TECHNOLOGY OF MANUFACTURING HIGH-QUALITY WELDED TUBES FROM CORROSION-RESISTANT STEEL IN UKRAINE

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Welded thin-walled tubes are widely applied in different industrial sectors owing to a number of their advantages, compared to seamless tubes. The paper describes the experience of mastering in Ukraine manufacturing of thin-walled small diameter tubes from TR 316L steel by two variants: with weld metal deformation by rolling-off and without deformation. Longitudinal welds are made by TIG welding. The paper gives the results of comprehensive testing of manufactured tube samples, which are indicative of the fact that they are not inferior to seamless tubes as to their technological and mechanical properties, corrosion resistance and metallographic characteristics, and are even superior to them by a number of parameters. They meet the requirements of the respective ASTM and EN standards. 10 Ref., 4 Tables, 4 Figures.

Keywords: *welded tube, technology, argon-arc welding, weld, quality, mechanical properties, intercrystalline corrosion, nuclear steam condensers*

Welded superthin-wall tubes from corrosion-resistant steel of TR 321/321H, TR 304/304L, TR-316L/316Ti grades to standards [1–3] are widely applied abroad in heat-exchanger equipment, in particular in turbine condensers in nuclear and heat generation, and in chemical industry. Domestic welded tubes supplied earlier to [4] were significantly inferior to them by a number of reasons: lower production standards because of unsatisfactory quality of the weld, lack of equipment for manufacturing, heat treatment and nondestructive testing of extended tubes, deficit of quality strip blank of up to 1 mm wall thickness, etc.

Historically, this resulted in lack of trust for welded tubes from corrosion-resistant steels, particularly, molybdenum-containing steels of 03Kh17N13M3 and 08Kh17N13M2T type. Therefore, in a number of cases, preference was given to other materials: seamless tubes from less expensive material (copper, copper-nickel alloys) or general purpose seamless tubes from corrosion-resistant steel of 08–12Kh18N10T type, supplied to different GOSTs. However, in NPP condensers replacement of tubes for welded ones from molybdenum-containing TR 316L/316Ti steels or of titanium was performed long ago practically all over the world [1, 5, 6]. The process of these tube manufacturing is highly efficient, and ensures lowering of welded tube cost compared to seamless tubes from similar steel by 30–35 %. Up to now, however, information on the quality of Ukrainian tubes, produced under modern conditions, remained rather limited. Therefore, in this work, comprehensive studies of welded tubes from a local manufacturer have been performed.

Under production conditions of ALFA-FINANS Ltd. (Dnepropetrovsk), a technology has been developed, by which electrically welded straight-seam tubes of 20 mm diameter with 0.8 mm wall thickness and up to 15 m length are manufactured from strip blank from corrosion-resistant steel TR 316L by two variants: with weld deformation (by rolling-off) in keeping with the requirements of ASTM A 249 standard (variant «r»), and without weld deformation (variant «n») that is allowed by local normative documents. Inert-gas nonconsumable-electrode welding (TIG), namely argon-arc welding, with weld factor $V = 1$ is applied.

Modern technology of welding fabrication by TIG process emerged at the beginning of 1940s and was used for welding aluminium and magnesium alloys [7]. This method, however, was the most profoundly perfected for welding corrosion-resistant steels and alloys. In TIG welding the electric arc is used for heating and melting metal edges, while shielding gas (argon), which is supplied from the gas nozzle, is fed into the welding zone, as well as on the tube inner surface and protects the weld from contamination penetration from the outside that promotes good penetration of the weld root. This welding process was later on called argon-arc welding. The electrode/cathode proper, made from refractory material (tungsten), is located in the center of the gas nozzle at a certain distance from the edges of metal being welded. Under the modern conditions of electric-welded tube manufacture, welding is performed automatically by three cathodes, ensuring melting, formation and maintaining of the so-called metal «pool» with uniform filling along the entire weld depth, without feeding any filler materials into the welding zone. Application of multiarc welding of the longitudinal weld in a chamber with protective atmosphere (argon) ensures its high quality, as in this case the parent metal composition is preserved completely in the weld structure. The advantage of argon-arc (TIG) welding is very high quality of the weld, absence of spatter, practical absence of slags or impurities. This process is highly versatile and allows application of variants of different current and gas mixture settings in welding austenitic, molybdenum, as well as ferritic steel grades with 0.4 to 3.0 mm metal thickness.

