Digital 3DLD Technology for Objective Evaluation of Welder Qualification and Its Application at the ARC CUP IWC International Welding Competition

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ABSTRACT

This paper presents a digital technology for evaluating practical welding skills based on 3D laser diagnostics of weld surface geometry (3DLD). The technology compares the real weld surface with a virtual defect-free reference profile calculated using the fundamental Laplace capillarity equation. Welder qualification is expressed through the WQI (Welder Qualification Index), an integral criterion quantifying deviations of the real weld profile from the reference corridor.

The 3DLD technology was first applied at the ARC CUP IWC International Welding Competition (Shanghai, 2017) and was officially included in the Technical File in 2018–2019. The paper presents examples of weld evaluation, comparison with traditional expert assessment, and visualization of weld surface deviations.

It is demonstrated that 3DLD provides objective, reproducible, and automated evaluation of practical welding skills, eliminates subjectivity, and enables digital ranking of welders in national and international competitions.

Keywords: 3DLD; digital evaluation of welding skills; virtual reference profile; Laplace equation; WQI; laser scanning; ARC CUP IWC; digital weld replicas.

1. INTRODUCTION

Current regulatory documents do not contain objective criteria for evaluating practical welding skills. In practice, the assessment of a welder's performance is based on subjective expert visual inspection of the Test Piece (TP) — the welded control specimen. This approach is widely used in welding competitions.

However, the traditional method has several significant drawbacks:

- subjectivity of expert judgement,

- low reproducibility of evaluation results,
- impossibility of comparing results obtained by different expert teams,
- low productivity due to the use of mechanical measuring tools.

The 3D laser diagnostic technology (3DLD), developed by Russian engineers, provides a quantitative evaluation of a welder's practical skills based on the geometry of the weld bead formed by the welder. The method compares the real weld surface with a defect-free reference corridor calculated using the fundamental Laplace capillarity equation and boundary conditions defined by standards (GOST, ISO) or customer requirements.

The deviation of the weld surface from the reference corridor is expressed through the Welder Qualification Index (WQI), which is calculated automatically.

2. 3DLD Technology

2.1 Scientific Basis

The geometry of a weld bead formed during fusion welding is determined by a complex interaction of physical processes, including the behavior of molten metal under heat input, interfacial surface tension, and gravitational forces.

The fundamental assumption of the 3DLD method is that any surface defects—dimensional deviations in width or height, pores, blowholes, cracks breaking through to the surface, overlaps, undercuts, and other imperfections—lead to measurable deviations of the real weld surface from the defect-free reference profile.

The reference profile of the weld surface is calculated using a physical-mathematical model [1, 2]. The model is based on the scientific hypothesis that interfacial surface phenomena and capillary equilibrium play a dominant role in forming the geometric profile of a weld bead during fusion welding [3, 4].

The calculation of the defect-free reference profile is based on the fundamental Laplace capillarity equation (Formula 1), which describes hydrostatic equilibrium under the combined action of surface tension and gravity.

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

Where:

- **K** – curvature of the surface
- $\mathbf{P_0}$ – excess pressure at the reference point (expressed in units of liquid column height)
- **h** – height above the reference point
- $\mathbf{a_k}$ – capillary constant

When welding in different spatial positions (PA, PB, PC, PF, PE, PD), the influence of gravity on weld formation changes significantly. For example, in the PC position, molten metal tends to flow downward, causing characteristic changes in bead shape. The Laplace model accounts for these effects and allows generating reference profiles for any welding position (Figure 1).

