**MACHINE BUILDING AND MACHINE SCIENCE**





UDC 621.791

https://doi.org/10.23947/2687-1653-2022-22-3-232-241

*Original article*

# Increasing the Durability of Butt-Welded Joints Operating under Cyclic Loads in a Biaxial Stress Field

**Yury G. Lyudmirsky[1], Valery P. Leonov[2], Semyon S. Assaulenko[1]** ✉

[1] Don State Technical University, 1, Gagarin sq., Rostov-on-Don, Russian Federation

[2] Central Research Institute of Structural Materials "Prometey" named after I. V. Gorynin of National Research Center "Kurchatov Institute", 49, Shpalernaya St., Petersburg, Russian Federation

✉ assaulenko_s@mail.ru

**Abstract**

***Introduction.*** In sheet and hull structures operating under pressure, destruction, as a rule, is localized along the transition line from the base metal to the weld metal. Methods of increasing the durability of butt-welded joints, which are aimed at reducing stress concentration and creating favorable residual compression stresses, are described.

***Materials and Methods.*** The tests were carried out on an installation for biaxial bending, which created a biaxial stress field. Factory-made coupons and samples with an additionally processed transition zone from the weld metal to the base metal were tested. The effectiveness of further processing is shown by the following methods:

– abrading;

– grit hardening;

– abrading with grit hardening;

– melting of the fusion line in argon without filler wire;

– melting of the fusion line in argon with filler wire EP-410U;

– melting of the fusion line without filler wire with plastic deformation between narrow rollers.

***Results.*** The origin, development of destruction, and its features were analyzed using different methods of further processing of joint welds. Confidence spans (95 %) of the origin and development of failures for joint welds and base metal were calculated. The efficiency of the proposed methods for further processing was evaluated.

***Discussion and Conclusions.*** An analysis of the effectiveness of methods for increasing the durability of butt-welded joints has shown that the creation of a smooth transition from the weld metal to the base metal reduces significantly the stress concentration. This provides increasing the number of cycles before the onset of destruction and the survivability of compounds. Due to compressive stresses in the near-weld area, it is possible to increase the durability of joint welds. The most effective methods of further processing of welds combine the reduction of stress concentration and the creation of residual compression stresses. The high-tech solution is remelting the transition zone in an argon medium with an additional EP-410U filler wire.

**Keywords:** durability increase, cyclic loads, butt joints, stress concentration, residual stresses, origin and development of fracture.

**Acknowledgements.** The authors are deeply grateful to V. F. Lukyanov, Dr.Sci. (Engineering), professor, Head of the Machines and Welding Fabrication Automation Department, for years of joint work and academic advising.

**For citation.** Y. G. Lyudmirsky, V. P. Leonov, S. S. Assaulenko. Increasing the Durability of Butt-Welded Joints Operating under Cyclic Loads in a Biaxial Stress Field. Advanced Engineering Research, 2022, vol. 22, no. 3, pp. 232–241. https://doi.org/10.23947/2687-1653-2022-22-3-232-241

**Introduction.** Welded hull and shell structures operating under pressure are widely used in shipbuilding, chemical, power engineering and other industries. Reducing the metal consumption of such structures while increasing their efficiency is a critical task [1–4]. To reduce the weight of structures, it is required to use stronger materials under stresses close to the yield point. In this case, special requirements are put forward for the implementation of welded structures to ensure high structural strength. In other words, it is required to develop measures that increase the durability of structures to values close to the indicators of the base metal.

The work is aimed at studying the possibilities of increasing the durability of welded joints operating under cyclic loads in a corrosive environment (3 % *NaCl* solution), with the help of additional processing of joints.

**Materials and Methods.** Butt-welded joints were made of chromium-nickel-molybdenum steel. Preliminary heat treatment of sheet material provided yield limits of 900 MPa; 1,100 MPa; 1,150 MPa. The tests [5, 6] were carried out with a biaxial stress field and simultaneous action of repeated static loads in a corrosive environment (3 % *NaCl* solution). Manual multi-pass welding was performed with low-alloy electrodes 48H 11, 48H13, and austenitic electrodes EA 981/15. The failure nucleated from the stretched fibers, so the stress state was studied on the stretched surface of the sample. The stresses were determined by calculation. They were measured with a lever Huggenberger tensometer and tensoresistors with a base of 5 mm at a distance of 10 mm from the weld. If the measured stress values differed from the calculated values by more than 5 %, the pressure under the sample was corrected.