Tube manufacturing technology. Tube manufacturing technology consists of the following operations:

1. In-coming inspection of the quality of fed cold-rolled coiled stock, which was pre-cut in longitudinal cutting machine that includes random visual inspection, continuous monitoring of geometrical dimensions and verification of compliance of quality certificate data.

2. Manufacturing tubes in electric-weld tube mills TESA 5-25 and TESA 10-60 (Italy) (Figure 1) includes the following sequence of operations: strip forming in the forming mill; edge welding in the welding assembly; eddy current testing of the quality of weld and HAZ; grinding outer and/or rolling-off the inner flash and tube calibration.

3. Tube heat treatment in shielding atmosphere (hydrogen).

4. Eddy current testing of tube body quality.

5. Grinding the tube outer surface as required by the user.

6. Tube marking using automatic jet printer.

7. Tube cutting up to specified length in flying shears.

8. Tube acceptance by QID, performance of testing specified by standards.

9. Tube packing.

10. Executing a quality document and required shipping documentation; tube shipping to user in keeping with the order.

The above-mentioned electric-weld tube mills allow manufacturing tubes of 5.0 up to 60.3 mm

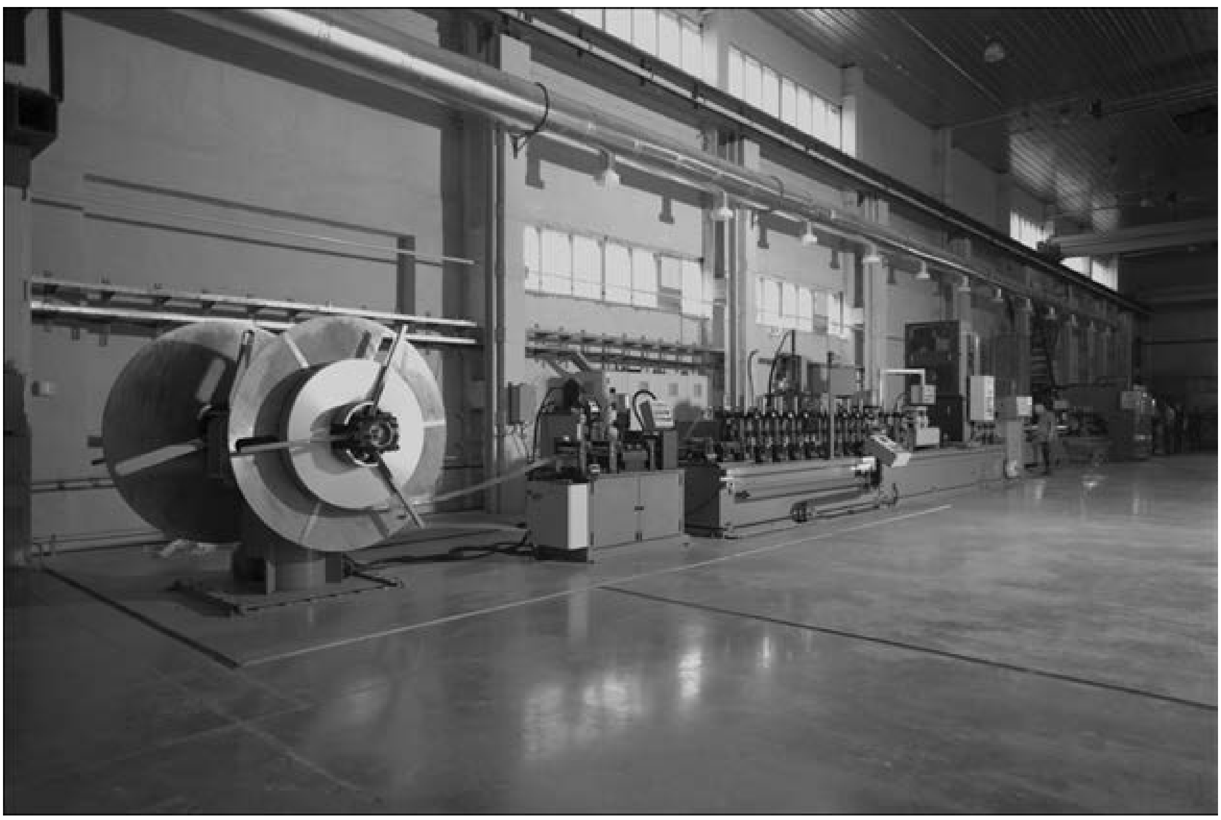

Figure 1. Appearance of electric-weld pipe line (mill 10-60) in the tube manufacturing shop