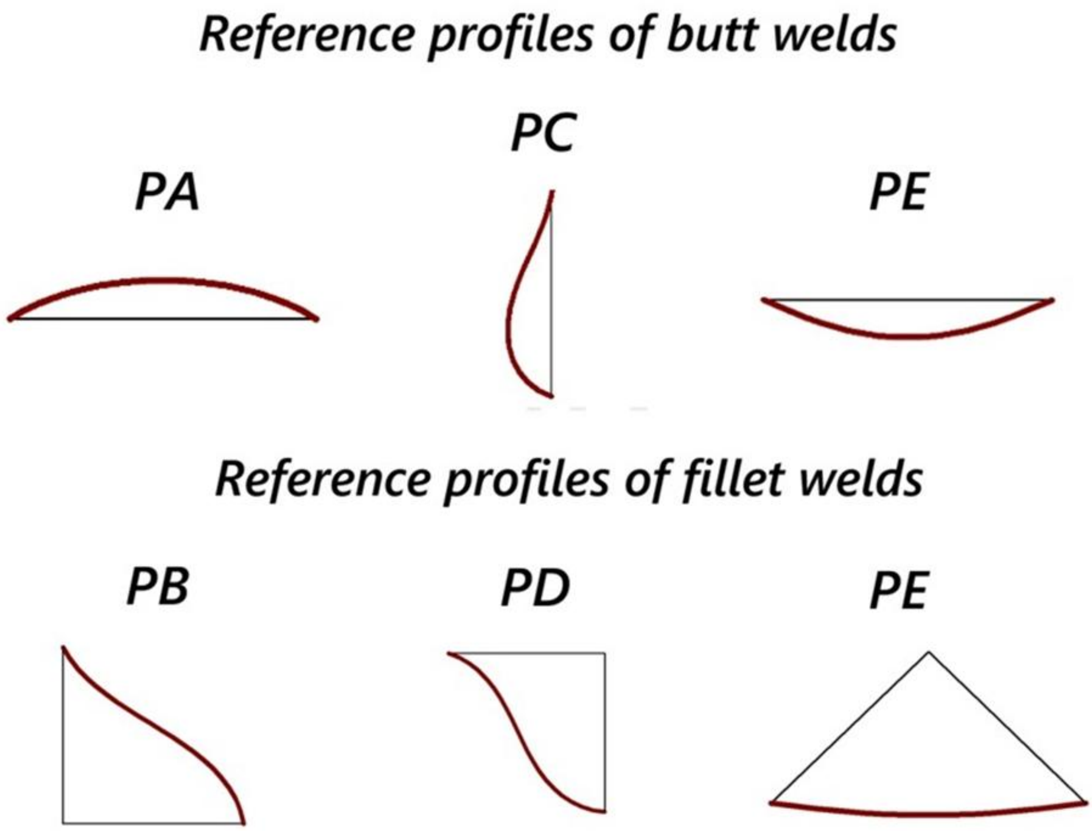


Figure 1. Reference profiles of butt welds (a) and fillet welds (b) in various welding positions.

When welding non-rotatable pipe Test Pieces in PH and H-L045 positions, the reference profile changes continuously along the circumference. The 3DLD technology generates a reference profile for each scanned cross-section, ensuring correct comparison between the real weld surface and the defect-free reference.

2.2 Principle of Operation and Capabilities of the 3DLD Technology

According to regulatory documents, the geometric parameters of a weld bead are defined by nominal values with specified tolerances. Therefore, weld quality may be evaluated either by nominal dimensions or by the allowable tolerance range of weld height and width (Figure 2).

The Welder Qualification Index (WQI) is calculated based on the deviation of the real weld surface area from the defect-free reference profile. The calculation is performed according to Formula 2.

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

Where:

- **WQI** — Welder Qualification Index;
- **N** — number of measured cross-sections;
- **Sstand** — area of the reference profile;
- **Sdeviat** — deviation area of the j-th cross-section.