The failure of welded joints was localized along the transition line from the base metal to the weld metal, as shown in Figure 1.

Fig. 1. Fracture pattern of the butt-welded joint (photo of the authors)

The main reasons for the decrease in the working capacity of welded joints compared to sheet metal [7–11]:

– geometric stress concentration;

– residual welding stresses;

– deterioration of the structure and properties of the base metal in the near-weld area under the influence of the thermal welding cycle.

The influence of each of these factors can be partially or completely neutralized.

At the Department of "Machines and Automation of Welding Production", DSTU, butt-welded joints of high strength steels have been tested by various post-treatment methods for many years (Table 1). The experiments corresponded to the loading conditions of real structures.

Table 1

Techniques of additional treatments of butt-welded joints in the transition zone from the joint to the base metal

| No | Treatment |
|---|---|
| 1 | Cleaning with an abrasive wheel with a grain size of 80. Fillet radius $R$ = 30–40 mm |
| 2 | Grit hardening with AD-1 shot blaster with DSL–1.5cast steel shot. Pressure is 5 atm, head travel speed is 75 mm/min. Processing zone at the transition point from joint to metal is 15–30 mm |
| 3 | Cleaning the weld metal – base metal transition zone with an abrasive wheel by the first method, and grit hardening – by the second method |
| 4 | Washing in argon medium without filler wire. Diameter of the tungsten electrode – 3 mm, current $I$ = 120 A, arc voltage $U$ = 10–12 B, welding speed is 8 m/h, transverse vibration frequency – 60 min$^{-1}$, vibration amplitude – 6 mm |
| 5 | Washing with EP–410U filler wire by the fourth method. Filler wire diameter is 1.6 mm |
| 6 | Washing without filler wire by the fourth method. Plastic deformation between the beads. Bead diameter – 120 mm, width – 20 mm. Bead pressure – 18,000 kgf, rolling speed – 1.4 m/min. |

Physical and metallurgical processes occurring under welding cannot be modeled in full. Therefore, the tests were carried out on full-scale butt-welded joints with full preservation of the factory welding technology and geometric parameters of the joints. Low-cycle fatigue of welded joints was studied on samples in the form of disks with a diameter of 550 mm and a thickness of 30 mm on UDI–550 installation [12]. They were pivotally fixed along the contour and loaded with hydrostatic oil pressure. Under the action of hydrostatic pressure, the disk was axially bent. Compression stresses appeared on the inner surface, tensile stresses appeared on the outer surface, and a corrosive medium, a 3 % aqueous solution of sodium chloride, affected it. The samples were tested under repeated static loading with a frequency of 10 cycles/min.

The maximum stresses occurred in the central part of the samples. On a large surface, the statistical probability of the occurrence and development of failure is higher, which in general brings the test conditions closer to the real working conditions of the loaded hull structures.

**Research Results.** Table 2 shows the test results of samples after additional processing of welded joints under cyclic loading.

Table 2

Influence of additional methods of processing butt-welded joints on performance characteristics

| No. | Yield strength, MPa | Welding materials | Type of joint processing | Max cycle voltage, MPa | Additional processing | Number of cycles before | | Breaking point |
|---|---|---|---|---|---|---|---|---|
| | | | | | | appearance of cracks, $N_T$ | loss of tightness, $N_p$ | |
| 1 | 1,100 | EA 981/15 | 1st method: abrading | 700 | No | 2,600 | 20,560 | Transition line* |
| 2 | | | | | | 3,890 | 24,401 | |
| 3 | | | | | Yes | 10,840 | 27,237 | |
| 4 | | | | | | 9,115 | 28,947 | |
| 5 | 1,100 | 48H13 | 2nd method: grit hardening | 860 | No | 2,000 | 7,430 | Transition line |
| 6 | | | | | | 2,100 | 11,500 | |
| 7 | | | | | Yes | 1,410 | 27,349 | Transition line |