Table 1. Composition of studied samples of initial strip and ∅20 × 0.8 mm welded tubes from TR 316L steel (wt.%)

Sample	C	Cr	Mn	Mo	Ni	P	S	Si
Strip	0.011	16.79	1.18	1.91	10.05	0.042	0.0099	0.477
To certificate	0.012	16.63	1.11	2.092	10	0.043	0.001	0.51
Tube «r»	0.015	16.77	1.17	1.94	10.07	0.044	0.012	0.494
Tube «n»	0.016	16.89	1.19	1.91	9.94	0.044	0.012	0.49
Norms of EN 10217-7 (1.4404)	max 0.03	16.5–18.5	max 2	2.0–2.5	10–13	max 0.045	max 0.015	max 1
Norms of ASTM A (TR 316L)	max 0.03	16–18	max 2	2–3	10–14	max 0.045	max 0.030	max 1

Notes. 1. Measurement error by molybdenum is equal to 0.08 %; in finished products deviation by molybdenum of ±0.1 % is allowed as per EN 10217-7. 2. Measurement error by nickel is equal to 0.11 %; in finished products deviation by nickel of ±0.15 % is allowed as per EN 10217-7.

outer diameter inclusive with 0.4 to 3.0 mm wall thickness and up to 15 m length.

All over the world welded tubes for condensers are most often supplied to standard [2]. Tubes studied in this work have been manufactured and tested in keeping with the main requirements of this standard. For illustration purposes evaluation of the obtained results was performed, allowing for European norms [8], as well as other norms, currently available for this kind of tubes.

As a set of high requirements are applied to tubes, we will include them into the category of precision items. Steel TR 316L and its analogs 03Kh17N14M3 and 1.4404, by the totality of their corrosion resistance, technological and thermophysical characteristics are regarded to be optimum for condenser and heat exchanger equipment, operating in aggressive media [6, 9, 10].

Investigations were performed at the facilities of Testing Center of SE «NITI», accredited for technical competence to DSTU ISO/IEC 17025:2006, for which purpose an integrated approach was applied. First, direct in-coming inspection of the initial blank (strip) for compliance to technical requirements of ASTM A 240 standard for thin strip and sheet was performed.

Analysis of chemical composition. It was established that metal belongs to steel of TR 316L grade to ASTM and its analog 1.4004 to EN norms (Table 1). Metal has rather low carbon content that is beneficial for corrosion resistance. Here, as a result of processing, carbon content in tubes rose slightly, compared to strips. It should be noted that phosphorus content is on the upper level, and content of expensive nickel and molybdenum is on the lower limit.

Table 2. Geometrical dimensions of studied ∅20 × 0.8 mm tubes

Manufacturing variants	Outer diameter D_{out}, mm	Wall thickness S, mm
«r»	19.94–20.01 19.93–20.02	0.77–0.79 0.78–0.80
«n»	19.93–20.03 19.94–20.02	0.77–0.79 0.78–0.80
Norms of ASTM for this size	19.90–20.11	0.72–0.88

Note. Tube ovality is 0.07–0.10 mm at norms from +0.11 up to −0.10 mm.

Visual inspection of tubes. Examination without magnifying devices showed that the surface is light-coloured, clean, and no inadmissible defects of the type of cracks, deep scratches, films, sticking, cavities, delaminations, etc. have been detected. Outer surface is after fine abrasive treatment (grinding), outer flash and weld are not visualized. The following is observed on the inner surface:

• variant «r» — a thin weld with deformation trace (inner flash is absent), and a longitudinal trace on the tube diametrally opposite side, which, most probably, formed from mechanical contact with the mandrel or gage at weld rolling-off;

• variant «n» without weld deformation — thin weld with inner flash height of up to 0.1 mm, diametrally opposite side of the weld is clean, without any speciall features.