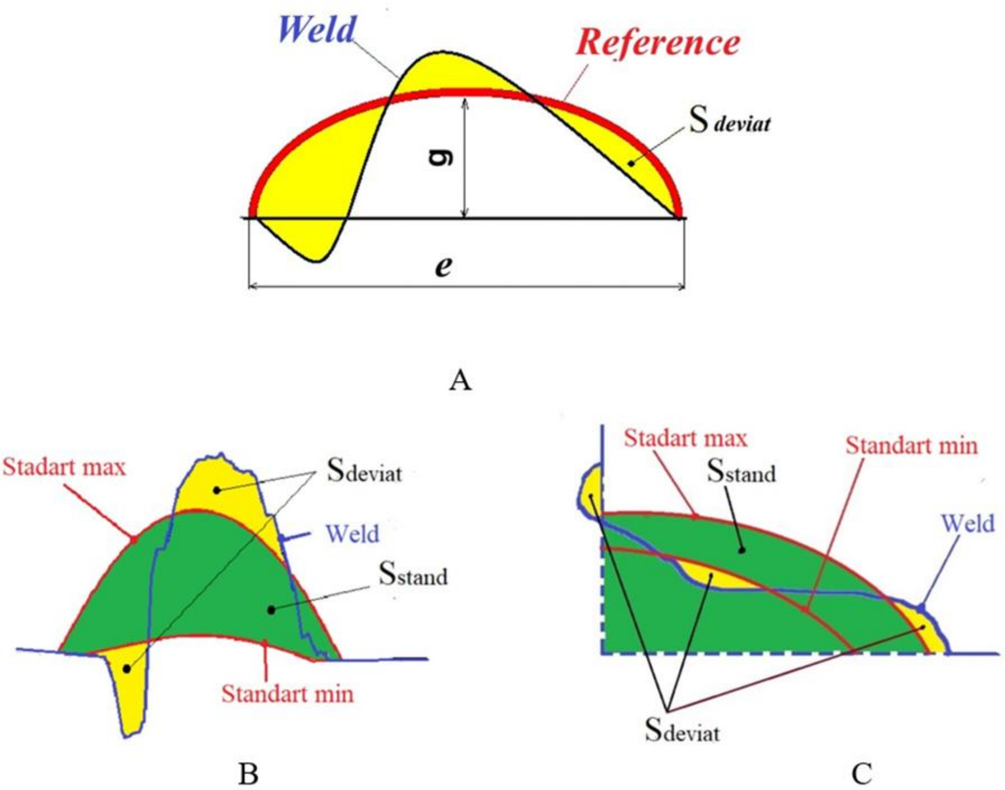


Figure 2. Evaluation of weld quality using a defect-free reference (A) and tolerance-based reference profiles (B, C).

The 3DLD technology provides an integral digital criterion characterizing a welder's practical skills — a criterion that does not exist in current standards. This is especially important in welding competitions, where objective determination of winners and ranking of participants is required.

The technology enables the creation of a unified national and international system for welder certification, forming a digital standard. It also allows generating a digital passport for each welder, containing complete information about all Test Pieces welded throughout their professional career.

In the context of Industry 4.0, digital weld evaluation becomes part of intelligent manufacturing systems, enabling the creation of digital twins of welded joints.

2.3 Equipment (Hardware–Software Complex) of the 3DLD Technology

The 3DLD technology is based on high-precision triangulation laser metrology. Measurement reproducibility is ensured by full automation and elimination of human factors.

The absolute measurement error of weld bead height does not exceed **0.05 mm**, which significantly surpasses the accuracy of mechanical gauges used in traditional visual inspection. The uncertainty of WQI calculation is less than **0.3 mm**, confirming the high reliability of practical skill evaluation using 3DLD.

Laser scanners are used for plate Test Pieces and for the outer and root surfaces of pipe welds. A triangulation laser sensor moves along the weld bead and scans the surface of the Test Piece (Figure 3).