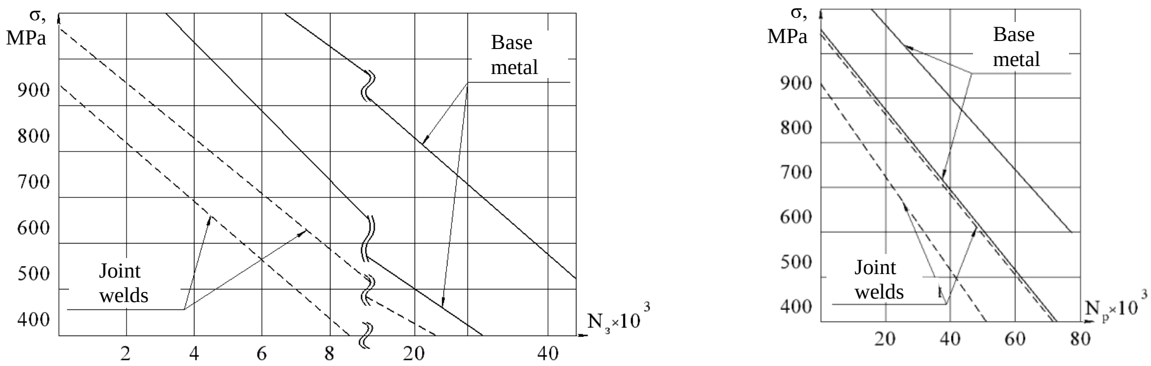
| No. | Yield strength, MPa | Welding materials | Type of joint processing | Max cycle voltage, MPa | Additio-nal process-ing | Number of cycles before: appearance of cracks, *N*т | Number of cycles before: loss of tightness, *Np* | Breaking point |
|---|---|---|---|---|---|---|---|---|
| 8 | | | | | | 2,000 | 14,051 | |
| 9 | 1,100 | 48H13 | 3rd method: abrad-ing and grit harden-ing | 700 | Yes | 10,670 | 32,310 | Transition line with access to the base metal |
| 10 | | | | | | 12,430 | 37,540 | |
| 11 | 1,100 | EA 981/15 | | 720 | Yes | 10,870 | 32,840 | |
| 12 | | | | | | 9,300 | 34,460 | |
| 13 | 1,100 | 48H13 | 4th method: wash-ing in argon without filler wire | 700 | No | 3,800 | 24,930 | Transition line with access to the base metal |
| 14 | | | | | | 2,680 | 21,980 | |
| 15 | | | | | Yes | 6,240 | 33,287 | |
| 16 | | | | | | 6,450 | 29,714 | |
| 17 | | EA 981/15 | | | Yes | 8,320 | 25,400 | |
| 18 | | | | | | 7,000 | 24,250 | |
| 19 | 900 | 48H11 | 5th method: surfac-ing of fillet bead with EP410U wire | 605 | No | 4,300 | 29,074 | Transition line |
| 20 | | | | | | 4,200 | 23,079 | |
| 21 | | | | | Yes | 25,600 | 100,000 | Base metal and perpendicular to the weld |
| 22 | | | | | | 29,800 | 58,384 | |
| 23 | | | | | | 30,910 | 91,300 | |
| 24 | | | | | | 24,100 | 86,000 | |
| 25 | 1,150 | 48H11 | 5th method | 720 | No | 3,386 | 22,639 | Transition line |
| 26 | | | | | | 2,566 | 22,433 | |
| 27 | | | | | Yes | 7,627 | 39,457 | Transition line and base metal |
| 28 | | | | | | 4,890 | 33,405 | |
| 29 | 1,150 | 48H13 | 5th method | 760 | No | 3,890 | 24,401 | Transition line |
| 30 | | | | | | 3,285 | 23,245 | |
| 31 | | | | | Yes | 8,500 | 36,400 | Transition line and base metal |
| 32 | | | | | | 9,886 | 34,636 | |
| 33 | 900 | 48H13 | Washing of fusion line + 6th method: weld rolling between narrow beads | 605 | No | 3,270 | 21,980 | Transition line |
| 34 | | | | | | 1,300 | 26,074 | |
| 35 | | | | | | 1,200 | 19,079 | |
| 36 | | | | | | 3,160 | 26,880 | |
| 37 | | | | | Yes | 20,860 | 48,210 | Base metal and cracks across the weld |
| 38 | | | | | | 19,321 | 139,300 | |
| 39 | | | | | | 17,300 | 93,552 | |
| 40 | | | | | | 24,475 | 99,910 | |
| 41 | | ЭА981/15 | | 720 | No | 3,386 | 22,630 | Transition line |
| 42 | | | | | | 2,566 | 22,433 | |
| 43 | | | | | Yes | 31,950 | 96,875 | Base metal and cracks across the weld |
| 44 | | | | | | 23,450 | 78,543 | |
| 45 | 1150 | 48H13 | | 760 | No | 3,285 | 23,245 | Transition line |
| 46 | | | | | Yes | 22,900 | 87,280 | Base metal and cracks across the weld |
| 47 | | | | | | 21,168 | 55,039 | |
| *from weld to base metal. | | | | | | | | |