Roughness Ra on the inner (working) surface at the requirement of not more than 2 μm is equal to: variant «r» — from 0.31 up to 0.76 μm (av. 0.56 μm), variant «n» — from 0.27 up to 1.34 μm (av. 0.63 μm).

Accuracy of tube geometrical dimensions. Measurement of diameter and wall thickness confirmed the high manufacturing accuracy (Table 2).

Macro- and microstructure were studied in the base metal, near-weld HAZ and weld zone, as well as in the strips.

Blank metal is clean as to non-metallic inclusion content. Evaluation of inclusions in the strip was performed to DSTU 3295–95 — scale 3 for

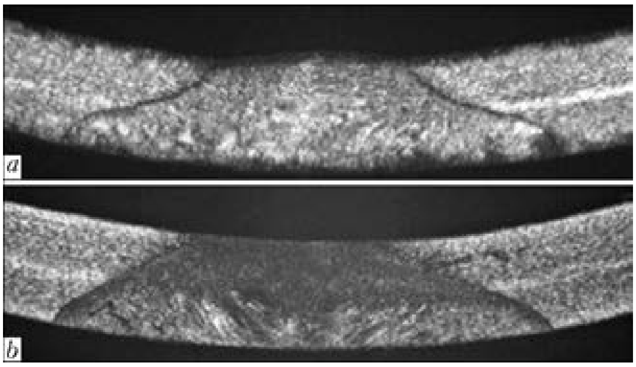

Figure 2. Macrostructure (×12) of welded joints of ∅20 × 0.8 mm tubes from TR 316L steel: *a* — undeformed weld; *b* — deformed weld

evaluation of metal with wall thickness below 2.5 mm. Content of isolated uniformly distributed globular-type inclusions is up to point 1. Strip microstructure is fine-grained, grain size is 9–10, with pronounced striation, characteristic for high-alloyed steels.

Tube macrostructure at 10-fold magnification does not have any defects in the form of pores, cracks, lacks-of-penetration, foreign inclusions, melts-through, etc. (Figure 2). Inner flash in the sample with undeformed weld is small — up to 0.1 mm (~0.08–0.09 mm, see Figure 2, *a*). Rolling-off changes weld geometry and it becomes wider (Figure 2, *b*).

The following is clearly visible in the microstructure:

- weld with the morphology of cast structure and presence of a small fraction of ferrite component;
- small (up to 200 μm) near-weld zone with slight (by 1 point) coarsening of the grain, compared to base metal;
- base metal with recrystallized grain 7–8 (grain in the base metal, coarsened only slightly, compared to initial strip, as a result of the performed heat treatment of tubes).

Tubes produced by two studied variants, passed all process testing, namely: flattening to achieve the specified distance H = 7.2 mm between the surfaces being flattened (weld located at 90° angle or in 3 o'clock position); complete flattening by ASTM procedure; static bending of tube sample (branch-pipe) through 90° around mandrel D_{man} = 60 mm; expansion up to outer diameter increase by 10 % by a mandrel with cone angle of 30°; flanging with 90° flanging angle.

After process testing there were no defects or fractures in the form of cracks, tears, lacks-of-penetration or overlaps.

Mechanical properties of initial strip and tubes were determined by tensile testing.

Results confirmed the strip compliance to ASTM A 240 standard for TR 316L steel (norm values are given in parenthesis): ultimate strength σ_t = 651–661 MPa (not less that 485), yield point $\sigma_{0.2}$ = 343 MPa (not less than 170), $\sigma_{1.0}$ = 379–381 MPa, relative elongation δ_{50} = = 42 % (not less than 40 %), δ_5 = 48–48.5 %.

Mechanical testing of tubes showed that they have a rather high level of strength and ductility properties. Compared to strip properties, the tubes showed higher values of relative elongation and lower values of ultimate strength and yield point that is due to slight coarsening of the grain as a result of tube heat treatment. Based on results of tensile mechanical testing tube metal corresponds to the norms of standards ASTM A 249 for steel of TR 316L grade and EN 10217-7 for steel-analog 1.4404 (Table 3).