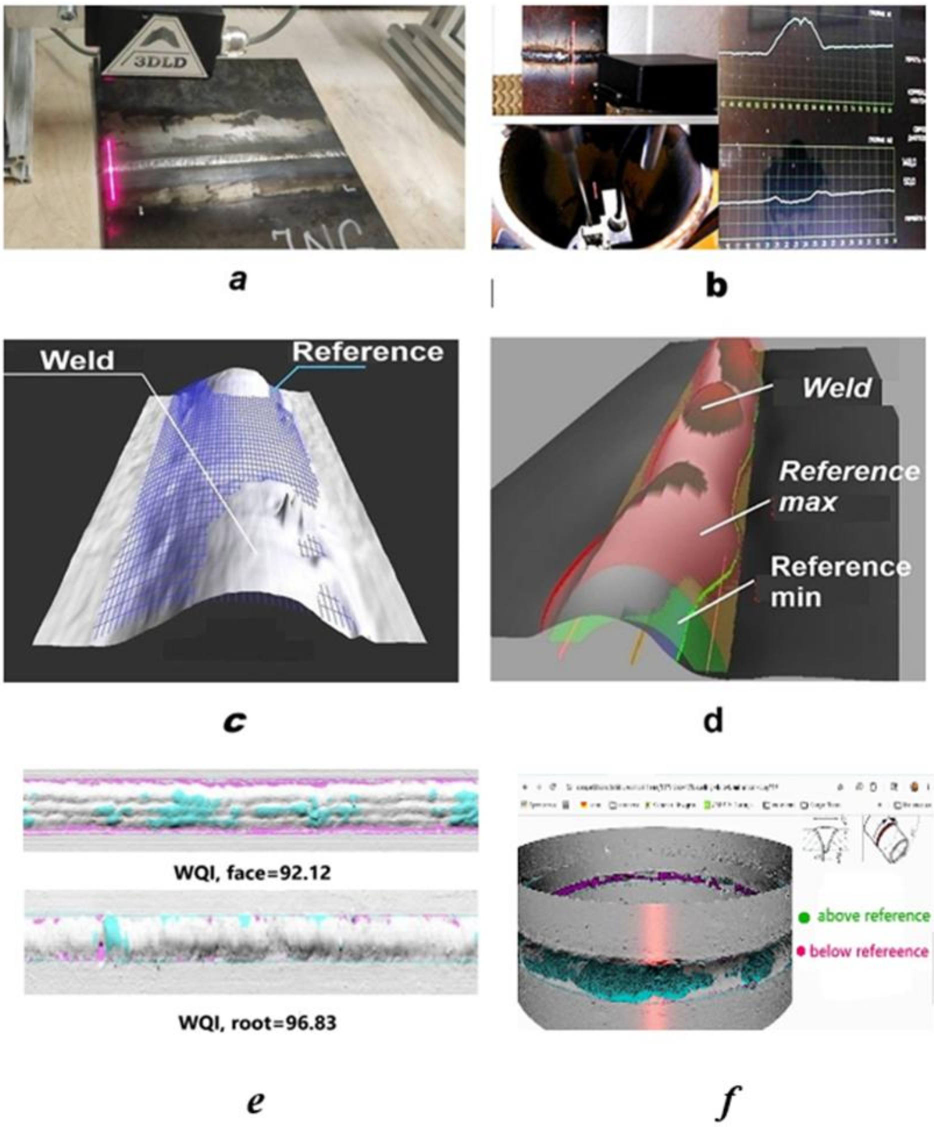


Figure 3. Laser scanners for plates (a), outer and root pipe welds (b); alignment of the reference profile with the digital replica calculated by nominal dimensions (c) and tolerance limits (d); visualization of deviations (e, f). ● above reference ● below reference.

The 3DLD software processes scan data, constructs 3D replicas of the weld surface, calculates defect-free reference profiles, aligns the replica with the reference, visualizes deviation maps, computes the WQI, and generates a complete evaluation report.

3. Application of the 3DLD Technology at the ARC CUP IWC International Welding Competition

The 3DLD technology was used as an independent digital method for determining winners and ranking participants at the ARC CUP IWC International Welding Competitions held in 2017, 2018, and 2019.

In 2017, the technology was applied in a test mode and used only for evaluating pipe Test Pieces welded using MMA 111 and GMA 135 processes. In 2019, the evaluation was expanded to all competition categories, including MMA 111, GMA 135, GTA 141, and OFG 311.

During the competitions, three 3DLD operators scanned and evaluated more than **500 Test Pieces**, determining winners in all categories and generating a complete ranking of all participants. The evaluation was performed in parallel with the traditional expert committee consisting of 20 highly qualified welding experts.

The full cycle of scanning and processing a single Test Piece takes approximately **3 minutes**, which significantly increases the productivity of the evaluation process compared to traditional visual inspection. The scanning results were displayed online on a large screen (Figure 4) in real time and could be broadcast over the Internet.

