surface quality was conducted. Premium European machines from the Kemppi line were compared with budget industrial inverters, Svarog MIG 3500 (J93) circa ~2015, during shielded metal arc welding (SMAW) and gas metal arc welding in a carbon

dioxide environment (GMAW in CO₂) on 6 mm thick steel plates in the flat and vertical positions:

- **In SMAW mode using Fox EV 50 electrodes:** the average Weld Profile Quality Index (WPQI) using the Kemppi MasterTig MLS 2300 ACDC inverter was 85.92 points, while on the Svarog MIG 3500 (J93) machine, it was 85.72 points. This parity of results (a difference of just 0.2%) is due to the fact that under standard modes and medium currents, the speed of the inverter boards of both machines was sufficient for basic arc stabilization.
- **In GMAW mode using ER70S-6 wire in a CO₂ environment:** the Kemppi Kempact inverter delivered an average index of 82.88 points, whereas the Svarog MIG 3500 (J93) scored 79.76 points. The 3.12% difference in favor of Kemppi is explained by more effective arc dynamics when maintaining the weld pool vertically. However, the use of active CO₂ shielding gas and the high heat capacity of the 6 mm metal naturally leveled out the intelligent advantages of the Finnish electronics.

3.3. Main Conclusion of Data Analysis

The experiment clearly showed that when solving standard production tasks, replacing a budget power source with a premium one improves bead formation stability by only 3–4%. Switching to high-quality welding consumables yields a quality increase within 4–8%. This result indicates that during the experiment, the technological potential and redundant capabilities of the premium Kemppi apparatus were not fully utilized.

Thus, the practical skills of the welder remain the dominant factor determining the reliability of a welded joint, which is why the digital evaluation of skills becomes a core element of quality management.

In modern manufacturing, the use of advanced power sources with intelligent pulsed welding modes (Pulse MIG, SuperPulse, STT) allows process management to be elevated to a brand new level. When welding in complex spatial positions (e.g., pipe joints in the 6G position), modern pulsed technology ensures a "cold" fine-droplet metal transfer with controlled crystallization of the weld pool on the fly. This significantly reduces defect rates (undercuts, overlaps, lack of fusion) and, consequently, multiply increases overall labor productivity at the enterprise, while 3DLD technology allows for the quantitative verification of this effect. The 3DLD technology has made it possible for the first time to mathematically separate these variables, eliminating mutual claims between equipment suppliers, material procurement agents, and production personnel.

4. PRACTICAL IMPLEMENTATION AND DIGITAL SKILLS PASSPORT

The global applicability and productivity of the 3DLD method were fully validated at regional and international welding competitions, specifically the Arc Cup International Welding Competition (Shanghai 2017, Zhuzhou 2018, Langfang 2019). Under tight time constraints, just 3 operators using laser scanners and 3DLD technology automatically scanned and evaluated more than 500 complex pipe and plate coupons in two days.

The digital ranking of winners matched the consensus evaluations of an international panel of 17 experts using manual tools almost 100%. The 3DLD technology completely eliminates the human factor from judging and enables the real-time display of evaluation results on large screens and the internet. This turns any competition into a show, and immediately after scanning, a color certificate is printed for the welder (Fig. 8).