For welded tubes an important criterion of their quality in terms of weld strength is their ability to withstand the above technological tests for flattening, expansion and bending. A not less important criterion is *rupture of transverse ring samples* with weld location at 90° to the axis of force application or in 3 o'clock position (Table 4).

Results confirm that tubes with a rolled-off weld have higher welded joint strength: rings fractured not through the weld, but through the base metal, i.e. they stood testing for ring rupture without anomalies.

Testing for intercrystalline corrosion (ICC) was performed by AMU GOST 6032 method by

Table 3. Mechanical properties of ∅20 × 0.8 mm tubes from TR 316L steel after tensile testing

Variant	σ_t, MPa	$\sigma_{0.2}$, MPa	$\sigma_{1.0}$, MPa	δ_{50}, %	δ_5, %
«r»	617 623	349 347	370 372	55 56.5	57.5 59.5
«n»	588 602	306 322	335 347	56 58.5	57 62
Norms of EN 10217-7	490–690	min 190	min 225	min 30	min 40
Norms of ASTM A 249	min 485	min 170	–	min 35	–

Table 4. Results of transverse rupture testing of ring samples to determine the strength of weld and near-weld zone

Sample	σ_t, MPa	Weld location	Fracture location
«r»	689 639 693	90° relative to applied force axis	Through base metal
«n»	650 642 673	Same	Through weld or in the HAZ (ductile fracture)

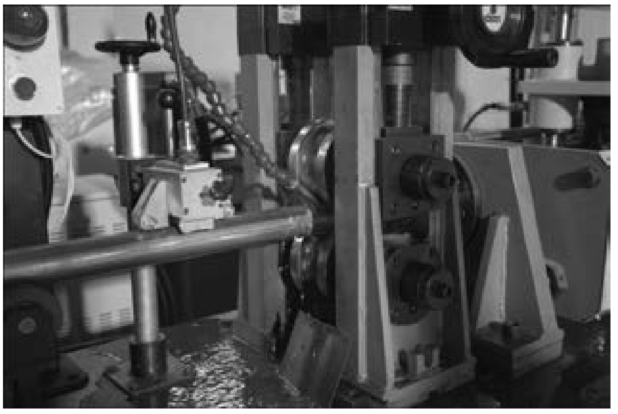

Figure 3. Eddy current flaw detector to monitor the continuity of weld and near-weld zone metal (located immediately after the welding assembly)

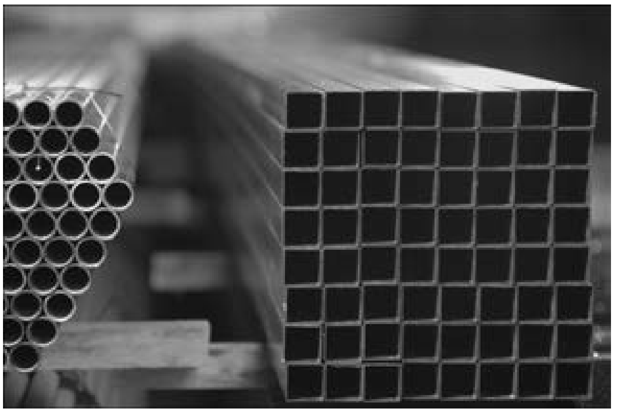

Figure 4. Kinds of standard export packing of square and round stainless steel tubes

boiling in copper sulphate solution for 8 h. According to this standard, the welded joints, deposited metal and weld metal are not subjected to provoking heating. In this case testing was performed both without the preliminary provoking heating, and in a more stringent mode with provoking preheating — 650 °C for 1 h. After that, all the samples were bent by a special method to detect possible cracks. After testing no cracks were revealed in the places of Z-shaped sample bends, either on the inner or on the outer tube surface, or in the weld and near-weld zone, or in the base metal, that is indicative of ICC resistance of tubes produced by both variants.