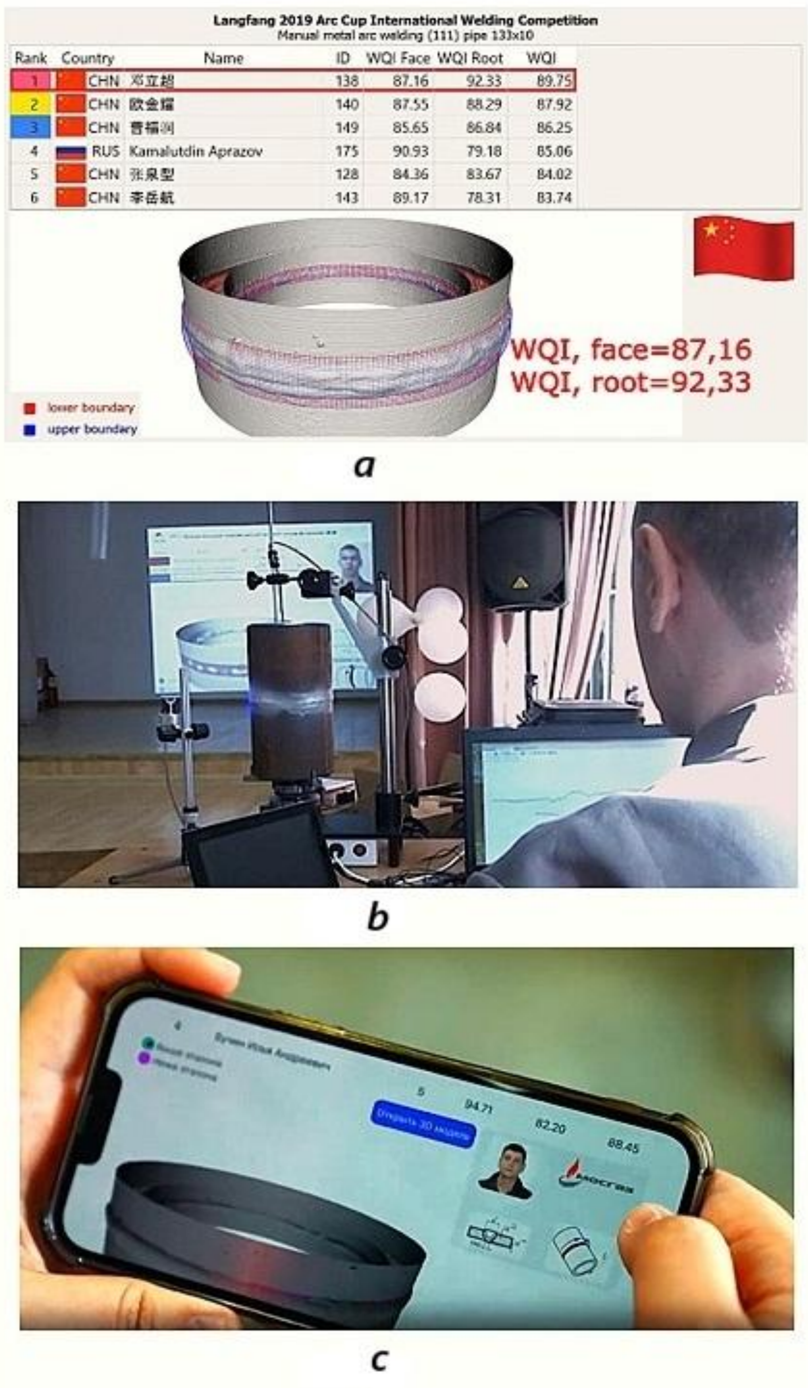