Additional processing of welded joints by the 1st and 4th method (Table 1) reduced the stress concentration through increasing the interface radius of the weld metal and the base metal.

The 2nd method created small compressive stresses in the weld area, but practically did not change their concentration. An alternative to the proposed method is rolling the transition zone, presented in [13].

The third, fifth and sixth methods, in addition to reducing the stress concentration, made it possible to obtain favorable residual compression stresses in the transition zone from the weld metal to the base metal.

Figure 2 *a* shows the confidence intervals (95 %) of the failure initiation, and Figure 2 *b* — intervals before failure for welded joints (dotted lines) made according to the factory technology, and for the base metal (solid lines). The intervals were plotted according to the data from Table 2.




*a*) *b*)

Fig. 2. Comparison of the operability of the base metal and butt-welded joints under repeated static loading:
*a* — number of cycles before appearance of cracks; *b* — number of cycles before failure

The spread of values of resistance to damage and durability of butt-welded joints (Fig. 2 *a*) and the base metal (Fig. 2 *b*) depending on the maximum stresses at zero pulsating loading cycle are presented.

It can be seen that the resistance to the failure nucleation $N_з$ and the durability of butt-welded joints before failure $N_p$ (in this case, before the loss of tightness) is much less than that of the base metal.

To determine the compressive stresses generated in the joints as a result of processing, residual stresses were measured. This method is described in [14, 15].

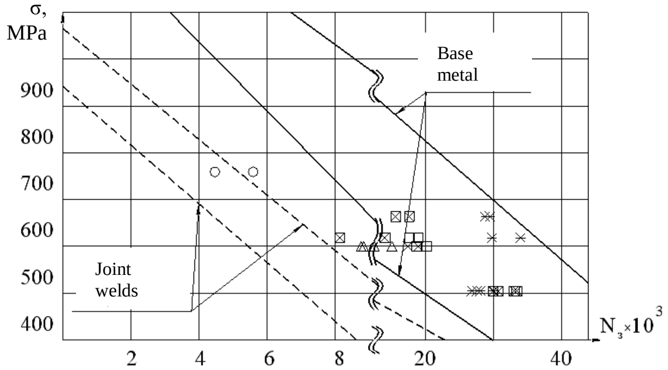
Table 3 presents the results of measurements of residual stresses in the direction perpendicular to the axis of the weld on the surface of the welded joints in the near-weld zone.