In this work *pitting corrosion* (PC) studies in keeping with the main postulates of GOST 9.912 and ASTM G 48 were performed as experimental ones to obtain additional comparative data on corrosion resistance of welded tube material (base metal and weld zone of the same tube). Tube samples were soaked in aggressive 10 % solution (ferrous trichloride hexahydrate ($FeCl_3{\cdot}6H_2O$)–100 g of salt per 900 cm^3 of distilled water) for 5 h at ≈20 °C (19.5 ± 0.5 °C). After soaking, the samples were washed, dried and their mass loss was assessed by weighing before and after soaking in an aggressive solution. Surface condition was also analyzed for presence, size, depth of pits and nature of their location, while paying special attention to the inner (working) surface. In keeping with the traditional concepts, it was confirmed that weld area is more prone to PC. In this case loss of mass of 0.004–0.008 g in samples with a weld is only slightly greater than loss of mass of 0.002–0.005 g in samples without a weld. However, in samples with rolled-off weld «r» mass loss of 0.006–0.008 g turned out to be greater than in samples with internal flash, i.e. without weld deformation «n» — 0.004 g. Moreover, samples with a rolled-off weld «r» demonstrated a greater susceptibility to weld pitting on the inner surface, while in samples with an unrolled weld «n» PC develops less intensively on the inner surface, but more actively over the outer surface. In base metal samples without a weld, pits are either totally absent, or are isolated shallow ones. Through-thickness pits were absent in all the cases. We can conclude that on the whole these tubes have relatively low rate of PC by the results of testing in $FeCl_3$ water solution.

NDT of welded tubes was performed with eddy current (ECT) and ultrasonic (UT) techniques.

ECT was performed in production in equipment of ALFA-FINANS, where the weld and tube body were tested in the mill line (Figure 3). Testing for longitudinal and transverse defects on the outer and inner surfaces was performed. ECT results did not reveal any defects, and 100 % of tested tubes were found to be fit.

UT was performed at NITI, for which purpose two standard samples with a rolled-off and unrolled weld were made for setting up the UT flaw detector (artificial longitudinal reflectors of «scratch» type of the depth of 10 % of nominal wall thickness). In the tested two variants of tubes «r» and «n» no defects, equivalent to artificial defects of the standard sample, were found. These tubes can be regarded as having passed UT, i.e. corresponding to specified requirements for condenser tubes.

Obtained results enable stating that welded tubes produced by ALFA-FINANS (Figure 4) are practically not inferior in any way to seamless tubes by their technological, mechanical, anticorrosion, metallographic characteristics, and they are even superior to seamless tubes in terms of accuracy of maintaining the wall thickness, both in the transverse section and longitudinally along the entire length, and geometrical dimensions simultaneously with the clean and light surface along the entire length.

Conclusions

Comprehensive testing of the metal of ∅20 × × 0.8 mm welded tubes from TR 316L steel for compliance to basic and additional requirements of standard ASTM A 249 has been performed.

Technology of manufacturing welded tubes from corrosion resistant steel in ALFA-FINANS Ltd. includes basic operations, which determine the tube quality and reliability: argon-arc (TIG) welding, manufacturing tubes with and without rolling-off the inner flash (with and without weld deformation), heat treatment in shielding atmosphere, eddy current testing of the weld and tube body with full compliance to all the procedures and recommendations of equipment manufacturer.

In terms of geometrical dimensions, the tubes correspond to manufacturer's high precision requirements with a high quality of both the inner, and the outer surfaces. Results of mechanical and technological testing revealed that mechanical properties at tube tension meet the requirements of ASTM A 249 and EN 10217-7 standards. All the samples passed flattening test (including complete back flattening), as well as flanging, expansion, static bending without formation of cracks, tears or other defects, both in the base metal, and in the weld and near-weld zone.

Metallographic examination did not reveal any inadmissible defects (lacks-of-penetration, melts-through, cracks or foreign inclusions) in the metal of weld, near-weld zone or on tube surface. Structure corresponds to requirements to precision tube grades from corrosion-resistant steel.

Tube metal is ICC-resistant. Samples from studied tubes are characterized by small mass losses as a result of testing for pitting corrosion. Tubes have passed nondestructive testing by UT and ECT techniques, and no defects were detected.

On the whole, comprehensive comparative testing demonstrated that tubes made by two variants — with and without weld rolling-off, meet the requirements of ASTM A 249 and EN 10217-7 standards. Here, tubes with rolled-off weld should be considered preferable by individual indices for critical applications.

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