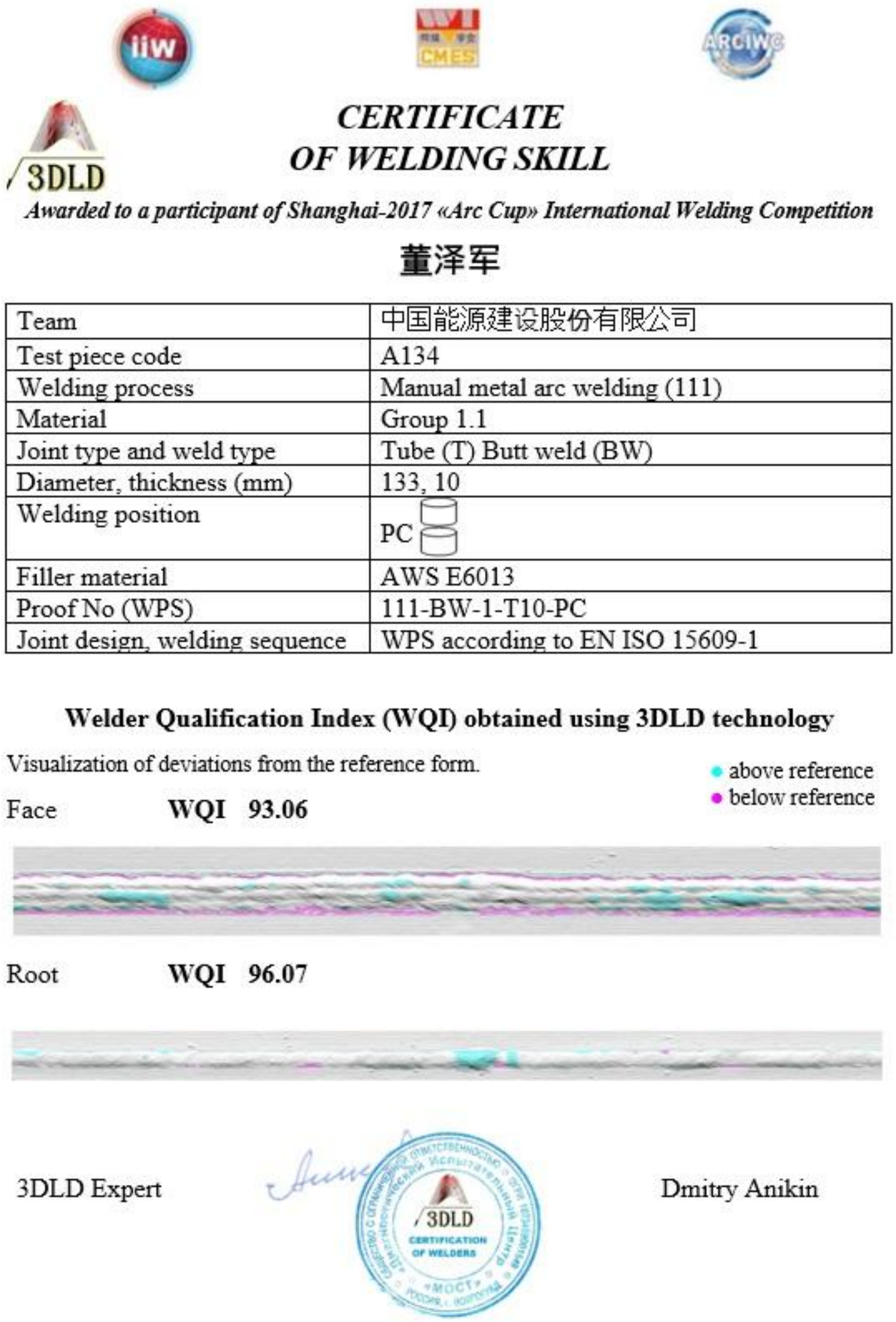