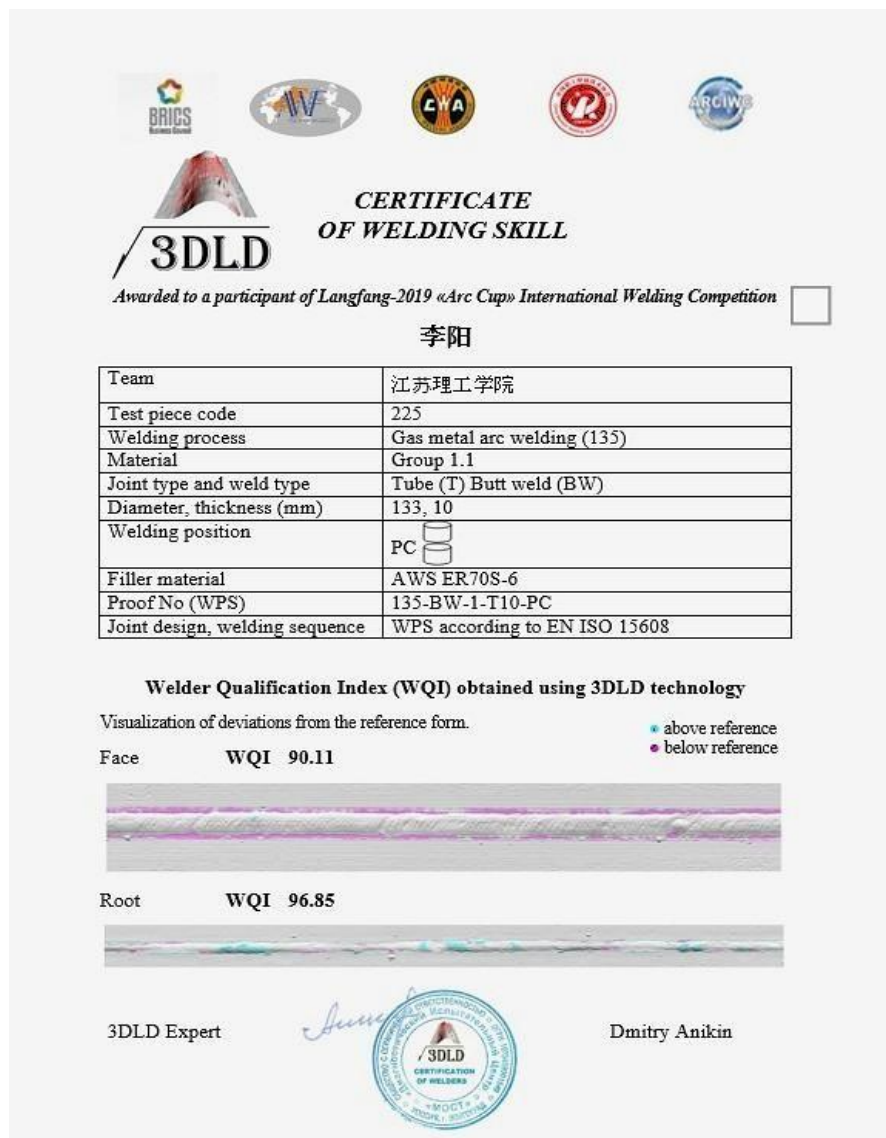


Figure 8. Certificate of an ARC Cup competition participant using 3DLD technology.

Remote evaluation of results not only allows competitions to be held between cities and countries but also enables remote qualification assessments, significantly reducing employers' costs for selecting welders with the required qualifications.

As part of its integration into the quality management systems of large enterprises, 3DLD technology implements the concept of a "Digital Passport of a Welder's Practical Skills" (Fig. 9)

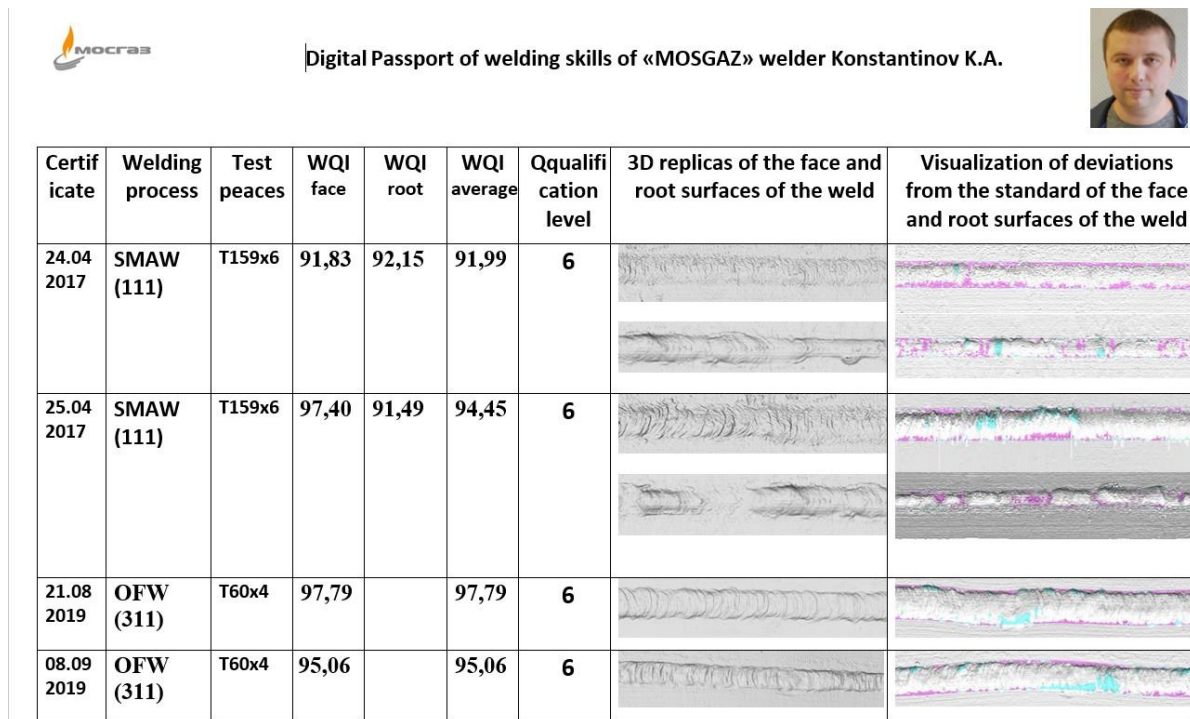


Figure 9. Digital Welder Passport Interface.