Table 3

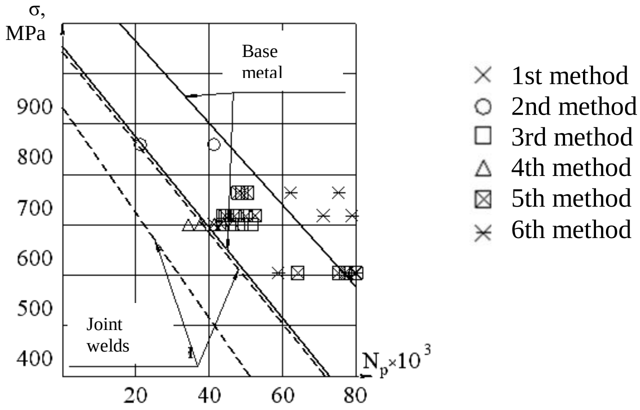
Residual compression stresses in the interface zone of weld metal and base metal,
depending on the additional processing methods

| Method of additional processing of the weld | Compressive stresses, MPa |
|---|---|
| 2nd and 3rd | 60–80 |
| 5th | 240–320 |
| 6th | 700–800 |

According to Table 2 and Figure 3, it is possible to judge the effectiveness of various methods of additional processing of welded joints operating under cyclic loading.




*a*)




*b*)

Fig. 3. Efficiency of methods of additional processing of the weld metal – base metal interface zone:
*a* — number of cycles before cracks appear; *b* — number of cycles before failure

Figure 3 shows the results of testing samples of butt-welded joints processed in different ways. Figure 3 *a* shows the confidence areas of the spread of values before the initiation of the destruction of the base metal and butt-welded joints without additional processing. Figure 3 *b* shows the same areas before the destruction of the samples (before loss of tightness).

Dressing the weld metal — base metal transition zone increased the resistance to the fracture nucleation due to a decrease in the concentration of stresses (Table 2). However, this method did not practically affect the fracture geometry. Cracks nucleated and developed along the interface line of the weld metal and the base metal.

Samples had a similar fracture pattern, in which the fusion line of the weld and base metal was washed by an arc in argon without a filler metal (4th method). This caused a decrease in stress concentration. As a result, the resistance to the failure nucleation increased. At the same time, the resistance to the development of fracture did not practically change (Fig. 3). The 4th method is more technologically advanced compared to the 1st one, since it does not require additional equipment other than welding.

Grit-hardening (2nd method) did not practically affect the damage resistance, determined by the number of cycles before the appearance of a visible crack — $N_T$, but increased the survivability — the number of cycles that the sample withstood after the formation of the first crack until it lost its bearing capacity (leak). This is due to the fact that grit-hardening does not guarantee uniformity of the surface deformation of the metal, specifically, at the junctions with undercuts, surges, craters, and non-melting outlines of the weld. It is here that failure starts. However, in places of smooth coupling of the weld metal and base metal, shot blasting, which caused the greatest compression stresses, prevented the formation of an extended main crack, which increased the resistance to the development of destruction.

To increase the efficiency of the grit-hardening, the 3rd method was proposed. Abrading was performed by the 1st method, and then shot blasting followed. In comparison to the 2nd method, the durability of the samples increased by about 20 % before the onset of fracture and before the loss of tightness. Comparison of the 1st and 3rd methods showed that the number of cycles before the fracture nucleation did not actually change, but the number of cycles before fracture (loss of tightness) increased by 20 %.

The 5th method [16] was washing with an EP–410U filler wire with a diameter of 1.6 mm. When cooled (140 $^{o}$C and below), the fillet beads underwent martensitic transformations. When cooled to room temperature, the volume increased by 1.5 % in total [11]. As it was shown earlier, this causes the appearance of residual compression stresses up to 300 MPa. Fillet beads with an increased specific volume contributed to an increase in damage resistance and the development of failure, i.e., an increase in survivability. In such joints, the first cracks appeared either on the base metal, away from the weld, or simultaneously along the transition line from the weld to the base metal (Table 2). Cracks found on the fusion line, as a rule, developed at a low rate, failure was caused by crack coalescence in the base metal and in the welded joint. The typical appearance of the welded joints, additionally processed by the 5th method, after the test is shown in Figure 4.