Figure 4. Welding Show:(a) real-time evaluation window displaying the pipe weld joint quality results and the welders' ranking;(b) demonstration broadcasted to a large screen and via the Internet;(c) visualization of the digital weld replica and evaluation criteria on a mobile device screen

Immediately after scanning, each welder received a personalized certificate (Figure 5) containing detailed information about the Test Piece and digital replicas of the face and root surfaces of the weld, including visualization of deviations from the defect-free reference profile.



CERTIFICATE OF WELDING SKILL

Awarded to a participant of Shanghai-2017 «Arc Cup» International Welding Competition

董泽军

Team	中国能源建设股份有限公司
Test piece code	A134
Welding process	Manual metal arc welding (111)
Material	Group 1.1
Joint type and weld type	Tube (T) Butt weld (BW)
Diameter, thickness (mm)	133, 10
Welding position	PC
Filler material	AWS E6013
Proof No (WPS)	111-BW-1-T10-PC
Joint design, welding sequence	WPS according to EN ISO 15609-1

Welder Qualification Index (WQI) obtained using 3DLD technology

Visualization of deviations from the reference form.

● above reference
● below reference

Face **WQI 93.06**

Root **WQI 96.07**

3DLD Expert Dmitry Anikin

Figure 5. Example of a participant’s certificate with visualization of deviations from the reference profile (face and root surfaces).

Thus, the 3DLD technology significantly increases the transparency and spectator appeal of welding competitions, maintaining the intrigue of determining the winner until the very end.

3.1 Evaluation Results (Comparison of Chinese and Russian Participants)

Due to space limitations, the comparison of evaluation results and rankings for ARC CUP 2017, 2018, and 2019 is provided only for MMA 111 pipe Test Pieces welded in the horizontal position (PC) (Table 1).

Table 1. *Comparison of Welder Qualification Index (WQI) values for MMA 111 pipe Test Pieces (PC position) at ARC CUP 2017–2019.*

Rating	ARC CUP 2017		ARC CUP 2018		ARC CUP 2019*	
	Team	WQI average	Team	WQI average	Team	WQI average
1	China 董泽军	94.57	China 魏朋	94.96	China *邓立超*	89.75
2	Russia *Sergei Silantev*	94.48	China 辛崇宝	92.71	China 欧金耀	87.92
3	China 王小玲	92.87	China 朱得银	91.90	China 曹福润	86.25
4	*China 冷康龙*	*92.72*	*China 陈一鸣*	*91,13*	*Russia Kamalutdin Aprazov*	*85.06*
7	*Russia Linar Shaikhinurov*	*91.21*	*Belarus Ratnikau Eduard*	*90.17*	*China 秦彬彬*	*83.60*
17	*Russia Vitalii Lobzhanidze*	*87.76*	*China 曹恒金*	*88.08*	*China 王大勇*	*80.88*

***Note:** The height tolerance requirements for the root bead are stricter (g = 0–1.0 mm) compared to ARC CUP 2017 and 2018 (g = 0–1.5 mm).

Analysis of the data shows that the differences in WQI values among the winners are fractions of a percent — a level of precision impossible to achieve using subjective expert evaluation. It is also impossible to construct a complete ranking of all participants using traditional methods.

The WQI values of winners and participants at ARC CUP 2019 were lower than those at ARC CUP 2017 and 2018 due to stricter root height tolerance requirements (as noted in Table 1).

The organizers did not provide the 3DLD team with the results of expert evaluation. Therefore, verification of the digital results was performed using the WQI values of Russian welders who were officially announced by the organizers as winners among foreign participants at ARC CUP 2017 *(Table 2)*:

- **Sergei Silantev (Russia)** — WQI = 94.48 → 1st place among foreign participants; 2nd place overall.
- **Linar Shaikhinurov (Russia)** — WQI = 91.21 → 2nd place among foreign participants; 7th place overall.
- **Vitalii Lobzhanidze (Russia)** — WQI = 87.76 → 3rd place among foreign participants; 17th place overall.

The digital evaluation results fully matched the expert committee's conclusions, confirming the correctness of the 3DLD methodology.

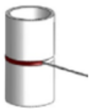
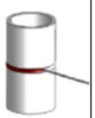
In 2019, WQI evaluation was performed for all Test Pieces in all categories. Comparison of WQI values revealed significant differences between pipe and plate Test Pieces welded using the same welding process.

For example, it is commonly assumed that welding a pipe in non-rotatable positions (PH and H-L045) qualifies a welder to perform any butt or fillet welds on plates. Therefore, one might expect that the best pipe welder would also be the overall winner.

However, the WQI values objectively demonstrated that the winner in the pipe category (WQI = 89.75) ultimately placed fourth in the overall ranking, while the overall champion welded the pipe Test Piece with a lower WQI (87.92).

This highlights the necessity of conducting separate evaluations for each type of Test Piece and welding position.