Instead of outdated paper certification conducted every two years, the system creates a dynamic digital database. The welder's passport records a continuous history of their work over several years (2017–2019) across different processes (SMAW and OFW). The electronic passport allows storing not only digital images of the weld surface and deviation visualization maps (Fig. 7) but also an electronic file enabling the analysis of the 3D surface and 2D cross-sections of the weld, making the passport a comprehensive tool for HR analytics.

Having 3DLD technology and equipment at an enterprise allows management to shift quality management into a continuous digital mode, reasonably select personnel for welding critical products, and guarantee defect-free production with absolute mathematical accuracy, aligning with the principles of Industry 4.0 and digital transformation.

CONCLUSION

1. The 3DLD technology is developed based on scientific concepts, protected by 7 Russian Patents [5-11], and allows abandoning the subjective method of expert weld quality evaluation, replacing it with objective digital metrology
2. 3DLD technology is an innovative digital tool with no global analogues, allowing the evaluation of all quality management components in welding production based on the shape of the face and root surfaces of the weld: practical skills of welders, quality of welding consumables, and equipment, while providing quantitative quality traceability.
3. 3DLD technology has undergone industrial approbation and can serve as a platform for developing corporate standards for digital weld quality assessment and quality management in welding production, as well as for integration into digital manufacturing and automated control systems

REFERENCES

1. AWS B1.11M/B1.11:2015. *Guide for the Visual Examination of Welds*. American Welding Society, 2015.
2. Pankov, V. V., Pankov, S. V., Bogorodsky, I. G., Bukin, V. M. Virtual reference of the weld shape during welding in various spatial positions for the purpose of evaluating welder qualifications. *Journal of Oil and Gas Construction*, 2014, No. 4, pp. 38–43.
3. Pankov, V. V., Pankov, S. V., Bogorodsky, I. G., Bukin, V. M. Weld shape measure as a basis for developing digital technologies for evaluating weld quality. *Journal of Oil and Gas Construction*, 2015, No. 2, pp. 20–26.
4. 3DLD Technology Research Portal, News. *AI: training and technical analysis of welder skills (electronic resource)*. URL: <http://3dld.ru> (Accessed: 21.06.2026).
5. V. V. Pankov, V. M. Bukin, S. V. Pankov, and I. G. Bogorodsky. *Method for surface quality control of a weld seam*. Russian Patent RU 2550979. Registered: April 15, 2015. Priority date: February 04, 2013. Assignee: LLC "TEKHMASHSERVIS".
6. V. V. Pankov, V. M. Bukin, S. V. Pankov, and I. G. Bogorodsky. *Method for determining the shape of a weld seam surface reference standard*. Russian Patent RU

2709177. Registered: December 16, 2019. Priority date: September 14, 2018.

Assignee: LLC "TEKHMASHSERVIS".

7. V. V. Pankov, S. V. Pankov, V. M. Bukin, and I. G. Bogorodsky. *Method for assessing a welder's qualification*. Russian Patent RU 2569276. Registered: October 26, 2015. Priority date: April 03, 2014. Assignee: LLC "TEKHMASHSERVIS".
8. V. V. Pankov, V. M. Bukin, S. V. Pankov, and P. A. Kryuchkov. *Device for surface quality control of a weld seam*. Russian Patent RU 2550673. Registered: April 10, 2015. Priority date: March 25, 2013. Assignee: LLC "TEKHMASHSERVIS".
9. V. V. Pankov, S. V. Pankov, and V. M. Bukin. *Mobile scanner for surface quality assessment of a weld seam*. Russian Patent RU 2644617. Registered: February 13, 2018. Priority date: June 21, 2016. Assignee: LLC "TEKHMASHSERVIS".
10. V. V. Pankov, V. M. Bukin, S. V. Pankov, and I. G. Bogorodsky. *Method for tracking and ranking welder qualifications*. Russian Patent RU 2763708. Registered: December 30, 2021. Priority date: November 13, 2020. Assignee: LLC "TEKHMASHSERVIS".
11. V. V. Pankov, S. V. Pankov, and I. G. Bogorodsky. *Method for calibrating a laser scanner for surface quality assessment of a weld seam*. Russian Patent RU 2821171. Registered: June 17, 2024. Priority date: November 20, 2023. Assignee: LLC "TEKHMASHSERVIS".