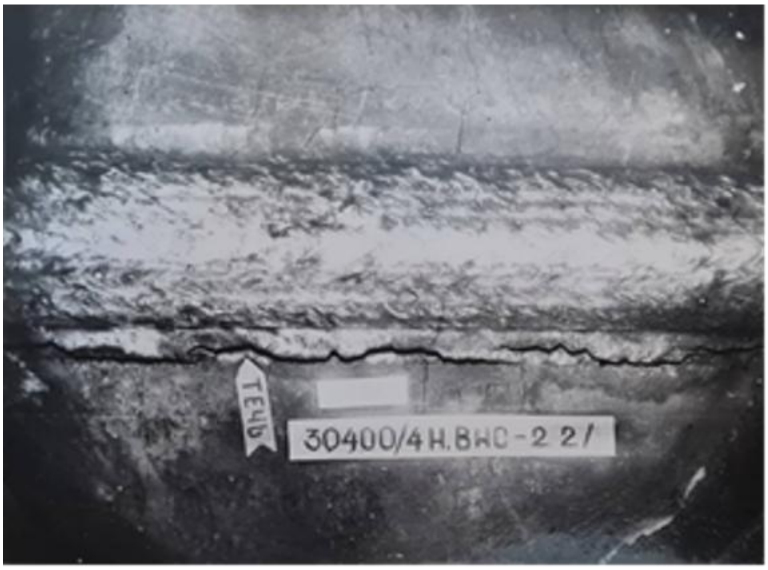


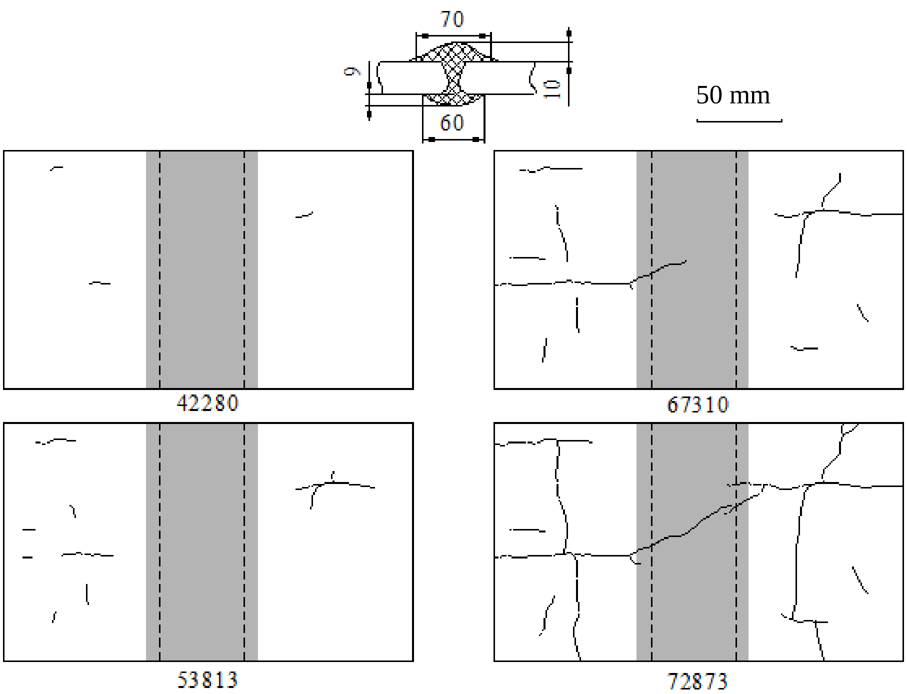

Fig. 4. Destruction of a butt-welded joint made by the 5th method (photo of the authors)

The considered type of treatment reduces the stress concentration along the entire length of the weld and creates favorable residual compression stresses in the area of the fillet beads with an increased specific volume.

The action of compressive stresses inhibits the fracture nucleation. With the development of cracks along the fillet bead, the action of transverse compressive stresses is no longer effective and is partly eliminated. This can explain the absence of the influence of beads of increased specific volume on the survivability of welded joints. If the failure nucleates not on the fillet bead, but on the base metal, the survivability of welded joints increases.

Treatment of the transition zone from the base metal to the weld metal by the 5th method increased the resistance to failure nucleation and development approximately 3–4 times. At the same time, the topography of the failure changed markedly. The first cracks, as a rule, originated in the base metal (Fig. 4). In the presence of poorly welded craters on the front surface of the weld, cracks initiated in these places and developed mainly perpendicular to the weld, but even in this case, the resistance to the failure nucleation and development remained quite high (Table 2, 5th method).