Table 2. *Comparison of WQI values and rankings for MMA 111 welders across different Test Piece types.*

T; BW; PC 	WQI average **89.75**	Rating **1**	P; BW; PF 	WQI average **85.80**	Rating **22**	P; FW; PE 	WQI **89.13**	Rating **32**	WQI average **88.22**	Rating total **4**
T; BW; PC 	WQI average **87.92**	Rating **2**	P; BW; PF 	WQI average **88.72**	Rating **11**	P;FW; PE 	WQI **98.40**	Rating **1**	WQI average **91.68**	Rating total **1**

4. Inclusion of the 3DLD Technology in the ARC CUP IWC Technical File (2018–2019) and Prospects for Its Application in Welding Competitions

After its successful application in 2017, the 3DLD technology was officially included in the Technical File of the ARC CUP IWC competitions in 2018–2019. This became possible thanks to the support of the competition organizers and the personal involvement of Dr. Liu Zhenning, who paid close attention to the scientific foundations of the 3DLD technology. Dr. Liu provided comprehensive support for the application of the 3DLD technology during the ARC CUP IWC competitions and made a significant contribution to introducing the international welding community to the capabilities of this innovative technology (Figure 6).

In this regard, the 3DLD technology development team expresses its deepest gratitude to Dr. Liu Zhenning and looks forward to further collaboration. This partnership aims to popularize the ARC CUP competitions, establish the Chinese National Registry of Practical Welding Skills, the BRICS Regional Welder Registry, and, ultimately, an International Welder Registry. Furthermore, the team envisions joint efforts in developing an international standard for digital technology in weld shape and surface quality assessment.

Figure 6. Head of the ARC CUP IWC Organizing Committee, Dr. Liu Zhenning, reviewing the 3DLD technology.

Since 2019, the 3DLD technology has been protected by seven Russian patents [6-12]. The 3DLD system trademark has been registered, and a voluntary system for evaluating welders' practical skills has been officially registered. The equipment has been substantially upgraded, enabling scanning of the root surface of welds in pipe Test Pieces with diameters starting from 57 mm. A mobile scanner has been developed for evaluating welds directly at industrial sites. The algorithm used for conducting welding competitions has been updated.

At present, interregional welding competitions are held in the Russian Federation using the 3DLD technology, involving cities located thousands of kilometers apart [5]. Competitors weld pipe Test Pieces at their own facilities, after which the scanning results are transmitted to a central server, where winners and participant rankings are determined automatically.

This approach significantly reduces costs, expands the audience, and enables the creation of an electronic registry for evaluating welders' practical skills.

The application of the 3DLD technology makes it possible to determine winners of welding competitions of various levels and to compare their results with those of ARC CUP IWC winners, effectively turning any competition into a remote mini world championship.

5. Conclusion

The developed digital technology for evaluating the quality of the weld surface (3DLD) is based not on traditional visual and measuring inspection (VT) of defects, but on assessing deviations of the weld surface geometry from a defect-free reference profile. The scientific approach, based on the fundamental Laplace capillarity equation, makes it possible to evaluate all surface defects of a weld bead using a single integral numerical criterion and allows:

• to define a welder's practical skills as the ability to form the face and root surfaces of a weld bead with specified dimensions, from specified materials, and in a specified spatial position;

• to perform automated evaluation of welders' practical skills, eliminating expert subjectivity;

• to create a unified database of welders' practical skills based on their electronic passports, containing the results of Test Piece evaluation throughout their professional careers, including digital twins (replicas) of the welds they have produced;

• to visualize deviations of the weld surface geometry from reference values;

• to compare the results of welding competition participants of different levels and correlate them with the results of ARC CUP IWC winners;

• to develop a digital standard for weld surface geometry.

The experience of applying the 3DLD technology at ARC CUP IWC has shown that digital evaluation of welders' practical skills can be successfully used and can replace traditional expert methods.

Supplementary Materials

Video demonstrations illustrating the operating principles, practical application, and automated evaluation process of the 3DLD technology are available online:

- **Video 1: 3DLD Technology on ARC CUP** — Demonstrates the deployment and application of the technology at the international welding competition. URL: https://youtu.be/k045JCqVVWo
- **Video 2: Principal of 3D Laser Diagnostics of Weld Shape** — Explains the core principles of the 3DLD method, surface scanning, and the elimination of the human factor. URL: https://youtu.be/ndlOKqTJgW8

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