Surface plastic deformation of the near-weld zone [12] in butt joints by rolling with narrow beads (6th method) made it possible to bring the resistance to nucleation and development of failure to the level of similar characteristics of the base metal. This conclusion was confirmed by the fracture pattern of welded joints made by the 6th method (Fig. 5).




*a*)

*b*)

Fig. 5. Fracture nucleation and development pattern of the welded joint, whose interface zone was run between narrow beads (6th method):
*a* — record of the sample fracture development; *b* — appearance of the welded joint during fracture (photo of the authors)

It can be seen that the fracture nucleated and developed according to the basic method (Fig. 5 *a*, Table 2, and the fracture pattern of the joints, shown in Fig. 5 *b*). The washing of the fusion line and its subsequent running between the narrow beads (6th method) increased the resistance to the fracture nucleation by about eight times, the survivability of welded joints — by about four times.

**Discussion and Conclusions**

1. As initial samples, we considered welded joints made according to the factory technology without additional processing of the transition zone. In this case, during cyclic loading along the transition line from the weld metal to the base metal, multistage nucleation of fatigue cracks was observed. They developed rapidly and were combined into one mainline. Then, it developed in depth, which caused loss of tightness. The durability of welded joints turned out to be 2–3 times less than that of the base metal.

2. Two types of additional processing were involved:

– abrading of the transition zone from the weld to the base metal (1st method);

– remelting of the transition zone from the weld to the base metal with a non-melting electrode, an arc burning in an argon medium (4th method).

This made it possible to increase the resistance to the fracture nucleation by almost 2 times. The survivability of these welded joints did not change much.

3. Grit hardening (2nd method) did not practically affect the number of cycles before the fracture nucleation, but slightly increased the number of cycles before fracture.

4. Preliminary abrading of the weld metal – base metal transition zone and subsequent grit hardening (3rd method) increased the resistance of welded joints to the fracture nucleation and development by almost 1.5 times.

5. When the fillet bead was surfaced with a material with suitable volumetric changes (5th method), cracks occurred in the transition zone and in the base metal. At the same time, the resistance to the fracture nucleation and development increased approximately 3–4 times.

6. Washing without filler wire (4th method) and plastic deformation between narrow beads (6th method) provided an increase in the resistance to fracture and survivability of welded joints almost to the level of similar characteristics of the base metal.

**References**

1. Vinokurov VA, Kurkin SA, Nikolaev GA. Svarnye konstruktsii. Mekhanika razrusheniya i kriterii rabotosposobnosti. BE Paton (ed.) Moscow: Mashinostroenie; 1996. 576 p. (In Russ.)

2. Leonov VP, Malyshevskii VA. Structural and Technological Strength of Steel for Marine Structures. Metal Science and Heat Treatment. 2001;43:444.

3. Ilyin AV, Leonov VP, Filin VYu. Opredelenie parametra treshchinostoikosti CTOD dlya metalla svarnykh soedinenii sudokorpusnykh stalei pri nizkikh klimaticheskikh temperaturakh. Research Bulletin by Russian Maritime Register of Shipping. 2009;32:120–146. (In Russ.)

4. Fetisova EA, Lupachev AG. Peculiarities of Diffusion Processes in Dissimilar Steels Welded Joints. Vestnik of Belarusian-Russian University.2014;3:79–87. https://doi.org/10.53078/20778481_2014_3_79

5. Ilyin AV, Filin VYu. On the Problem of Quantitative Service Life Assessment for High-Strength Steel Welded Structures under the Effect of Corrosion Medium. Procedia Structural Integrity. 2019;14:964–977. https://doi.org/10.1016/j.prostr.2019.07.078

6. Kazuo Tateishi, Takeshi Hanji. Low Cycle Fatigue Strength of Butt-Welded Steel Joint by Means of New Testing System with Image Technique. International Journal of Fatigue. 2004;26:1349–1356. https://doi.org/10.1016/j.ijfatigue.2004.03.016

7. Peredelsky VA, Harchenko VY, Chernogorov AI, et al. On Detection of Crack-Like Welding Defects by Existing Quality Control Methods. Advanced Engineering Research. 2021;21(1):89–95. https://doi.org/10.23947/2687-1653-2021-21-1-89-95.

8. Bychenok VA, Berkutov IV, Mayorov AL, et al. Residual Stress Control in the near Seam Zone of the Welding Joint. Tekhnologiya Mashinostroeniya. 2019;12:45–50.

9. Leonov VP, Schastlivaya IA, Igolkina TN, et al. Application of Finite Element Method for Simulation of Stress-Strain State in Manufacturing of Long Turbine Blades Made of High-Strength Titanium Alloys. Inorganic Materials: Applied Research. 2014;5:578–586. https://doi.org/10.1134/S2075113314060069

10. Zerbst U, Hensel J. Application of Fracture Mechanics to Weld Fatigue. International Journal of Fatigue. 2020;139:105801. https://doi.org/10.1016/j.ijfatigue.2020.105801

11. Jong-Hyun Baek, Yun-Chan Jang, Ik-Joong Kim, et al. Influence of Weld Joint Geometry and Strength Mismatch on Load Bearing Capacity of API Pipeline. International Journal of Pressure Vessels and Piping. 2022;199:104737. https://doi.org/10.1016/j.ijpvp.2022.104737

12. Ilyin AV, Sadkin KE. Assessment of Structural and Technological Stress Concentration in Welded Joints for Fatigue Strength Estimation of Hull Structures. Materials Science Issues. 2012;2:161–176.

13. Lyudmirskii YG, Assaulenko SS, Ageev SO. Constructive and Technological Method of Increasing Durability of "Choke Connections". Journal of Physics Conference Series. 2021;2131:042061. https://doi.org/10.1088/1742-6596/2131/4/042061

14. Franks J, Wheatley G, Zamani P, et al. Fatigue Life Improvement Using Low Transformation Temperature Weld Material with Measurement of Residual Stress. International Journal of Fatigue. 2022;164:107137. https://doi.org/10.1016/j.ijfatigue.2022.107137

15. Ritsu Nishimura, Ninshu Ma, Yong Liu, et al. Measurement and Analysis of Welding Deformation and Residual Stress in CMT Welded Lap Joints of 1180 MPa Steel Sheets. Journal of Manufacturing Processes. 2021;72:515–528. https://doi.org/10.1016/j.jmapro.2021.10.050

16. Xiaohui Zhao, Yanjun Fan, Yu Liu, et al. Evaluation of Fatigue Fracture Mechanism in a Flash Butt Welding Joint of a U75V Type Steel for Railroad Applications. Engineering Failure Analysis. 2015;55:26–38. https://doi.org/10.1016/j.engfailanal.2015.05.001

Received 08.08.2022
Revised 29.08.2022
Accepted 07.09.2022

*About the Authors:*

**Lyudmirsky, Yury G.,** professor of the Machines and Automation of Welding Production Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), Dr.Sci. (Eng.), professor, ScopusID, ORCID, lyudmirskiy40@mail.ru

**Leonov, Valery P.,** Deputy director general, Central Research Institute of Structural Materials “Prometey” named after I.V. Gorynin of National Research Center “Kurchatov Institute” (49, Shpalernaya St., Petersburg, 191015, RF), Dr.Sci. (Eng.), ScopusID, ORCID, leonov_vp@spbstu.ru

**Assaulenko, Semyon S.,** senior lecturer of the Machines and Automation of Welding Production Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344003, RF), ScopusID, ORCID, assaulenko_s@mail.ru

*Claimed contributorship:*

Yu. G. Lyudmirsky: academic advising; the text revision; formulation of conclusions. V. P. Leonov: analysis of the research results; correction of the conclusions. S. S. Assaulenko: basic concept formulation; research objectives and tasks; computational analysis; text preparation.

*Conflict of interest statement*

The authors do not have any conflict of interest.

*All authors have read and approved the final manuscript.*